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REGIONAL-LEVEL ANALYSIS FOR THE MATERIAL FLOWS AND PROCESS ENERGY DEMANDS OF ALUMINUM AND STEEL IN THE AMERICAN AUTOMOTIVE INDUSTRY

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CENTER FOR
SUSTAINABLE SYSTEMS
UNIVERSITY OF MICHIGAN

Regional-level analysis for the material flows and process energy demands of aluminum and steel in the American automotive industry

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ACRONYMS AND ABBREVIATIONS

Acronyms:

AA	Aluminum Association
AAPC	American Automotive Policy Council
ACC	American Chemistry Council
ACCCI	American Coke and Coal Chemicals Institute
AHSS	advanced high strength steel
AISI	American Iron and Steel Institute
ANL	Argonne National Laboratory
BIW	body in white
BOF	basic oxygen furnace
DRI	direct reduced iron
EAF	electric arc furnace
GHG	greenhouse gas
GREET	The greenhouse gases, regulated emissions, and energy use in transportation model
HDV	heavy duty vehicle
IEA	International Energy Agency
IETD	Industrial Efficiency Technology Database
IPP	Institute for Industrial Productivity
kt	thousand metric ton
LCA	life cycle assessment
LCI	life cycle inventory
LDV	light duty vehicle (passenger cars and light duty trucks/commercial vehicles)

MFA	material flow analysis
NERC	North American Electric Reliability Corporation
OEM	original equipment manufacturer
OICA	International Organization of Motor Vehicle Manufacturers
SEC	United States Securities and Exchange Commissions
SRI	Steel Recycling Institute
TJ	terajoule
UHSS	ultra high strength steel
USA EIA	United States Energy Information Administration
USA EPA	United States Environmental Protection Agency
UN	United Nations
USGS	United States Geological Survey

Abbreviations:

American automotive industry	*For aluminum*: the LDV industry in the USA and Canada *For steel*: the automotive industry in the USA
Automotive aluminum and steel	The aluminum and steel that ultimately enter the American automotive industry
Entering the American Automotive Industry	*For aluminum*: upstream of aluminum mill products, when a material is referenced as entering the American automotive industry, it means it is processed in stages until reaching the mill product form factor, where it then enters the American automotive industry *For steel*: upstream of steel mill products and steel in finished parts, when a material is referenced as entering the American automotive industry, it means it is processed in stages until reaching the mill product form factor, where it then enters the American automotive industry

EXECUTIVE SUMMARY

Aluminum and steel dominate the material composition of American light duty vehicles (LDV), representing 12% and 54% of an LDV's curb weight, respectively, as of 2018 (Ducker FSG Holdings, LLC [Ducker], 2018). With rising concerns about the American automotive sector's sustainability, gaining a better understanding of the automotive aluminum and steel supply chains can provide valuable insight towards better assessing the energy demand and greenhouse gas burden of a vehicle's materials on a global and regional basis.

This study details the development of a method and framework for regionally linked, sector-specific material flow analysis (MFA) models and presents the results of such models for aluminum and steel entering the American automotive industry (henceforth termed automotive aluminum and automotive steel). Additionally, the models facilitate a regionalized perspective of the process energy demands associated with automotive aluminum and steel, including their respective raw materials.

Figure ES 1 shows the geography of material flows for automotive aluminum in 2016. The mass flows of mill products (sheet and extrusions) are sorted by North American Electric Reliability Corporation (NERC) regions if originating from the USA and Canadian provincial region if originating from Canada. Mass flows unable to be distinguished into such categories were aggregated into a regionally unresolved Local region with boundaries of the USA and Canada. Major mill product mass flow regions include NPCC (23%), SERC (20%), MRO (18%), RFC (13%), and Local (18%). Of the primary aluminum entering the American automotive industry, 94% is sourced from within the USA and Canada, with Quebec accounting for nearly 70% of the primary aluminum supply. Aluminum scrap flows entering the American automotive industry were determined to be out of the scope of this study and not regionally analyzed. Upstream of primary aluminum, the alumina entering the American automotive industry is largely internationally sourced (91%). Further upstream, bauxite is completely internationally sourced. Both materials come primarily from the southern hemisphere. Considering the entire production cycle of automotive aluminum, from bauxite to mill product, the regional distribution of the total process energy demand embodied in automotive aluminum by energy input is shown in Figure ES 2. It is largely influenced by the primary aluminum entering the American automotive industry (Figure ES 3). This highlights the significant energy, particularly electricity, required for primary aluminum production and its dominance of energy demand in automotive aluminum's production cycle.

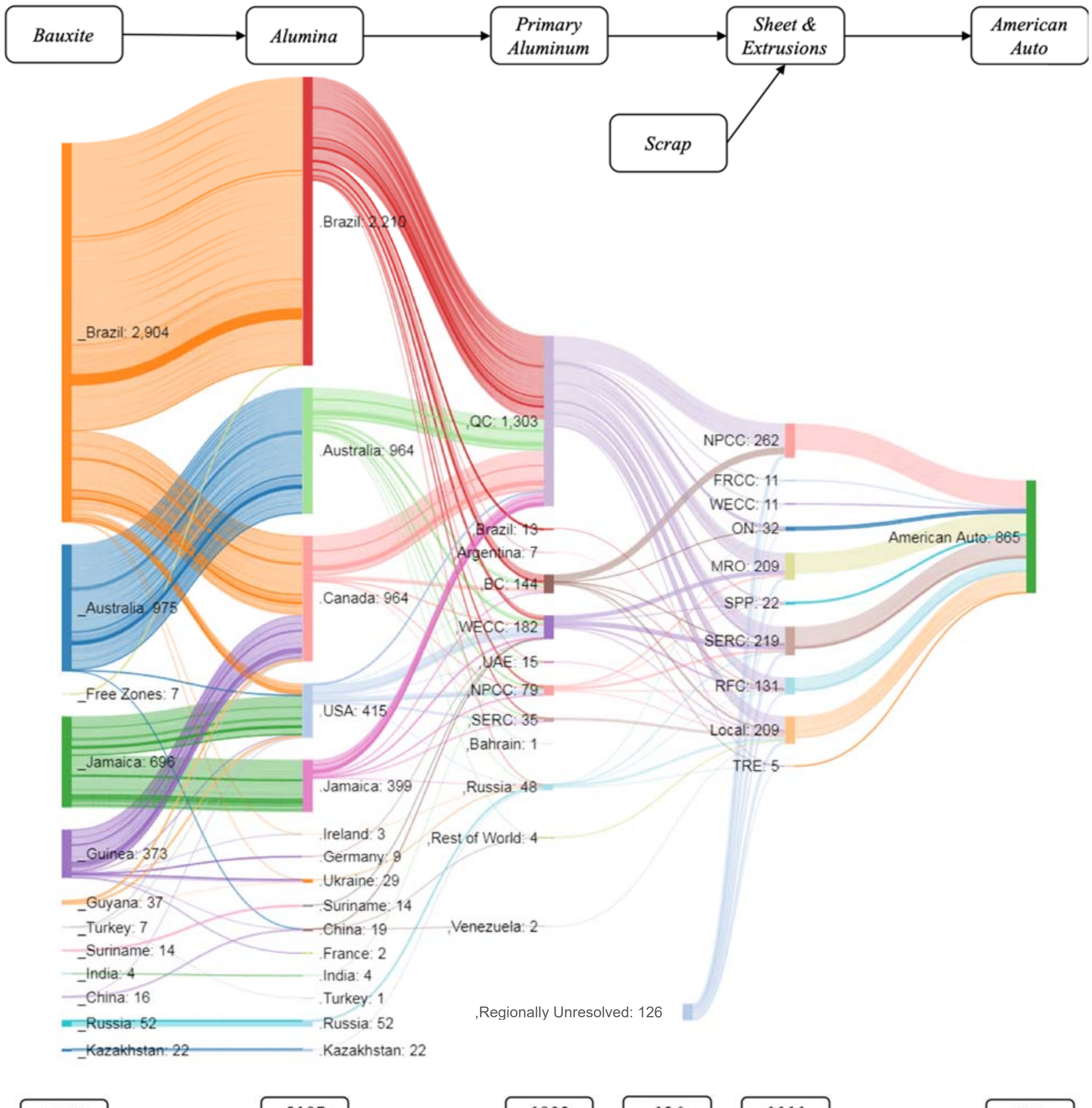

Figure ES 1: The flow of aluminum into the American automotive industry. Nodes represent from left to right: bauxite, alumina, primary aluminum, scrap, aluminum mill products, and the American automotive industry. For primary aluminum and aluminum mill products, USA is divided geographically into NERC regions plus a regionally unresolved Local region, Canada is divided by province, and other countries are not divided. For bauxite and alumina, regional analysis is kept at the country level. While scrap is not regionally analyzed in this study, it is assumed that all scrap entering the American automotive industry comes from the USA here in this Sankey. Flows account for masses of each material product (in kt) and losses occur at each node. Total mass flows at each material product stage are represented at the bottom of the figure. The left most value is the total mass of bauxite required. The mass flow value below Scrap represents only the mass flow of Scrap. The mass flow value below Sheet & Extrusions represents only the mass of primary aluminum entering sheet and extrusions production. Each subsequent value represents the mass flow of the direct upstream material. Individual flows less than 1 kt are not represented and therefore total mass flows at each material product state shown here differ from actual modeled values.

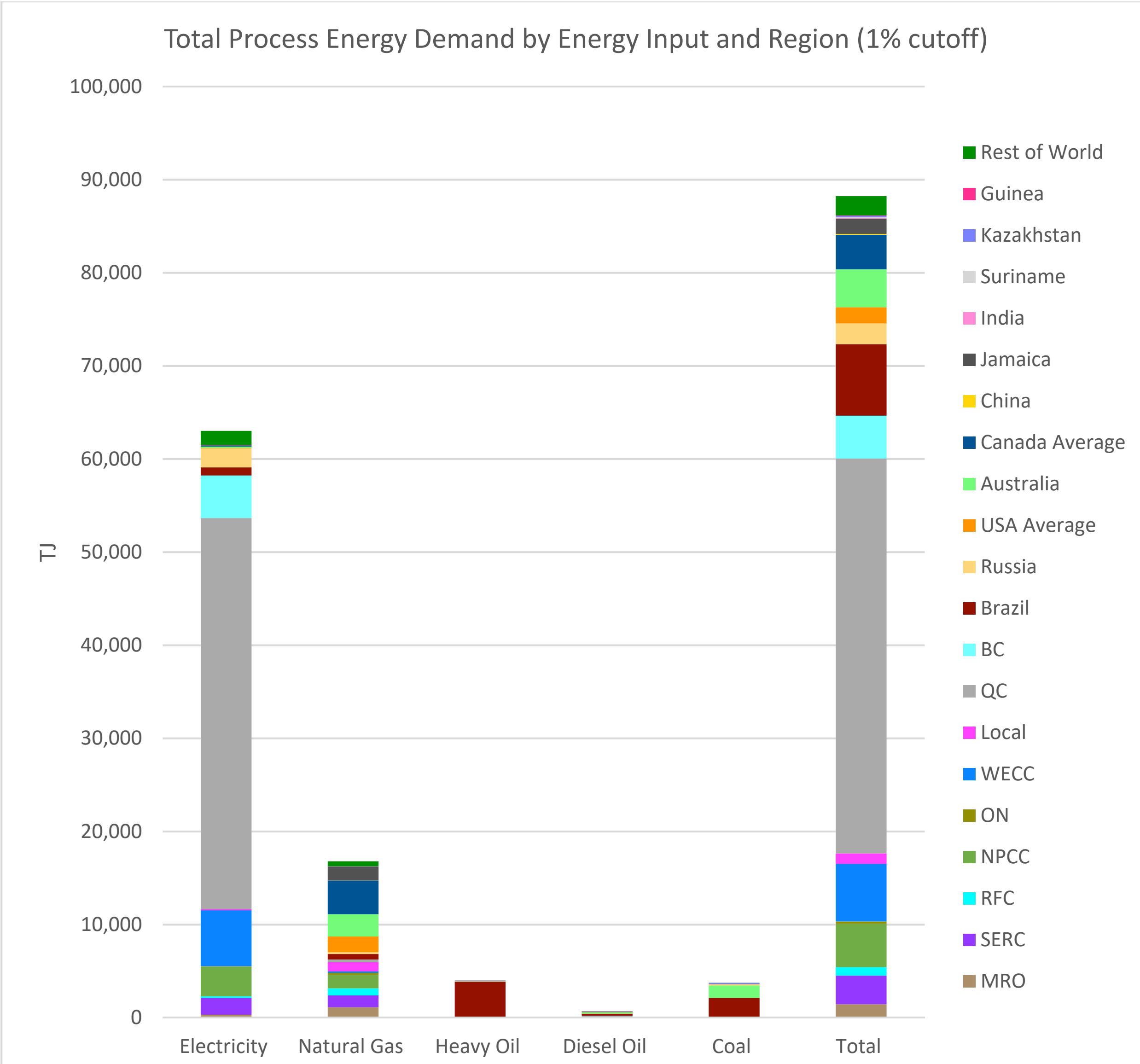

Figure ES 2: Regional distribution of total process energy demand for automotive aluminum by energy input. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

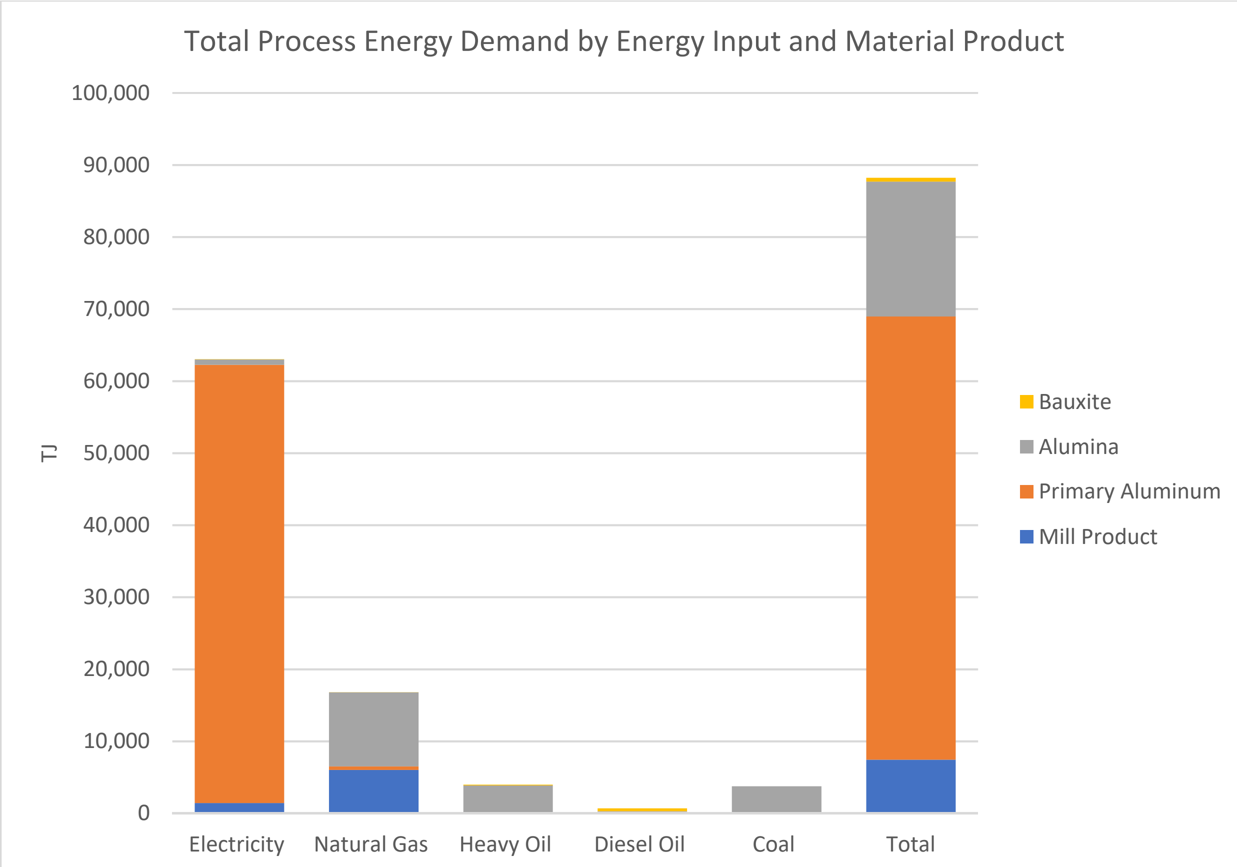

Figure ES 3: Distribution of the total process energy demand for automotive aluminum by energy input and further separated by material product.

Figure ES 4-Figure ES 9 show that the large majority of automotive steel mill product comes from the RFC (63%) and SERC (20%) NERC regions, with only Canada and Turkey contributing over one percent of the overall mass flow. The same regional dominance by the RFC and SERC regions is observed for crude steel that enters the American automotive industry. RFC processes 69% of the crude steel supply by mass while SERC processes 7%. The regional distributions of coke, coking coal, iron ore, lime, and steel scrap exhibit the dominance of the USA in supplying these raw materials for automotive steel. Coke is primarily sourced from the RFC (67%) and SERC (10%) regions in large part because those are the regions where most crude steel is produced in the USA (Figure ES 4). Conversely, the majority of direct reduced iron (DRI) and pig iron used for automotive steel is internationally sourced. SERC represents 24% and TRE 16% of the total DRI supply for automotive steel, but international sources constitute 56% of the total, with Trinidad and Tobago alone supplying 30% (Figure ES 8). The pig iron supply for automotive steel is heavily dominated by international sources, with Russia (38%), Ukraine (16%), and Brazil (16%) supplying the largest fractions (Figure ES 9). Although the total process energy demand for automotive steel is dominated by the USA (75%) and especially the RFC (54%) and SERC (10%) regions, large international sourcing of energy intensive DRI and pig iron brings down the USA's overall share in total process energy demand (Figure ES 10) compared to its share in total mass of material products supplied. Further, through Figure ES 11 we observe that coke is the largest contributor to the process energy embodied by automotive steel.

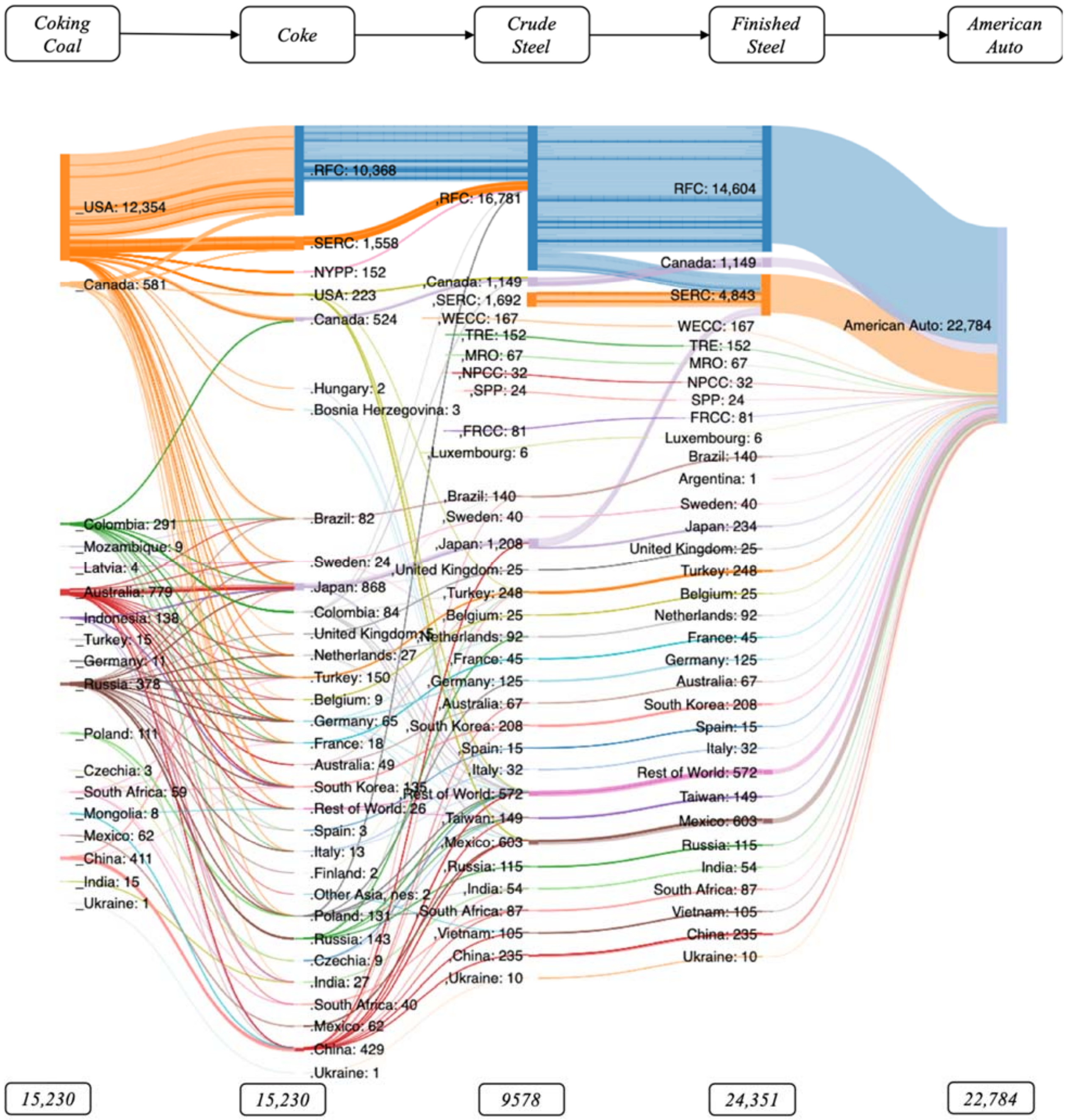

Figure ES 4: The flows of coking coal, coke, crude steel, and finished steel (steel mill products and steel in finished automotive parts) into the American automotive industry. Nodes represent (from left to right): coking coal, coke, crude steel, finished steel, and the American automotive industry. USA is divided geographically by NERC region, except for coking coal which is totaled by country. A general USA region is observed for coke because the USA is a large net exporter of coke to crude steel producing countries from which the USA imports crude steel. Flows account for masses of each material product (in kt). Coke is only one material input for crude steel production. Losses occur at each node. Total mass flows at each material product stage are represented at the bottom of the figure. The left most value is the total mass of coking coal required. Each subsequent value represents the mass flow of the direct upstream material. Individual flows less than 1 kt are not represented and therefore total mass flows at each material product state shown here differ from actual modeled values.

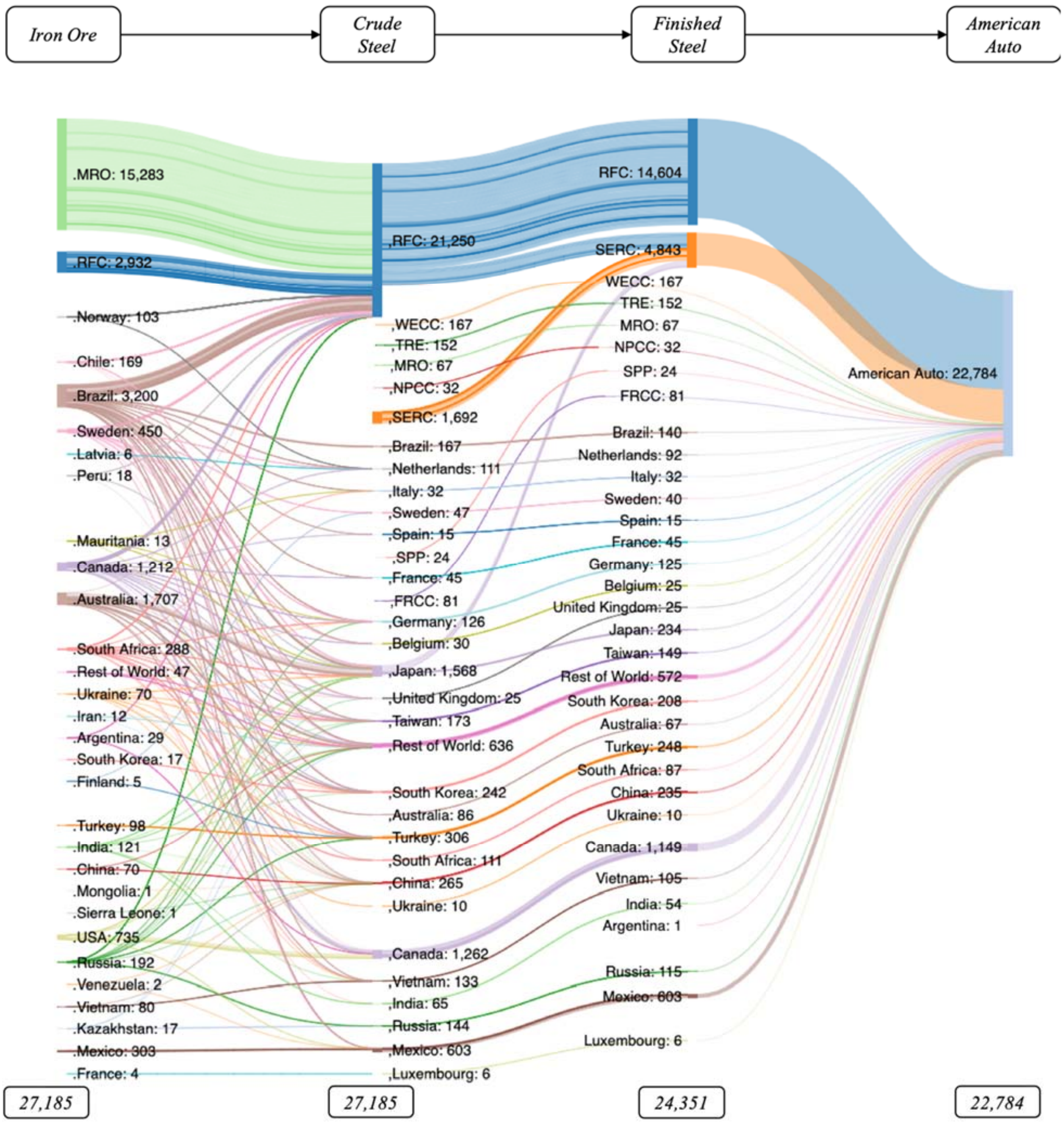

Figure ES 5: The flow of iron ore, crude steel, and finished steel (steel mill products and steel in finished automotive parts) into the American automotive industry. Nodes represent (from left to right): iron ore, crude steel, finished steel, and the American automotive industry. USA is divided geographically by NERC region. A general USA region is observed for iron ore because the USA is a large net exporter of iron ore to crude steel producing countries from which the USA imports crude steel. Flows account for masses of each material product (in kt). Iron ore is only one material input for crude steel production. Losses occur at each node. Total mass flows at each material product stage are represented at the bottom of the figure. The left most value is the total mass of iron ore required. Each subsequent value represents the mass flow of the direct upstream material. Individual flows less than 1 kt are not represented and therefore total mass flows at each material product state shown here differ from actual modeled values.

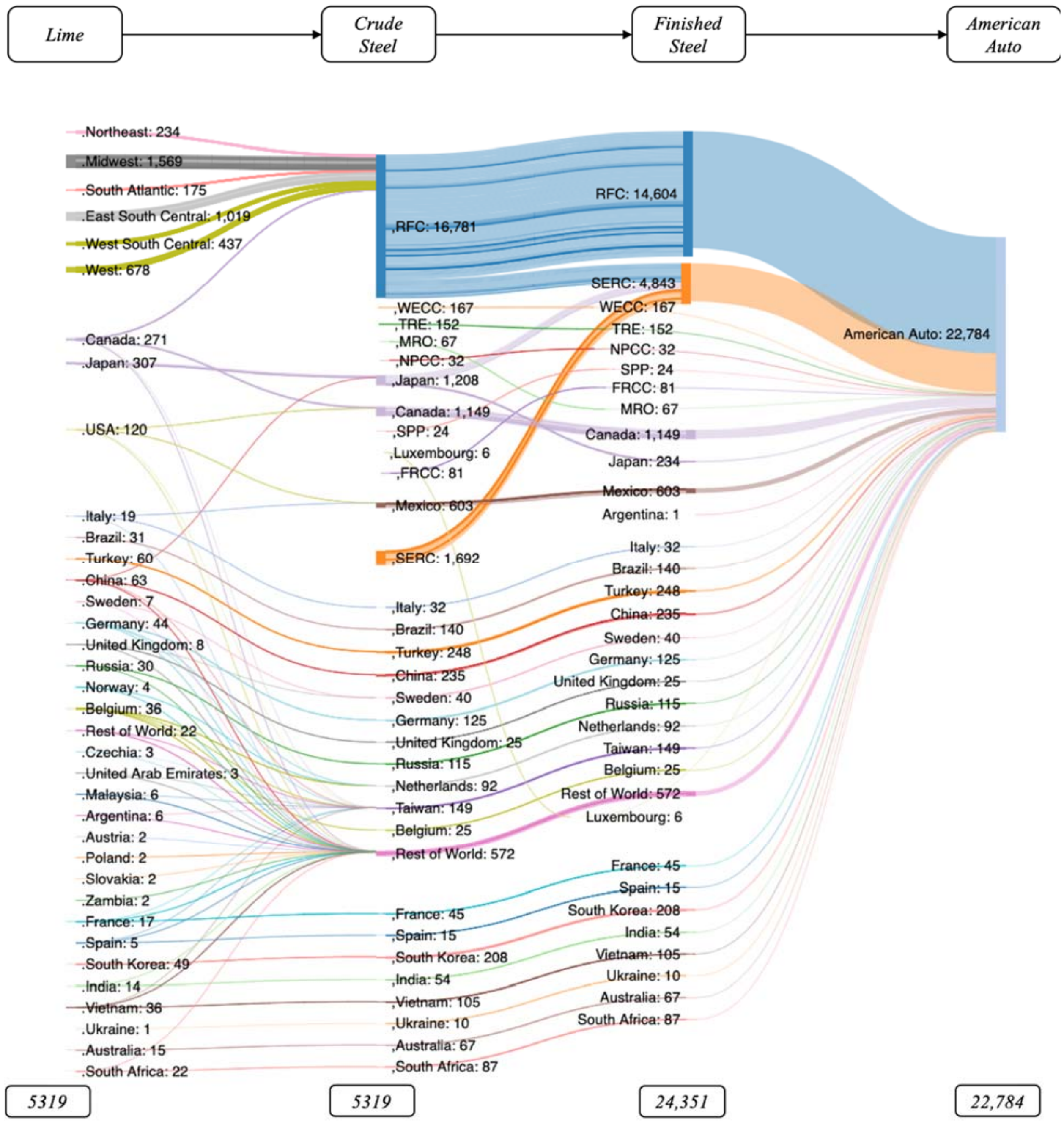

Figure ES 6: The flow of lime, crude steel, and finished steel (steel mill products and steel in finished automotive parts) into the American automotive industry. Nodes represent (from left to right): lime, crude steel, finished steel, and the American automotive industry. USA is divided geographically by NERC region, except for lime which is divided geographically by census region and division. A general USA region is observed for lime because the USA is a large net exporter of lime to crude steel producing countries from which the USA imports crude steel. Flows account for masses of each material product (in kt). Lime is only one material input for crude steel production. Losses occur at each node. Total mass flows at each material product stage are represented at the bottom of the figure. The left most value is the total mass of lime required. Each subsequent value represents the mass flow of the direct upstream material. Individual flows less than 1 kt are not represented and therefore total mass flows at each material product state shown here differ from actual modeled values.

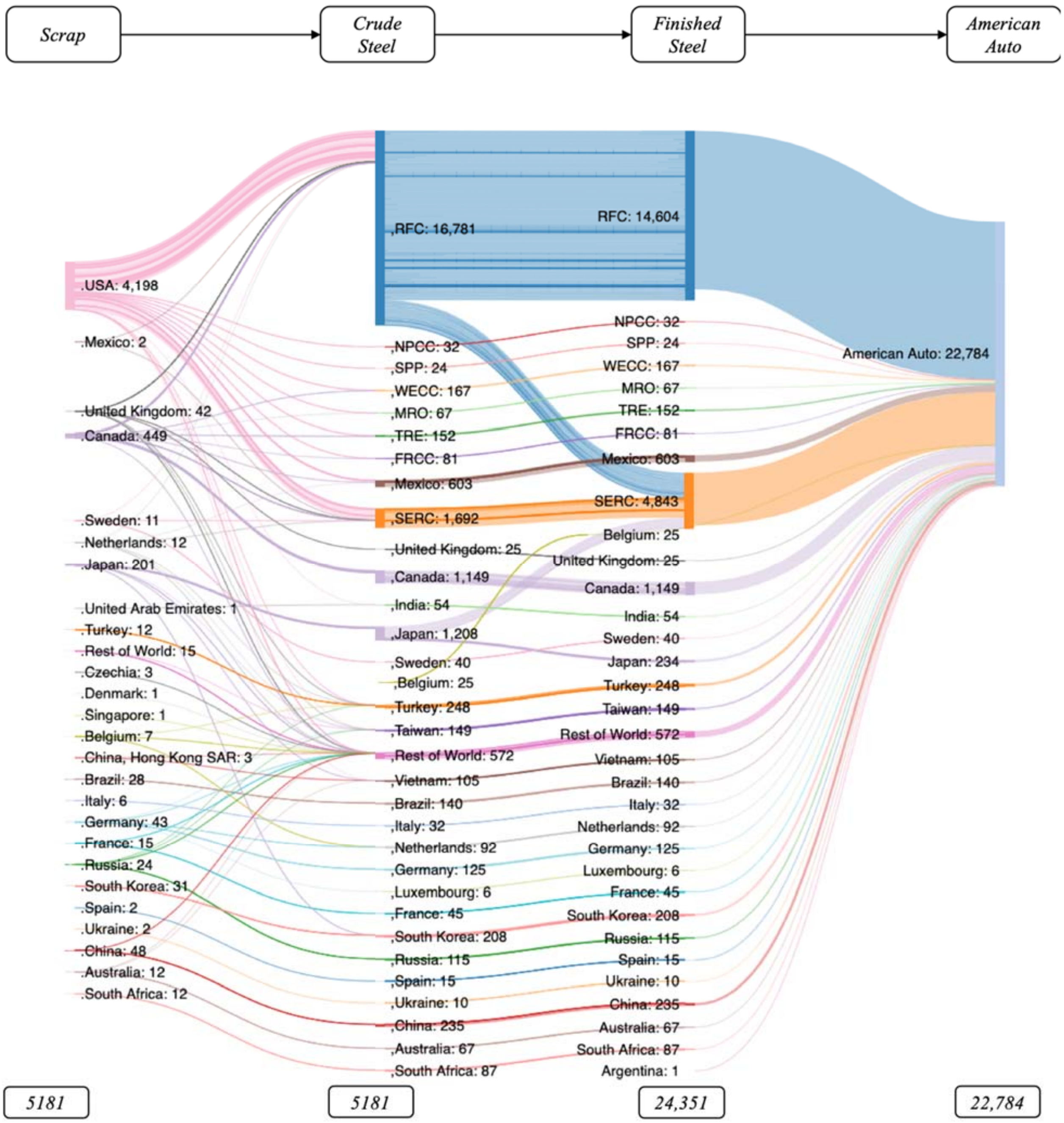

Figure ES 7: The flow of scrap, crude steel, and finished steel (steel mill products and steel in finished automotive parts) into the American automotive industry. Nodes represent (from left to right): scrap, crude steel, finished steel, and the American automotive industry. USA is divided geographically by NERC region, except for scrap which is totaled by country. Flows account for masses of each material product (in kt). Scrap is only one material input for crude steel production. Losses occur at each node. Total mass flows at each material product stage are represented at the bottom of the figure. The left most value is the total mass of scrap required. Each subsequent value represents the mass flow of the direct upstream material. Individual flows less than 1 kt are not represented and therefore total mass flows at each material product state shown here differ from actual modeled values.

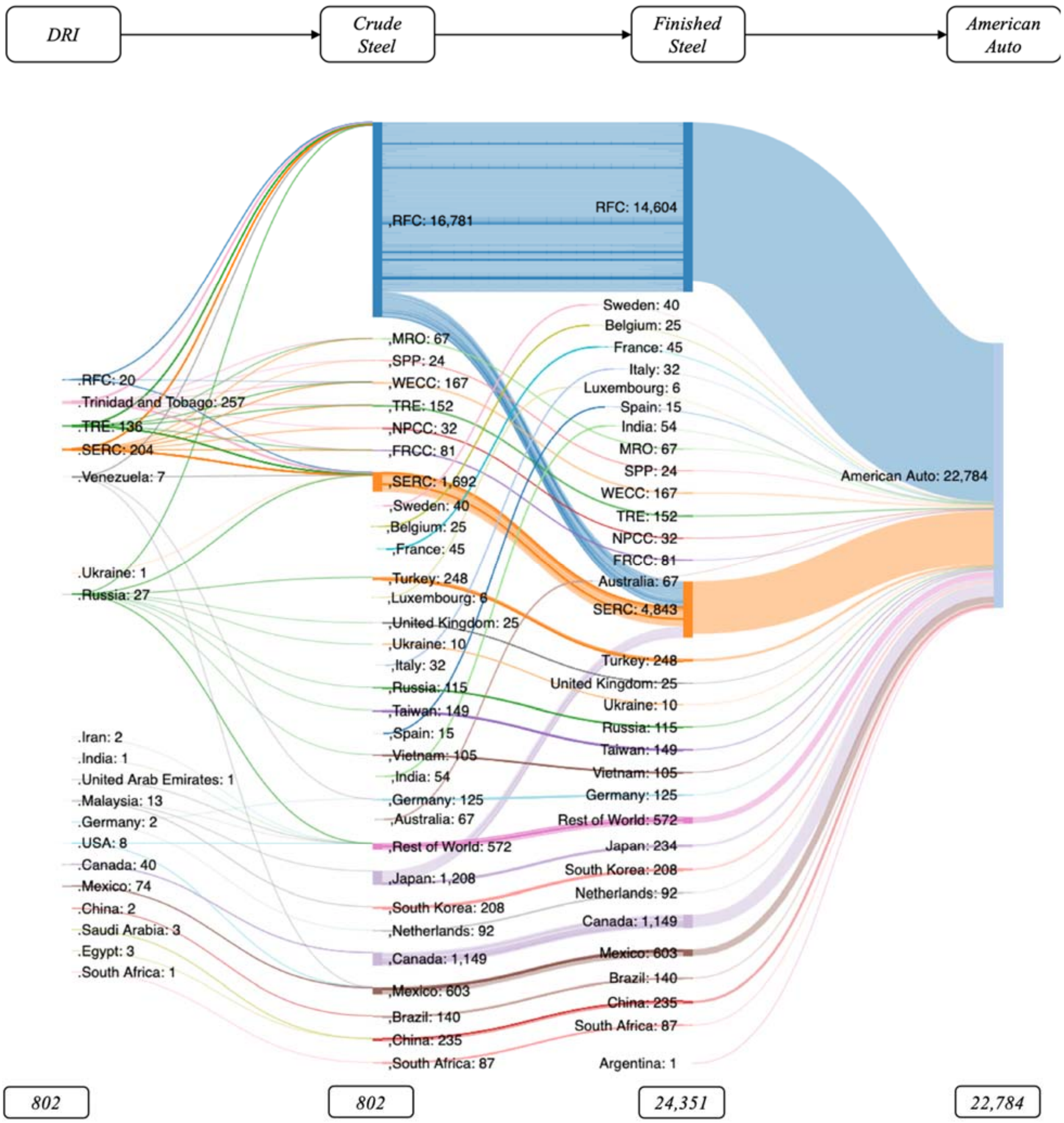

Figure ES 8: The flow of DRI, crude steel, and finished steel (steel mill products and steel in finished automotive parts) into the American automotive industry. Nodes represent (from left to right): DRI, crude steel, finished steel, and the American automotive industry. USA is divided geographically by NERC region. A general USA region is observed for DRI because the USA is a large net exporter of DRI to crude steel producing countries from which the USA imports crude steel. Flows account for masses of each material product (in kt). DRI is only one material input for crude steel production. Losses occur at each node. Total mass flows at each material product stage are represented at the bottom of the figure. The left most value is the total mass of DRI required. Each subsequent value represents the mass flow of the direct upstream material. Individual flows less than 1 kt are not represented and therefore total mass flows at each material product state shown here differ from actual modeled values.

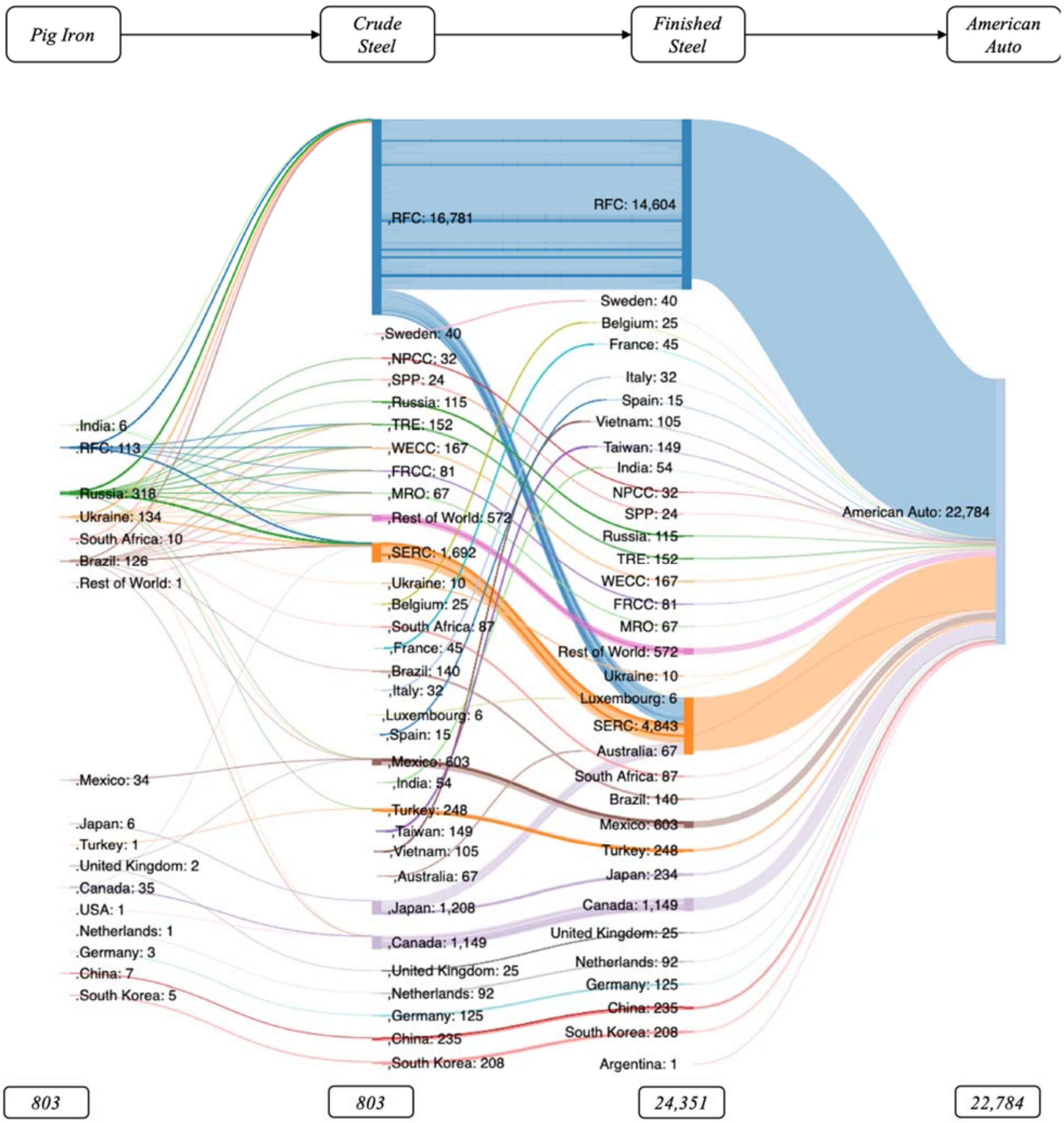

Figure ES 9: The flow of pig iron, crude steel, and finished steel (steel mill products and steel in finished automotive parts) into the American automotive industry. Nodes represent (from left to right): pig iron, crude steel, finished steel, and the American automotive industry. USA is divided geographically by NERC region. A general USA region is observed for pig iron because the USA is a large net exporter of pig iron to crude steel producing countries from which the USA imports crude steel. Flows account for masses of each material product (in kt). Pig iron is only one material input for crude steel production. Losses occur at each node. Total mass flows at each material product stage are represented at the bottom of the figure. The left most value is the total mass of pig iron required. Each subsequent value represents the mass flow of the direct upstream material. Individual flows less than 1 kt are not represented and therefore total mass flows at each material product state shown here differ from actual modeled values.

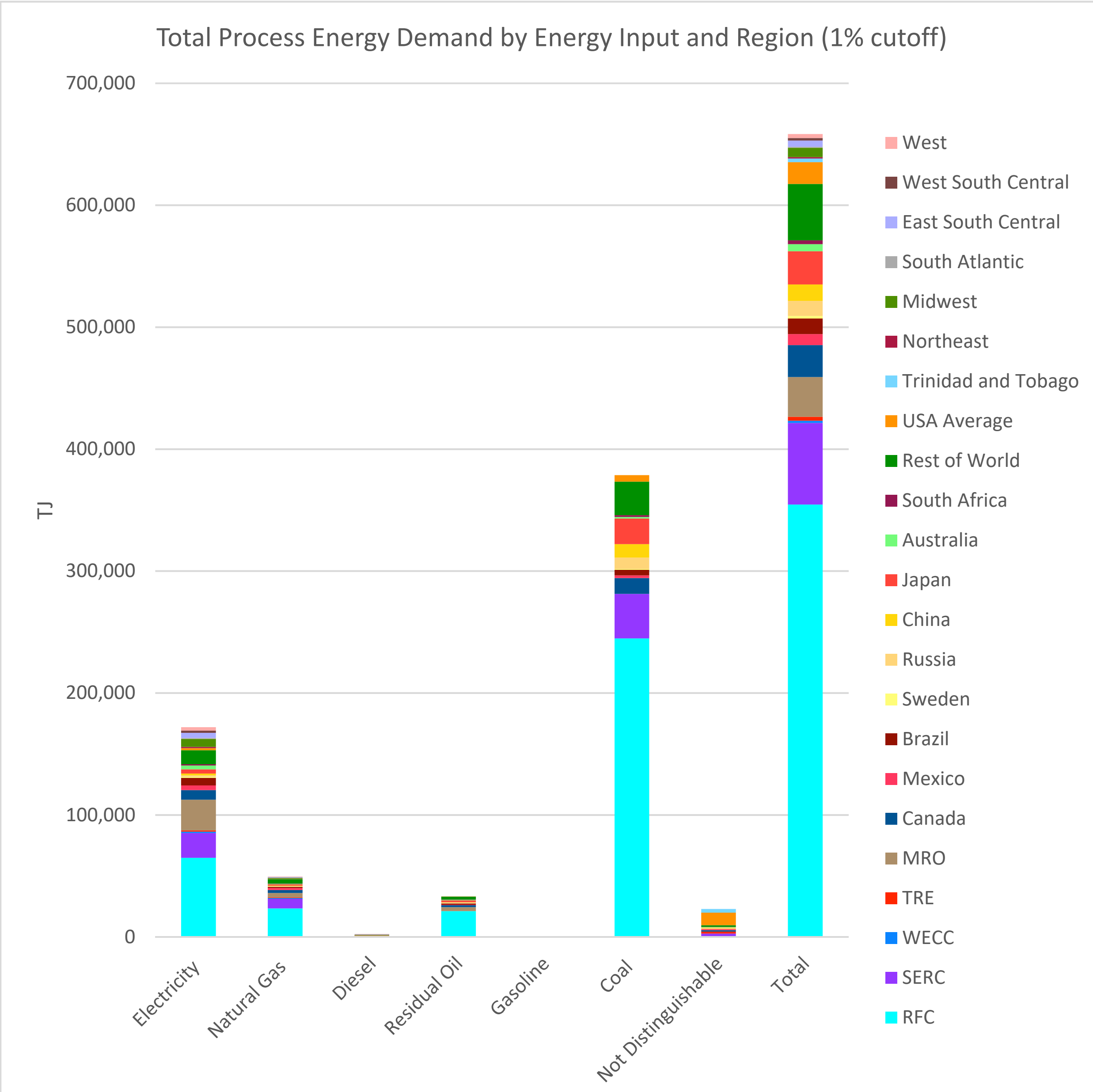

Figure ES 10: Regional distribution of total process energy demand for automotive steel by energy input. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

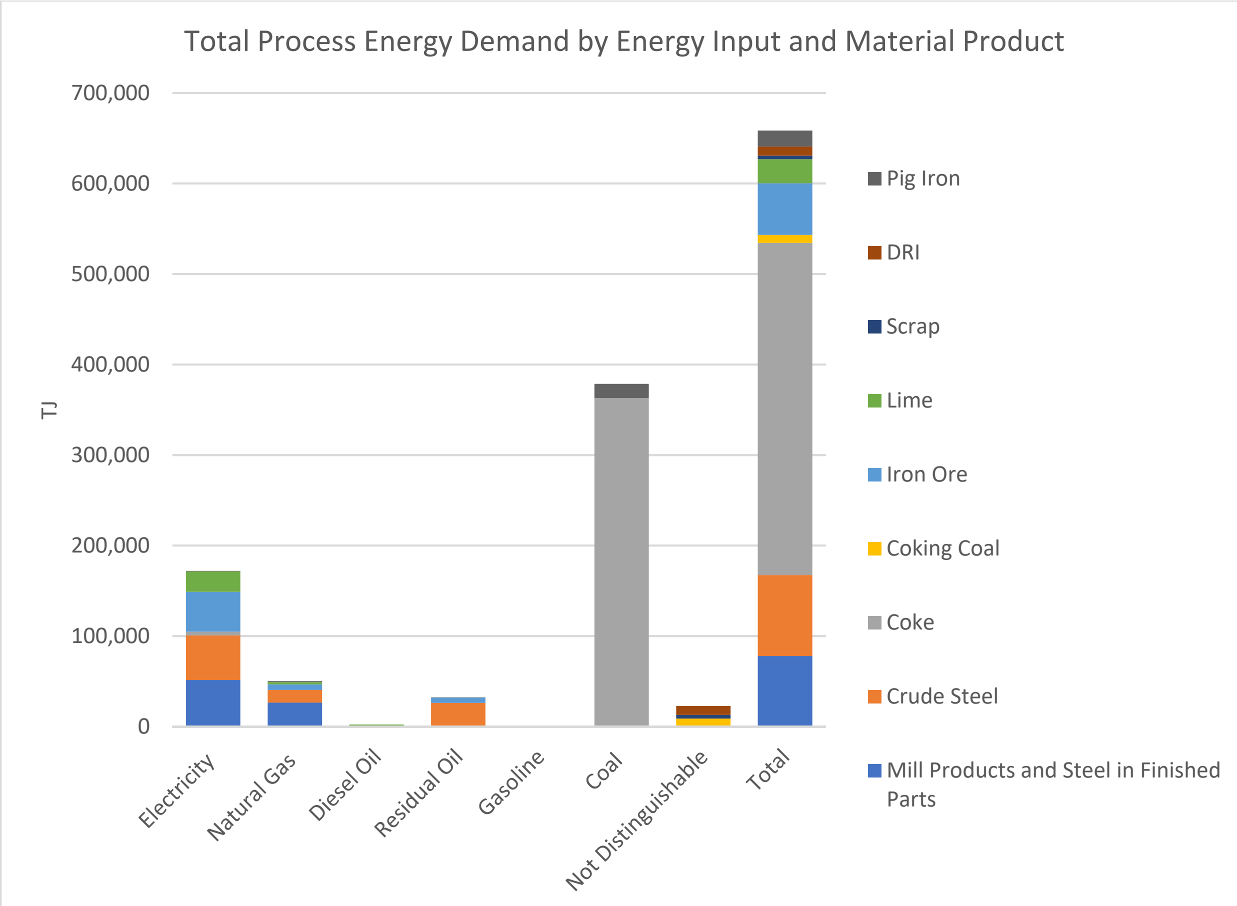

Figure ES 11: Distribution of the total process energy demand for automotive steel by energy input and further separated by material product.

The method and framework developed by this study, outlined briefly in Figure ES 12, can be used to inform future MFAs seeking regional details of the flow of a specific material into a specific sector. The results from applying this method to automotive aluminum and steel may be used to help inform the sustainability of the American automotive, aluminum, and steel industries and integrated into future automotive centric life cycle assessment (LCA) models to provide more geographically specific energy demand data.

1. Obtain sector-specific industry shipment data for a specific material
2. Decide on desired levels of regionality
3. Disaggregate sector-specific shipment data by material products
4. Identify material product producers and facility locations
5. Weight material product producers by market share and facility supply share
6. Identify upstream crude material product(s) if any
7. Identify crude material producers and producer locations
8. Weight crude material producers by market share and facility supply share
9. Identify major supply relationships between material product producers and crude material producers
10. Determine crude material raw material inputs
11. Identify country level supply mixes of raw materials for crude material producers
12. Calculate regional material flows along the material life cycle
13. Aggregate results to the desired level of regionality

Figure ES 12: Generalized framework for developing a regionally linked, sector-specific MFA.

1. INTRODUCTION

1.1 BACKGROUND AND INTEREST

The transportation sector is responsible for the most greenhouse gas (GHG) emissions in the USA (USA Environmental Protection Agency [USA EPA], 2018) and second most in Canada (Environment and Climate Change Canada, 2019), with LDVs representing over half of those emissions in both countries. As the need to restrict GHG emissions becomes increasingly urgent for climate change mitigation, the light duty vehicle industry faces a major challenge and opportunity.

Aluminum and steel are the two most dominant materials in light duty vehicles—composing the bulk of the vehicle body, chassis, and powertrain—and as of 2018 represent 12% and 54% of an LDV's curb weight by mass respectively (Ducker, 2018). As such, these two metals significantly influence the vehicle's life cycle impacts.

The use of aluminum in LDVs is projected to continue increasing to 16% of a LDV's weight sometime between 2025 and 2028 (Ducker, 2017b) as automakers seek to continue reducing vehicle weight, primarily through the integration of aluminum sheet and extrusions (Ducker, 2017a) into bodywork. Although reducing a vehicle's weight using aluminum may increase fuel economy, it is not without consequences since automotive-grade aluminum sheet and extrusions often require large amounts of primary aluminum (UChicago Argonne, LLC [ANL], 2018), which is highly electricity-intensive (World Aluminum, 2017).

Steel has long been the predominant metal used in LDVs and, although projected to slightly decrease to 47% of curb weight between 2025 and 2028, will remain the dominant vehicular metal (Ducker, 2017b). While automotive steel has traditionally been dominated by basic oxygen furnace (BOF) steel production, which is heavily coal dependent due to the necessary use of coke, electric arc furnace (EAF) steel production with its electricity-intensive process to melt steel scrap, pig iron, and DRI is projected to increase in automotive steel production (Tolomeo, Fitzgerald, & Eckelman 2019).

The persistence and projections of aluminum and steel in LDVs motivate the need for more detailed material flow analysis associated with the two metals. Further adding to the motivation is the complexity of supply chains within the American automotive industry, with materials and components being sourced from a large variety of suppliers in various locations. In order to best characterize the impacts of aluminum and steel to the vehicle cycle of an LDV, regional mass flows associated with the two metals must be identified and quantified. Such regionality can be used to better localize the energy demands and environmental implications of automotive aluminum and steel.

1.2 MATERIAL FLOW ANALYSIS

MFA is a widely used approach to trace the mass flows of a material along its life cycle from mineral extraction, through material production processes, to use, and finally to end-of-life management. The primary goals of a metal-centric MFA are: (1) to gain a better understanding of past and current metal stocks and flows; (2) to show change in stocks and flows over time; (3) to predict global future scrap flows and the extent to which future worldwide metal market demand will be met by recycling versus new smelter capacity; (4) to develop scenarios for inventories of future industrial greenhouse gas emissions; and (5) to forecast the energy and ecological benefits of increased recycling rates, the use of metal products in energy saving applications, and potential improvements in industry efficiency (Bertram, Martchek, & Rombach, 2009). Additionally, MFA can be used to specifically trace the accumulation and embodied energy demand of a metal in use, identify and forecast the depletion of raw materials associated with a metal, and trace the imports and exports of a metal at the various stages in its life cycle.

There are two main approaches in MFA—the top-down approach and the bottom-up approach. The top-down approach is the most commonly used. It is well suited for analysis at large spatial dimensions, analyzes all flows into or out of a clearly defined system, and aggregates stocks over time. The bottom-up approach is beneficial for smaller spatial dimensions, where production and trade data may be lacking. It is based on empirical statistics of different products in use or in waste flows within a specific geographic region at a given point in time and assumptions of the average metal content per product (Glöser, Soulier, & Tercero Espinoza, 2013).

The inherent supply-chain-like framework of MFA and its ability to analyze the flows of a material to a specific sector dictated its use as the foundational method for this study.

1.3 LITERATURE REVIEW

The use of MFA to specifically analyze both global and country level stocks and flows of aluminum (Martchek, 2006; (Hatayama, Yamada, Daigo, Matsuno, & Adachi, 2007)) and steel (Wang, Müller, & Graedel, 2007; Müller, Wang, Duval, & Graedel, 2006) began in the 2000s. Since then, aluminum and steel MFAs have been conducted at the global scale (Cullen and Allwood 2013; Global Aluminum Recycling Committee [GARC], 2009; Menzie et al., 2010; Hatayama, Daigo, Matsuno, & Adachi, 2010; Yellishetty, Ranjith, & Tharumarajah, 2010; Cullen, Allwood, & Bambach, 2012) and for countries including the USA (Chen & Graedel, 2012; Pauliuk, Wang, & Müller, 2013), Austria (Buchner, Laner, Rechberger, & Fellner, 2014), the United Kingdom (Geyer et al., 2007), Japan (Hirato, Daigo, Matsuno, & Adachi, 2009), Korea (Park, Hong, Kim, Lee, & Hur, 2011), Australia (Yellishetty & Mudd, 2014), and China (Chen & Shi, 2012; Ding, Yang, & Liu, 2016; Reck, Chambon, Hashimoto, & Graedel, 2010). While these studies can account for major flows of aluminum and steel into large sector categories such as transportation, they do not resolve the supply locations of these flows.

Many aluminum and steel MFAs focus on recycling and scrap, with studies assessing the recycling potential of aluminum in various countries (Hatayama, Daigo, Matsuno, & Adachi, 2009), discussing the role of automobiles in aluminum scrap recycling and the potential for a scrap surplus (Modaresi & Müller, 2012), recommending strategies to increase recycling of automotive aluminum (Løvik, Modaresi, & Müller, 2014), evaluating efficient and optimal recycling of steel scrap and its alloying elements (Ohno et al., 2015; Ohno et al., 2017), and discussing steel scrap generation versus consumption (Davis et al., 2007). While these studies focus on the circular potential of scrap and its importance in resource and energy conservation, they do not provide detail on sources of scrap flows.

More specific aluminum MFAs have created trade-linked maps of the contemporary global journey of aluminum (Liu & Müller, 2013), dynamically analyzed in-use aluminum stocks at the product level (Chen, 2018), developed a world region tool to trace material flows of wrought and unwrought aluminum products (Bertram et al., 2017), and accounted for aluminum stocks and flows in USA passenger vehicles and their implications for energy use (Cheah, Heywood, & Kirchain, 2009), but these works do not provide a means to regionally discern the aluminum that enters a specific sector. For steel, MFAs have helped inform circular economy theory (Wang, Jiang, Geng, & Hao, 2013; Pauliuk, Wang, & Müller, 2012), identified regional distribution of steel scrap to be dependent on quality and application (Pauliuk, Kondo, Nakamura, & Nakajima, 2017), and developed a new physical input-output method to identify a steel product and its ultimate location in a passenger vehicle (Nakamura, Kondo, Matsubae, Nakajima, & Nagasaka, 2011), but there is a lack of literature on the regional distribution of steel material flows into a particular sector. Additional detailed analysis on the state of knowledge of regional aluminum and steel sourcing and review of literature on the subjects of aluminum and steel MFAs can be found in Appendix A.

This literature review identifies a major knowledge gap in understanding the volume and sources of aluminum and steel flows entering the American automotive industry. In order to better understand the energy demands and greenhouse gas burdens of automotive aluminum and steel, the sources of aluminum and steel mass flows and their volumes must be determined.

1.4 PURPOSE AND IMPORTANCE OF STUDY

The purposes of this study are: (1) to develop a general method and framework to regionalize the material flows of a given material entering a specific sector; and (2) to develop Excel-based models that regionalize material flows and associated process energy demands of aluminum and steel entering the American automotive industry at the NERC-level in the USA and the country level outside the USA (with provincial-level regions for Canada in the aluminum model).

The results of this study will provide a better understanding of the American automotive industry's metals supply chain and can help improve the sustainability of the American automotive, aluminum, and steel industries. This study holds the potential to provide spatially specific data to be integrated into LCA databases and is intended to provide increased spatial resolution on automotive aluminum and steel process energy demands for future automotive LCA studies.

2. METHOD DEVELOPMENT AND FRAMEWORK FOR REGIONALLY LINKED, SECTOR-SPECIFIC MFAs

2.1 METHOD FRAMEWORK OVERVIEW

Traditional top-down and bottom-up MFAs lack the ability to regionally allocate the flows of a material into a specific sector since the primary goal of these two approaches is to account for material flows into defined categories such as mining and raw material production rather than to determine the geographic source of material flows. In order to address this shortcoming, we have developed a general method to disaggregate and regionalize material flows to product fabrication and other process steps. This method is outlined in Table 1.

Table 1: A detailed procedural framework and potential references for developing a regionally linked, sector-specific MFA.

	Description	Resources
1	**Obtain sector-specific industry shipment data** • Choose spatial and temporal system boundaries according to spatial specificity of industry shipment data	• Industry associations
2	**Decide on desired levels of regionality** • Regional levels should be chosen to align with the goals of the study and may be different for material flows within and outside of the geographic boundary of the system	-
3	**Disaggregate sector-specific shipment data by material products** • Decide the product forms of the material that are of particular interest to the study	• Industry association statistics
4	**Identify material product producers and producer facility locations**	• Industry professionals • Industry news article • Industry reports and presentations • Company websites

	• Consultations with industry professionals are beneficial starting points. • Company websites and annual reports are a good resource to identify sector-specific producer locations	• Company annual reports and 10-K SEC filings • IBISWorld reports • Bloomberg terminal supply chain tool
5	**Weight material product producers by market share and producer facility locations by supply share** • Market share and facility level production data is often not publicly available. • Utilize proxy methods to estimate distribution percentages. • Proxy methods can include material product producer sales figures, material product producer shipment data, facility level nameplate production capacities, facility level investments particular to the material product, back-calculation of production via emissions data, informed estimates, etc. • Without any proxy data, utilize uniform distributions. • Synthesize the identified material product producers and producer facility locations along with their weights into a supply mix.	• Industry professionals • Industry news article • Industry reports and presentations • Company websites • Company annual reports and 10-K SEC filings • IBISWorld reports • Bloomberg terminal supply chain tool • D&B Hoovers • USA EPA Enforcement and Compliance History Online (ECHO) tool
6	**Identify upstream source material, if any** • Are the material products entering the chosen sector fabricated from a major source material (i.e., a crude, primary metal)? • Acquire material input or fabrication efficiency data in order to accurately account for the amount of required crude material. • If no major source material is identified, proceed to step 10	• Material product LCI data or previously conducted LCAs
7	**Identify crude material producers and producer facility locations** • See step 4	• See step 4
8	**Weight crude material producers by market share and producer facility locations supply share** • See step 5	• See step 5
9	**Identify major supply relationships between material product producers and crude material producers**	• Industry professionals • Industry news article • Industry reports and

	• Analyze annual reports and 10-K SEC filings to see if supply agreements exist between any material product producers and crude material producers. • If a major supply relationship does exist, assume an exclusive supply of crude material. • If no major supply relationship exists, assume that a sector-specific material producer sources crude material from the previously determined crude material supply mix in step 8.	presentations • Company websites • Company annual reports and 10-K SEC filings • IBISWorld reports • Bloomberg terminal supply chain tool • D&B Hoovers
10	**Determine material raw material inputs** • Disaggregate material(s) by their required raw materials. • Acquire raw material input data to account for the total amount of raw materials required.	• Crude material LCI data or previously conducted LCAs
11	**Identify country level supply mixes of raw materials** • Associate the appropriate country to each identified material producer facility location. • For each material supplying country, determine supply mixes for each raw material input using raw material production and import/export data. • Repeat this step as needed until all raw materials through the material life cycle have been disaggregated.	• USGS • IEA • UN Data • UN Comtrade • Industry associations
12	**Calculate regional material flows through the material life cycle** • Track the material flows through the material life cycle by applying appropriate producer market shares and producer facility location supply shares at each stage of the material life cycle.	-
13	**Aggregate resulting regional material flows to the desired level of regionality** -	-

NOTE: It is best to pursue the smallest level of location identification possible since results can always be aggregated up to desired levels of regionality.

Our method begins with establishing spatial and temporal boundaries for the system of interest. Industry shipment data of a specific material product to a specific sector are then gathered. The method continues with the identification of material product producers and their locations, use of proxy data and methods to weight regional flows of material products (as described by step 5 in Table 1), and repetition of these steps for upstream material inputs. This method can be viewed as a hybrid MFA approach marrying statistical data and pathway weighting schemes with trade information across a large spatial scale to create unique paths of material flows from a specific sector, as visualized in a flow chart following the general structure of Figure 1.

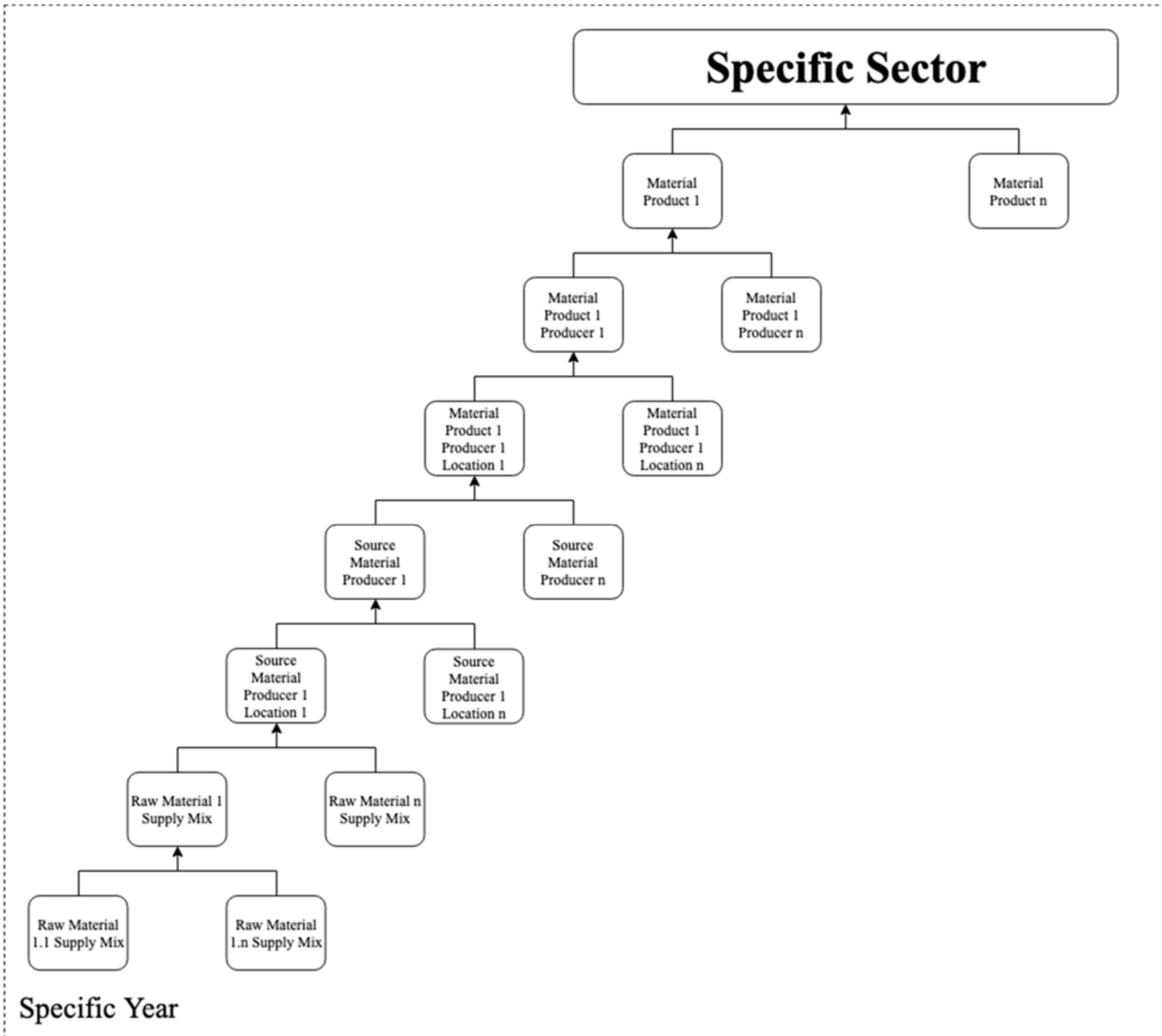

Figure 1: A flow chart representation of a general regionally linked, sector-specific MFA. Each node is only branched twice for simplicity but in practice would be branched as many times as necessary for the analyzed system.

While adjustments to the method to account for the intricacies of a chosen material and sector may necessarily need to be made, we present it as a framework to help guide future MFAs.

2.2 APPLICATION OF DEVELOPED METHOD FRAMEWORK TO AUTOMOTIVE ALUMINUM AND STEEL

Section 2.1 is a general overview of the framework upon which detailed system boundaries, equations, data sources, and methods for specific materials are built. We applied the developed method to automotive aluminum and steel to demonstrate how it can be used effectively. Sections 3 and 4 provide detailed explanations on the processes taken to obtain regionalized material flow and associated process energy demand results for automotive aluminum and steel. Figures and tables showing system boundaries, data sources for regional disaggregation and identification of material producers for each metal are given, and equations used to calculate regional mass flows and energy demands are provided. The presentation of method framework development in Section 2 acts as a primer for the detailed method discussions in Sections 3 and 4.

2.3 MODELLING PLATFORM

Excel was chosen as the platform to create both the automotive aluminum and steel models because of the software’s ability to incorporate data into a flat array, perform organized calculations, and visually represent results in one location. Alternatively, we acknowledge that other platforms such as R and Matlab may better automate and provide easier manipulation of models in future applications.

3. REGIONALLY LINKED AUTOMOTIVE ALUMINUM MFA

3.1 METHODS

3.1.1 SYSTEM BOUNDARIES, SCOPE, AND DESIRED REGIONALITY

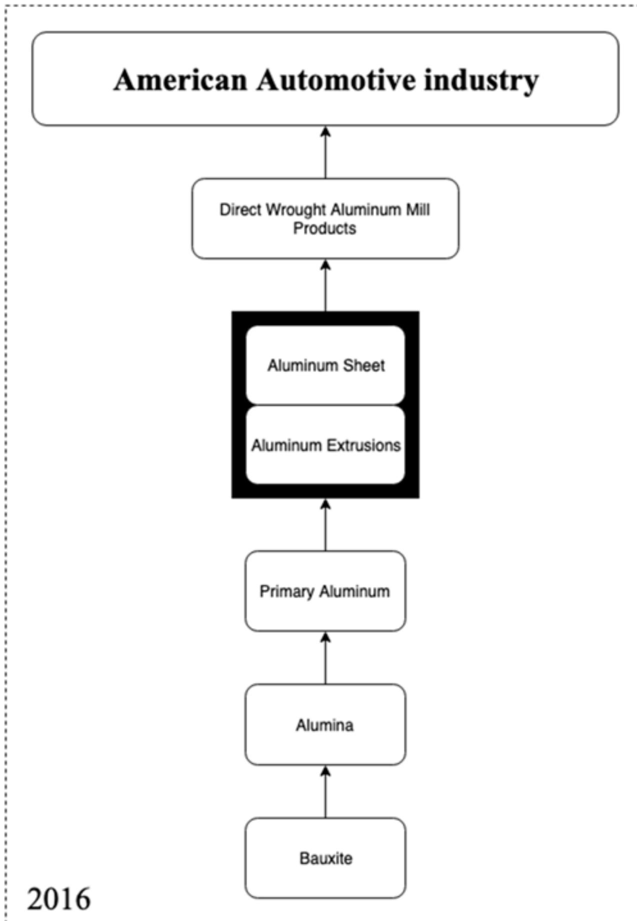

Figure 2: System boundaries for the analyzed automotive aluminum system. The automotive aluminum mill products traced are boxed in black.

The system boundaries for the automotive aluminum system, shown in Figure 2, are dictated by the resolution of industry data from the Aluminum Association (AA) (The Aluminum Association [AA], 2017). The spatial boundary of the American automotive industry was defined to be the USA and Canada and the temporal boundary was the year 2016.The spatial boundary of the American automotive industry is assumed to include automotive original equipment manufacturers (OEMs) and tier 1 and 2 suppliers.

The mass flows analyzed in the automotive aluminum system only includes flows associated with wrought aluminum to the American automotive industry. This decision assumes that sheet and extrusion mill products are expected to grow in LDV application while penetration of aluminum castings in LDVs is projected to remain flat (Ducker, 2017a). The complexity and opacity in aluminum scrap flows (a primary input for cast aluminum) and sourcing of aluminum castings and automotive parts containing cast aluminum also contributed to the decision to focus on wrought aluminum products.

The regional units for this analysis were NERC regions for the USA, the provinces for Canada, and the country level elsewhere. These regional units were chosen so that meaningful energy demand, and particularly electricity demand, results could be extracted.

3.1.2 REGIONALIZING AUTOMOTIVE ALUMINUM MILL PRODUCTS

Using the industry shipment data of aluminum mill products to the American automotive industry as a starting point (AA, 2017), we first isolated sheet and extrusion shipments. We combined reported sheet and plate into an "aluminum sheet" category while we combined rod and bar, extruded shapes, and extruded pipe and tube into "aluminum extrusions." From there, we identified automotive sheet and extrusions producers and their locations by consulting a variety of resources including an industry professional from AA, aluminum industry presentations and reports, aluminum mill product producer websites, aluminum mill product producer annual reports and 10-K SEC filings, aluminum industry news articles, and automotive industry news articles. Specific sources employed are outlined in Table *2*. AA indicated that the supply of aluminum mill products to the American automotive industry can reasonably be assumed to be wholly within the geographic boundaries of the USA and Canada. Additionally, a Local region was established for automotive aluminum extrusions because, aside from the four identified major producers, automotive extrusions entering the American automotive industry are largely supplied by producers within close proximity to OEMs and tier 1 and 2 suppliers (Sapa, 2017). The Local region geographically includes the USA and Canada. It was not disaggregated further due to its complexity and obscurity. While various proxy methods could potentially be used to disaggregate the Local region, it was beyond the scope of this study.

Table 2: Methods used and sources consulted to identify and weight the mass flows of automotive aluminum mill products.

Parameter	Method	Source(s)
Automotive Aluminum Sheet Producers and Producer Locations	-	• (Wang, 2019) • (Richman and Abraham, 2017) • (Novelis Inc. [Novelis], 2019) • (Arconic Inc. [Arconic], 2019) • (Arconic, 2017)
Automotive Aluminum Extrusion Producers and Producer Locations	-	• (Richman and Abraham, 2017) • (Sapa, 2017) • (American Metal Market LLC [AMM], 2018) • (Norsk Hydro ASA, 2019) • (Kaiser Aluminum Corporation [Kaiser], 2019) • (AACOA Division of Bonnell Aluminum [AACOA], 2019) • (Bonnell Aluminum [Bonnell], 2019)
Automotive Aluminum Sheet Producer Market Shares	Proxy	• (Arconic, 2014) • (Arconic, 2015) • (Novelis, 2016) • (Novelis, 2013)

Automotive Aluminum Sheet Producer Location Supply Shares	Proxy	• (USA EPA, 2019a) • (Novelis, 2016) • (Novelis, 2013)
Automotive Aluminum Extrusion Producer Market Shares	Proxy	• (Sapa, 2017) • (Kaiser, 2017) • (Tredegar Corporation [Tredegar], 2017)
Automotive Aluminum Extrusion Producer Location Supply Shares	Proxy and uniform distribution	• (Sapa, 2017) • (Ducker, 2014)

Aluminum mill product producer market shares and intra-producer location supply shares were estimated by either using proxy methods that leverage different sources of data which can be reasonably associated with production or ascribing uniform distributions. Descriptions of proxy methods used and sample calculations are provided in Appendix B. The identified distribution of aluminum mill product producers, their locations, and their appropriate NERC or provincial regions are anonymized and shown in Table *3*. Estimated market shares are intentionally withheld in order to prevent their improper use and protect identified companies. Given uncertainty in these estimates due to data availability, it would be inappropriate to assign these specific market shares to producers, though the regional trends are still valid. Regional automotive aluminum mill product mass flows were then calculated according to Equation 1.

Equation 1:

$$M_{j,i} = M_j(A_{j,k} * B_{j,k,l})$$

Where:
$M_{j,i}$ = mass of mill product j from location i
M_j = total mass of aluminum mill product j shipped to the American automotive industry
$A_{j,k}$ = estimated market share of aluminum mill product j from producer k
$B_{j,k,l}$ = estimated supply share of aluminum mill product j from producer k's location l

Energy input data for the production of aluminum mill products were obtained from AA (AA, 2013). Extrusions were assumed to undergo only the extrusion process while sheet for automotive application was assumed to undergo both hot and cold rolling. Regional automotive aluminum mill product energy demands were calculated using Equation 2.

Equation 2:

$$ED_{j,i} = M_{j,i} * EI_{j,i}$$

Where:
$ED_{j,i}$ = energy demand of mill product j from location i
$M_{j,i}$ = mass of mill product j from location i
$EI_{j,i}$ = energy input per unit mass of mill product j from location i

Table 3: Automotive aluminum mill product producers, their locations, and their appropriate region labels by mill product.

Mill Product	Mill Product Producer	Mill Product Producer Location	Appropriate Region
Sheet	A	A1	MRO
	A	A2	SERC
	A	A3	TRE
	A	A4	SERC
	A	A5	SPP
	A	A6	RFC
	B	B1	NPCC
	B	B2	ON
Extrusion	C	C1	RFC
	C	C2	RFC
	C	C3	ON
	C	C4	ON
	C	C5	RFC
	C	C6	RFC
	C	C7	SPP
	C	C8	FRCC
	C	C9	FRCC
	C	C10	MRO
	C	C11	WECC
	C	C12	WECC
	D	D1	ON
	D	D2	RFC
	D	D3	SERC
	D	D4	SERC
	D	D5	TRE
	E	E1	SERC
	F	F1	RFC
	Local	Local	Local

3.1.3 REGIONALIZNG THE PRIMARY ALUMINUM THAT ENTERS THE AMERICAN AUTOMOTIVE INDUSTRY

We assume that the primary aluminum composition of both aluminum sheet and extrusions is 89%, as noted in the GREET 2 model (ANL, 2018b), and the remaining 11% is secondary aluminum. We recognize that this assumption by the GREET 2 model may be outdated and should be updated once new and reliable information is released and made available. The fabrication efficiency for rolling automotive aluminum sheet, 77.36%, was calculated by sequencing the efficiencies of hot-rolling and cold-rolling aluminum sheet published by AA while the fabrication efficiency for aluminum extrusions, 77.52%, was calculated directly from the material inputs for extruding (AA, 2013). Applying the primary aluminum material composition and respective fabrication efficiencies to automotive aluminum sheet and extrusions yields the required amount of primary aluminum to be regionalized.

We adapted Bushi's USA and Canadian supply mix for primary aluminum (Bushi, 2018) to provide detailed NERC and provincial regional disaggregation (shown in Table 4) by marrying industry statistics from AA with production information from primary aluminum producer annual reports and websites. Primary aluminum supply from within the USA and Canada was weighted by smelter location and estimated production volume. Estimated location weights associated with each USA and Canada location are here withheld in order to prevent their improper use and protect identified companies. The sum of these supply weights equates to the NA domestic weight of 81.2% given by the Bushi study. Primary aluminum supply weights from international sources, including the Rest of World, were taken directly from the Bushi study and rely on the study's criteria.

Table 4: The USA and Canadian primary aluminum supply mix in 2016.

Producer	Producer Location	Region	Location Weights (%)
G	G1	NPCC	-
G	G2	WECC	-
G	G3	QC	-
G	G4	QC	-
G	G5	QC	-
H	H1	SERC	-
H	H2	SERC	-
H	H3	SERC	-
I	I1	QC	-
J	J1	QC	-
J	J2	QC	-
J	J3	QC	-
J	J4	QC	-
J	J5	QC	-
J	J6	BC	-
-	Russia	Russia	10.4
-	UAE	UAE	3.6
-	Argentina	Argentina	1.9
-	Brazil	Brazil	0.3
-	Bahrain	Bahrain	0.3
-	Venezuela	Venezuela	0.7
-	Rest of World	Rest of World	1.5

In order to provide more detailed regional description of primary aluminum sourcing by automotive aluminum producing mills, if a major supply relationship was mentioned in a corporate annual report from an automotive aluminum mill product producer or primary aluminum producer, aluminum industry news article, or aluminum industry report, that automotive aluminum mill producer was assumed to wholly source primary aluminum from the named primary aluminum producer. The total amount of primary aluminum required by these automotive aluminum mill product producers was then removed from the adapted aluminum supply mix. Remaining automotive aluminum mill product producers that didn't mention major relationships with specific primary aluminum producers were assumed to source primary aluminum from the resulting primary aluminum supply after these modifications.

The primary aluminum sourcing pattern of automotive aluminum mill product producers is shown in Table 5. Equation 3 was used to calculate the mass flows of primary aluminum. Weighted sourcing patterns are once again withheld to preserve confidentiality and prevent improper use. Specific sources used in creating the primary aluminum mix and sourcing patterns are shown in Table 6. Examples of the proxy methods used to calculate variables E_m and $F_{m,n}$ are provided in Appendix B.

Equation 3:

$$M(primary)_n = \frac{M_j\left(A_{j,k} * B_{j,k,l} * C_j\right)}{D_j} * E_m * F_{m,n}$$

Where:
$M(primary)_n$ = mass of primary aluminum from location n
M_j = total mass of aluminum mill product j shipped to the American automotive industry
$A_{j,k}$ = estimated market share of aluminum mill product j from producer k
$B_{j,k,l}$ = estimated supply share of aluminum mill product j from producer k's location l
C_j = primary aluminum content of aluminum mill product j
D_j = fabrication efficiency of aluminum mill product j
E_m = estimated market share of primary aluminum from producer m
$F_{m,n}$ = estimated supply share of primary aluminum from producer m's location n

Regional energy input data for primary aluminum production were obtained from World Aluminum (World Aluminum, 2017) and applied to mass flows following Equation 4, in order to determine the regional energy demand associated with primary aluminum production.

Equation 4:

$$ED(primary)_n = M(primary)_n * EI(primary)_n$$

Where:
$ED(primary)_n$ = energy demand of primary aluminum from location n
$M(primary)_n$ = mass of primary aluminum from location n
$EI(primary)_n$ = energy input per unit mass of primary aluminum from location n

Table 5: Primary aluminum sourcing patterns of automotive aluminum mill product producers.

Mill Product Producer	Primary Aluminum Producer

	Producer	Producer Location	Region
A	G	G1	NPCC
		G2	WECC
		G3	QC
		G4	QC
		G5	QC
B	J	J1	QC
		J2	QC
		J3	QC
		J4	QC
		J5	QC
		J6	BC
	I	I1	QC
C	I	I1	QC
	Brazil	Brazil	Brazil
D, E, F, Local	G	G1	NPCC
		G2	WECC
		G3	QC
		G4	QC
		G5	QC
	H	H1	SERC
		H2	SERC
		H3	SERC
	I	I1	QC
	J	J1	QC
		J2	QC
		J3	QC
		J4	QC
		J5	QC
		J6	BC
	Russia	Russia	Russia
	UAE	UAE	UAE
	Argentina	Argentina	Argentina
	Brazil	Brazil	Brazil
	Bahrain	Bahrain	Bahrain
	Venezuela	Venezuela	Venezuela
	Rest of World	Rest of World	Rest of World

Table 6: Specific sources used to identify the primary aluminum mix for the USA and Canada and sourcing patters between automotive aluminum mill product producers and primary aluminum producers.

Parameter	Method	Source(s)
American Primary Aluminum Supply Mix Identification	-	• (Bushi, 2018) • (Alcoa Corporation [Alcoa], 2017) • (Century Aluminum Corporation [Century], 2017) • (Natural Resources Canada, 2019) • (Rio Tinto, 2019) • (Rio Tinto, 2017)
American Primary Aluminum Supply Mix Weights	Proxy	• (Bushi, 2018) • (Alcoa, 2017) • (Century, 2017) • (AA, 2017) • (Rio Tinto, 2019) • (Rio Tinto, 2017)
Primary Aluminum Sourcing Patterns	-	• (Arconic, 2017) • (Alcoa, 2017) • (Consumer News and Business Channel [CNBC], 2018) • (Norsk Hydro ASA, 2017a) • (Norsk Hydro ASA, 2017b)

3.1.4 REGIONALIZING THE ALUMINA THAT ENTERS THE AMERICAN AUTOMOTIVE INDUSTRY

Ratios of alumina required for primary aluminum by world region were extracted from published life cycle inventory (LCI) data (World Aluminum, 2017) and applied, at a country level, to the identified sources and mass flows of primary aluminum to determine the amount of alumina required by each primary aluminum producer for automotive aluminum mill products. Country level alumina supply mixes were compiled for each primary aluminum supplying country using the United States Geological Survey (USGS) for production data (Bray, 2018), the United Nations (UN) Comtrade database for import and export data (United Nations [UN], 2019a), and the rules in Equation 5. Applying alumina supply mixes to each primary aluminum supplying country's respective primary aluminum mass flow resulted in regionalized flows of alumina at the country level (Equation 6).

A Rest of World alumina supply was calculated based on country level alumina production and applied to primary aluminum supplying countries that lacked import and export data from UN Comtrade as well as to primary aluminum from Rest of World.

Regional energy input data for alumina refining were obtained from World Aluminum (World Aluminum, 2017) and applied to the regionalized alumina mass flows using Equation 7 to determine regional energy demand.

Equation 5:

$$\text{If } P = 0 \text{ or } P < E\text{:}$$
$$\text{Supply Mix} = I$$

If P > E:

$$Supply\ Mix = P - E + I$$

Where:
P = production
E = exports
I = imports

Equation 6:

$$M(alumina)_p = \frac{M_j\left(A_{j,k} * B_{j,k,i} * C_j\right)}{D_j} * E_m * F_{m,n} * G * H_o * I_{o,p}$$

Where:
$M(alumina)_p$ = mass of alumina from location p
M_j = total mass of mill product j shipped to the American automotive industry
$A_{j,k}$ = estimated market share of aluminum mill product j from producer k
$B_{j,k,i}$ = estimated supply share of aluminum mill product j from producer k's location i
C_j = primary aluminum content of aluminum mill product j
D_j = fabrication efficiency of aluminum mill product j
E_m = estimated market share of primary aluminum from producer m
$F_{m,n}$ = estimated supply share of primary aluminum from producer m's location n
G = units of alumina required to produce one unit of aluminum
H_o = estimated market share of alumina from producer o
$I_{o,p}$ = estimated supply share of alumina from producer o's location p

Equation 7:

$$ED(alumina)_p = M(alumina)_p * EI(alumina)_p$$

Where:
$ED(alumina)_p$ = energy demand of alumina from location p
$M(alumina)_p$ = mass of alumina from location p
$EI(alumina)_p$ = energy input per unit mass of alumina from location p

3.1.5 REGIONALIZING THE BAUXITE THAT ENTERS THE AMERICAN AUTOMOTIVE INDUSTRY

The material flows of bauxite entering the American automotive industry were regionalized at the country-level by the same procedure used for alumina. Ratios of bauxite required for alumina by world region were extracted from published LCI data (World Aluminum, 2017) and applied, at a country level, to the identified sources and mass flows of alumina to determine the amount of bauxite required by each alumina producer. Country-level bauxite supply mixes were compiled for each alumina supplying country using USGS for production data (Bray, 2018), the UN Comtrade database for import and export data (UN, 2019), and rules in Equation 5. Equation 8 applies the country level bauxite supply mixes to alumina mass flows and calculates the regional flows of bauxite. A Rest of World region bauxite supply mix was calculated by weighting country level bauxite production. It was applied to the Rest of

World alumina supplying region as well as to alumina supplying countries lacking import and export data from UN Comtrade.

Equation 8:

$$M(bauxite)_r = \frac{M_j(A_{j,k} * B_{j,k,l} * C_j)}{D_j} * E_m * F_{m,n} * G * H_o * I_{o,p} * J * K_q * L_{q,r}$$

Where:
$M(bauxite)_r$ = mass of bauxite from region r
M_j = total mass of aluminum mill product j shipped to the American automotive industry
$A_{j,k}$ = estimated market share of aluminum mill product j from producer k
$B_{j,k,i}$ = estimated supply share of aluminum mill product j from producer k's location l
C_j = primary aluminum content of aluminum mill product j
D_j = fabrication efficiency of aluminum mill product j
E_m = estimated market share of primary aluminum from producer m
$F_{m,n}$ = estimated supply share of primary aluminum from producer m's location n
G = units of alumina required to produce one unit of aluminum
H_o = estimated market share of alumina from producer o
$I_{o,p}$ = estimated supply share of alumina from producer o's location p
J = units of bauxite required to produce one unit of alumina
K_q = estimated market share of bauxite from producer q
$L_{q,r}$ = estimated supply share of bauxite from producer q's location r

Bauxite mining energy input data obtained from World Aluminum (World Aluminum, 2017) were applied to the regionalized mass flows to obtain regional energy demand (Equation 9).

Equation 9:

$$ED(bauxite)_r = M(bauxite)_r * EI(bauxite)_r$$

Where:
$ED(bauxite)_r$ = energy demand of bauxite from location r
$M(bauxite)_r$ = mass of bauxite from location r
$EI(bauxite)_r$ = energy input per unit mass of bauxite from location r

3.1.6 SCENARIO AND SENSITIVITY ANALYSES

A scenario analysis was conducted to examine how different sourcing patterns and supply mixes of primary aluminum influence the regional flows of primary aluminum, alumina, and bauxite and associated process energy demands.

The base scenario assumed supply relationships between aluminum mill product producers and primary aluminum producers when possible, resulting in the primary aluminum sourcing pattern shown in Table 5. The first alternative scenario eliminated aluminum mill product producer and primary aluminum producer supply relations and assumed that each aluminum mill product producer sourced primary aluminum from the same primary aluminum supply mix (Table 4). The second alternative scenario assumed the same primary aluminum sourcing pattern as the first alternative scenario, but adapted the primary aluminum supply mix from Table 4 by assuming that all of the aluminum ingot imports to the USA in 2016 reported in the AA industry statistics (AA, 2017) were primary aluminum ingots (Table 7). Reported aluminum ingot imports to the USA were assumed to represent the imported ingot supply of both the USA and Canada since Canada is a large net exporter of aluminum ingots. Estimated production at each primary aluminum producer location in the USA and Canada was not changed. Estimated supply weights associated with each USA and Canada location are again withheld in order to prevent their improper use and protect identified companies. The sum of the USA and Canadian supply equates to 67.3%. The primary aluminum sourcing pattern by aluminum mill product producers in both alternative scenarios is presented in Table 8.

Table 7: USA and Canadian primary aluminum mix assuming all imported aluminum ingots are primary in 2016.

Producer	Producer Location	Appropriate Region	Location Weights (%)
G	G1	NPCC	-
G	G2	WECC	-
G	G3	QC	-
G	G4	QC	-
G	G5	QC	-
H	H1	SERC	-
H	H2	SERC	-
H	H3	SERC	-
I	I1	QC	-
J	J1	QC	-
J	J2	QC	-
J	J3	QC	-
J	J4	QC	-
J	J5	QC	-
J	J6	BC	-
-	Russia	Russia	12.1
-	UAE	UAE	9.3
-	Argentina	Argentina	2.9
-	Brazil	Brazil	0.5
-	Bahrain	Bahrain	1.8
-	Venezuela	Venezuela	1.1
-	Rest of World	Rest of World	5.0

Table 8: Alternate primary aluminum sourcing pattern for primary aluminum scenario analysis.

Mill Product Producer	Primary Aluminum Producer	Primary Aluminum Producer Locations	Primary Aluminum Producer Region
Company A-F, Local	Company G	G1	NPCC
		G2	WECC
		G3	QC
		G4	QC
		G5	QC

	Company H	H1	SERC
		H2	SERC
		H3	SERC
	Company I	I1	QC
	Company J	J1	QC
		J2	QC
		J3	QC
		J4	QC
		J5	QC
		J6	BC
	Russia	Russia	Russia
	UAE	UAE	UAE
	Argentina	Argentina	Argentina
	Brazil	Brazil	Brazil
	Bahrain	Bahrain	Bahrain
	Venezuela	Venezuela	Venezuela
	Rest of World	Rest of World	Rest of World

Scenario and sensitivity analyses were also conducted for the regional distributions of aluminum mill products. The base case scenario weighted the regional distributions of aluminum mill products using a combination of proxy and uniform distribution methods. A uniform distribution scenario assumed all aluminum mill product producers by product category held equal market shares. Respective mill locations for each aluminum mill product producer were also assumed to hold equal supply shares. From the uniform distribution scenario, a ± 10% sensitivity analysis was conducted for each aluminum mill product producer market share. All scenario and sensitivity analyses performed are described in Table *9*.

Table 9: Scenario and sensitivity analyses performed on the automotive aluminum MFA model.

Parameter	Model Scenario	Alternate Scenario 1	Alternate Scenario 2	Sensitivity
Primary Aluminum Sourcing	Relationship identification where possible, otherwise supply mix sourcing	Supply mix sourcing	Supply mix sourcing from increased imports supply	
Mill Product Producer Market Shares and Producer Location Supply Shares	Proxy and uniform distribution	Uniform distribution	-	+/- 10% for each mill product producer market share

3.2 RESULTS

3.2.1 AUTOMOTIVE ALUMINUM MILL PRODUCT REGIONALITY

The regional distribution of automotive aluminum mill product mass flows is largely dominated by the NPCC (23%), SERC (20%), MRO (20%), and RFC (13%) NERC regions as well as the unresolved Local region (18%), as shown in Figure 3. All of the mill product mass flow from NPCC is sheet and all of the mill product mass flow from Local is extrusions. The Local region accounts for ~58% of extrusion mass flows, though extrusions represent only ~31%% of the total automotive aluminum wrought product by mass.

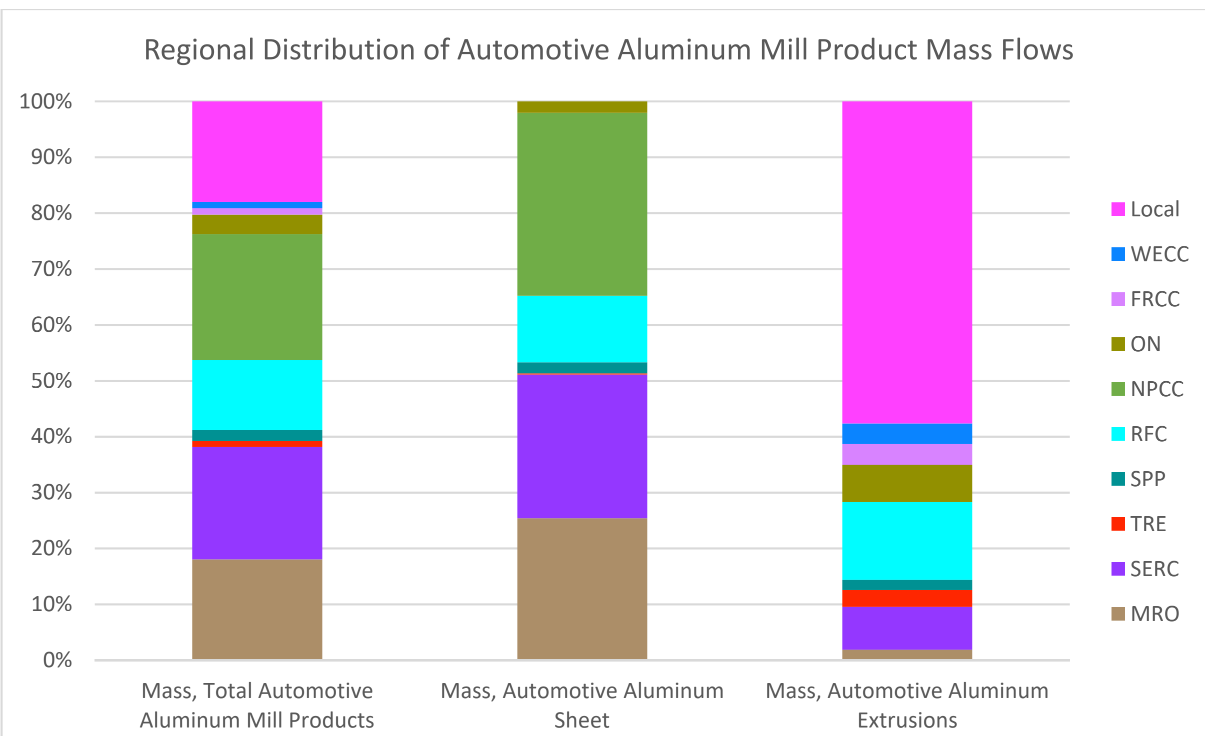

Figure 3: Regional distributions of automotive aluminum mill product mass flows. Regions are listed by either NERC region, Canadian province, or Local."

Energy demand follows the same regional distribution as mass for automotive aluminum mill products (Figure 4-Figure 6). Differences in the distribution for aggregated automotive aluminum mill products are due to the different energy inputs required for aluminum sheet and extrusions. Energy inputs for automotive aluminum mill products are dominated by natural gas (Figure 7). Note that this is the energy inputs for the fabrication stage of aluminum mill products and is not inclusive of the other stages.

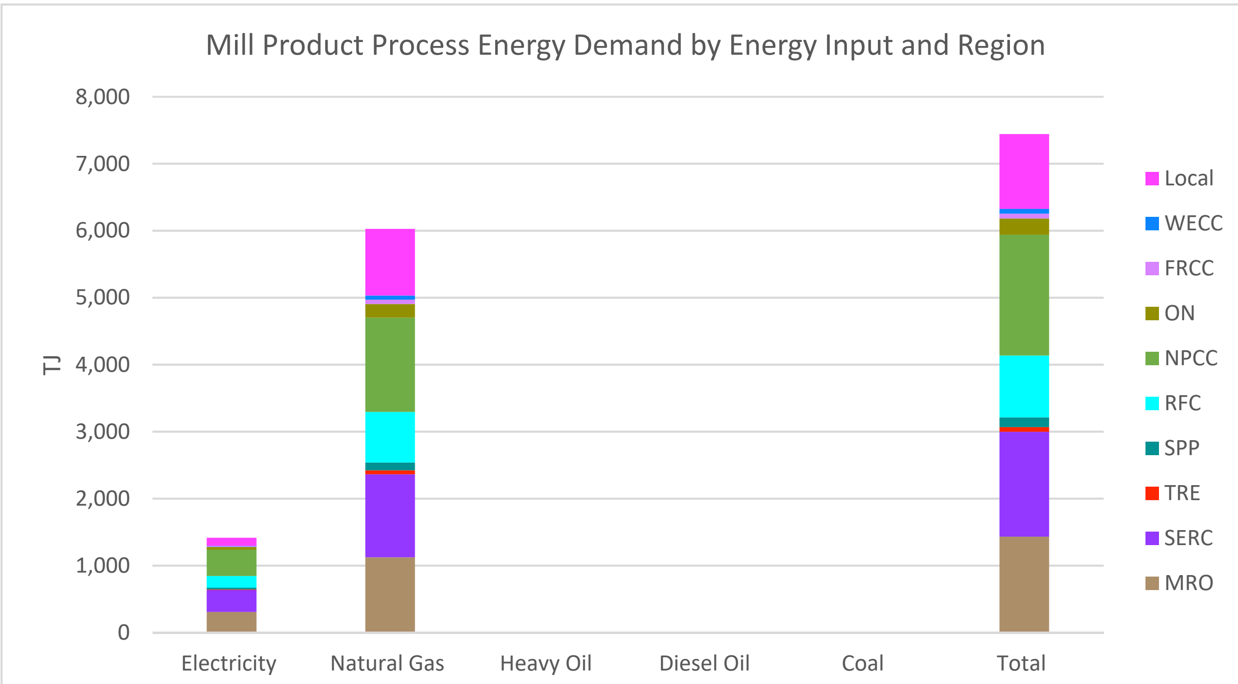

Figure 4: Regional distributions of automotive aluminum mill product process energy demand by energy input. Regions are listed by either NERC region, Canadian province, or Local.

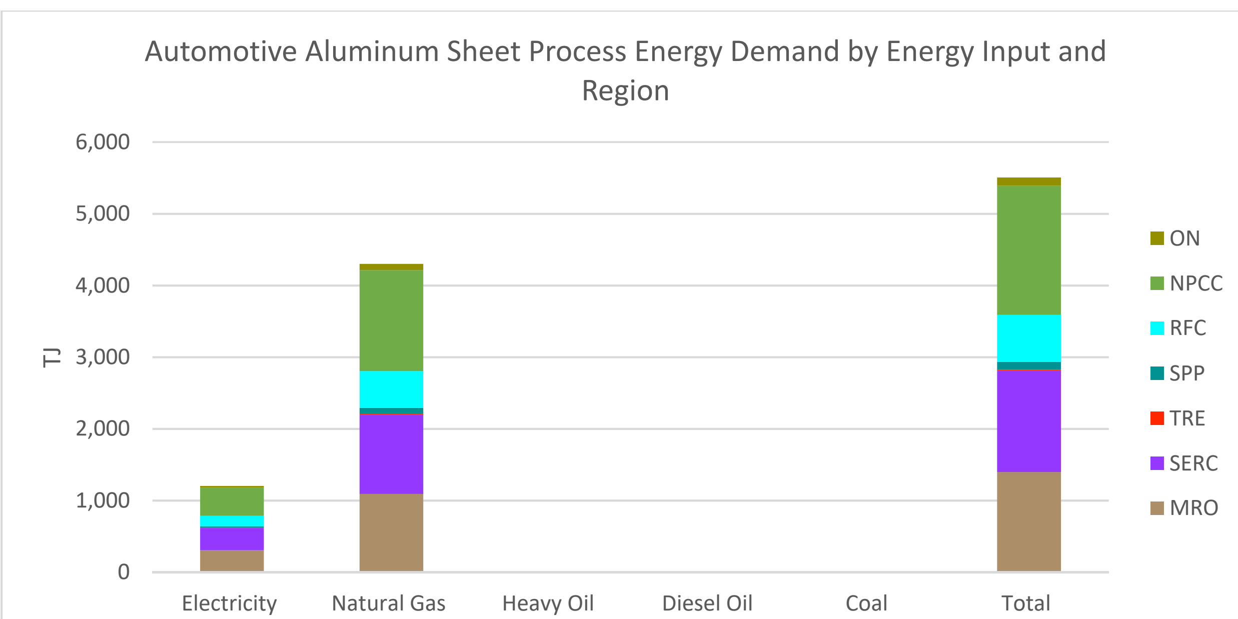

Figure 5: Regional distributions of automotive aluminum sheet process energy demand by energy input. Regions are listed by either NERC region or Canadian province,

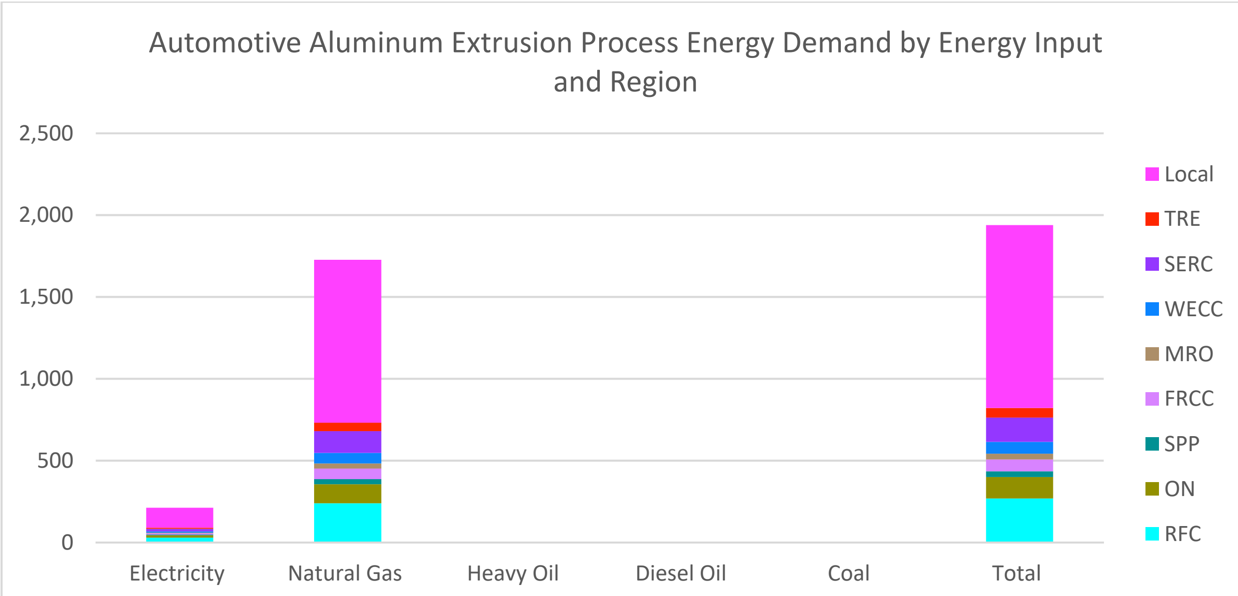

Figure 6: Regional distributions of automotive aluminum extrusion process energy demand by energy input. Regions are listed by either NERC region, Canadian province, or Local.

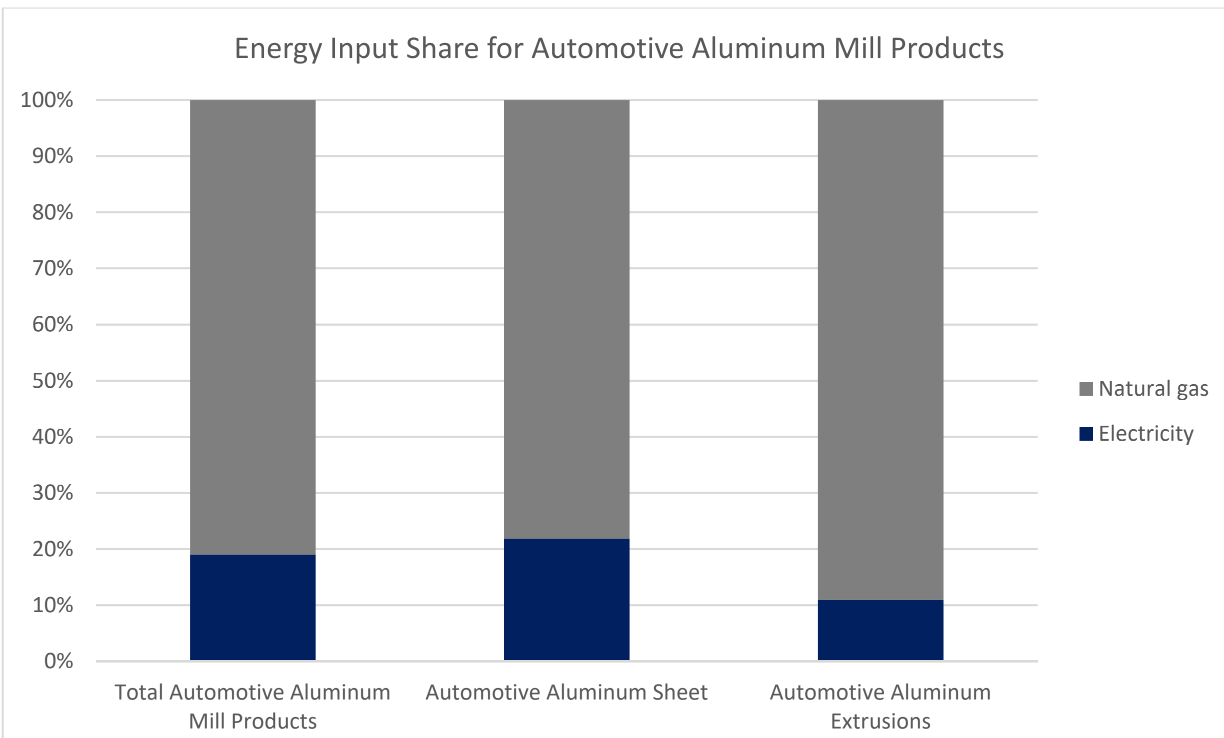

Figure 7: Shares of different energy inputs for automotive aluminum mill products.

3.2.2 PRIMARY ALUMINUM REGIONALITY

Figure 8 illustrates that the regional distribution of primary aluminum entering the American automotive industry is heavily dominated by Canada (70%) and in particular, Quebec (69%). The USA and Canada combined are responsible for 94% of the primary aluminum entering the American automotive industry. As a reminder, this primary aluminum doesn't directly enter the American automotive industry, but rather goes onward to mills for further processing as described in the abbreviations section.

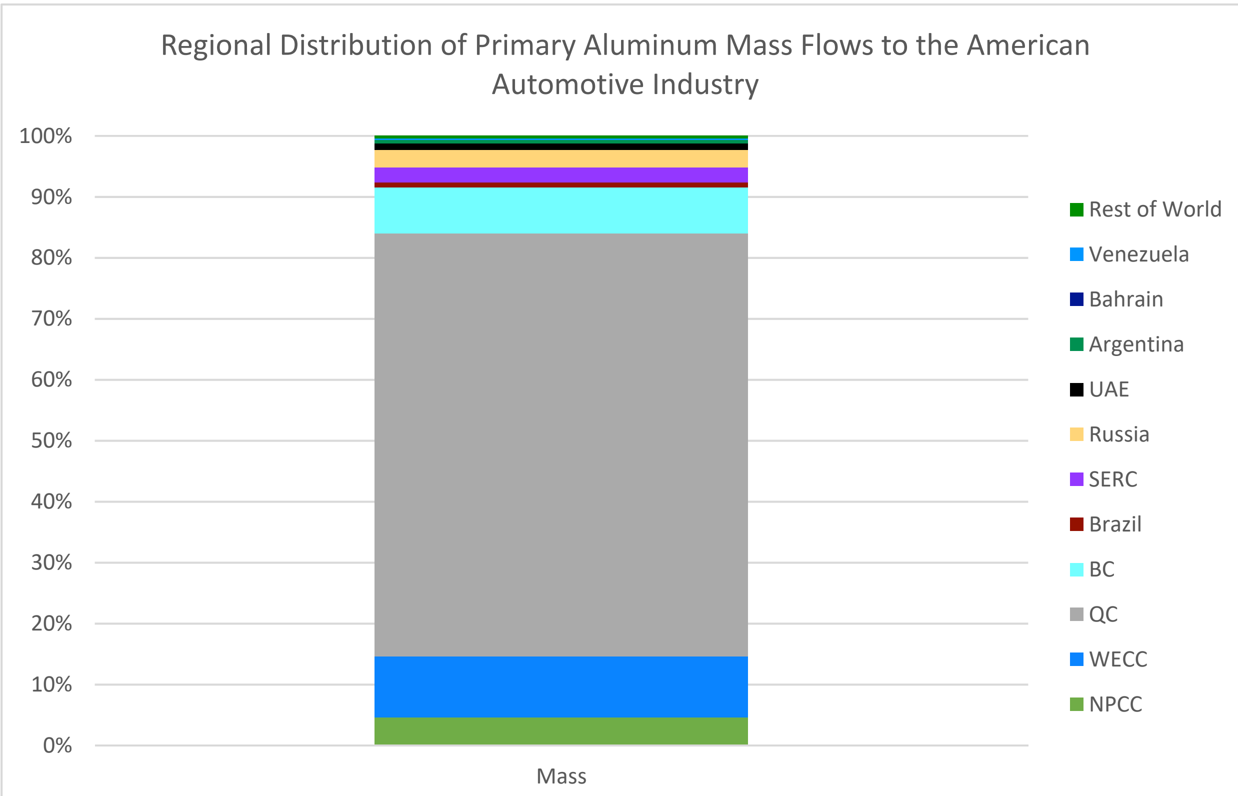

Figure 8: Regional distribution of mass flows for primary aluminum that enters the American automotive industry.

The distribution of energy demand for primary aluminum that enters the American automotive industry follows nearly the same distribution as the material's mass flows, but with slight differences due to varying efficiencies for the Hall–Héroult process by world region. Figure 9 shows the regional distributions of energy demand for primary aluminum by energy input and that electricity accounts for nearly 99% of the total energy required.

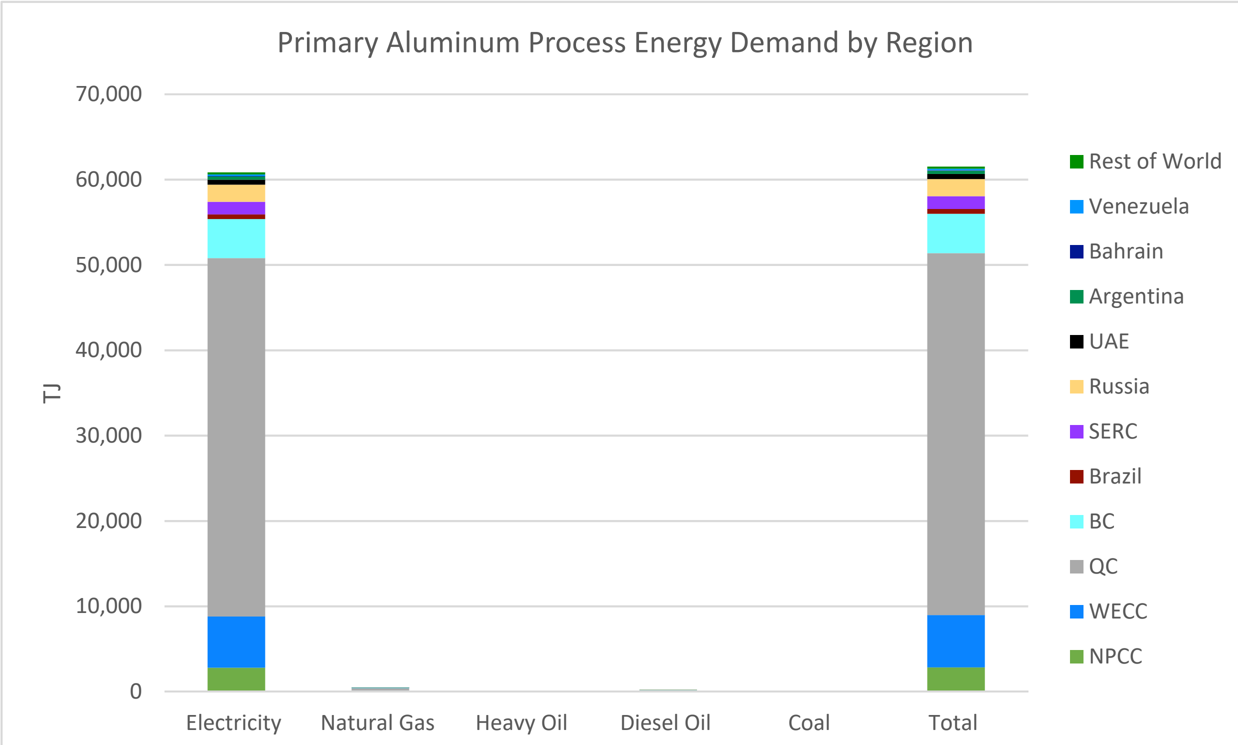

Figure 9: Regional distributions of primary aluminum process energy demand by energy input. Regions are listed by either NERC region, Canadian province, country, or Rest of World.

3.2.3 ALUMINA REGIONALITY

The countries that supply greater than 1% of the alumina entering the American automotive industry are shown in Figure 10 and represent 96% of the total alumina. Here, we show that countries located in North and South America dominate the alumina supply, providing 80% of the total. Brazil accounts for 43% of the total supply while the USA and Canada combined represent 29%. The mass flow distribution for alumina shows the dominance of countries with large bauxite reserves—Brazil, Australia, and Jamaica—and suggests a vertical integration with respect to alumina refining. Energy demands for alumina refining generally follow the material's regional distribution of mass flows with minor differences attributable to varying refining efficiencies.

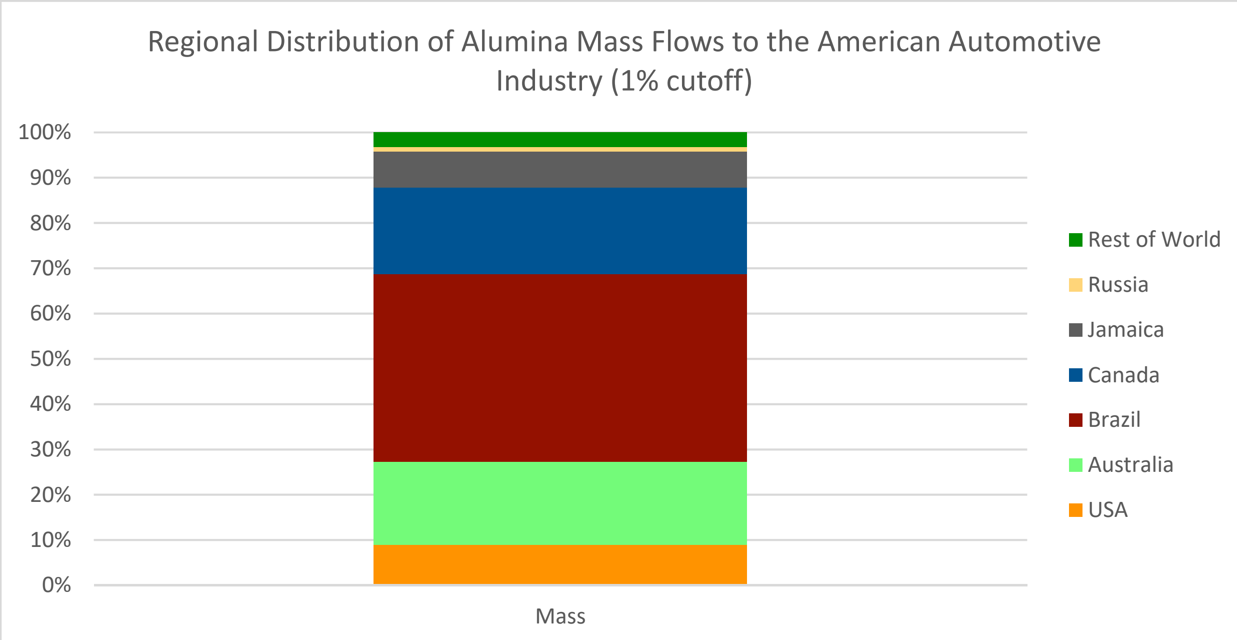

Figure 10: Regional distribution of mass flows for the alumina that enters the American automotive industry. Only regions contributing over 1% of the total mass flow are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

Regional energy demands for alumina refining, separated by energy inputs, are shown in Figure 11 and exhibit the dominance of fossil fuels.

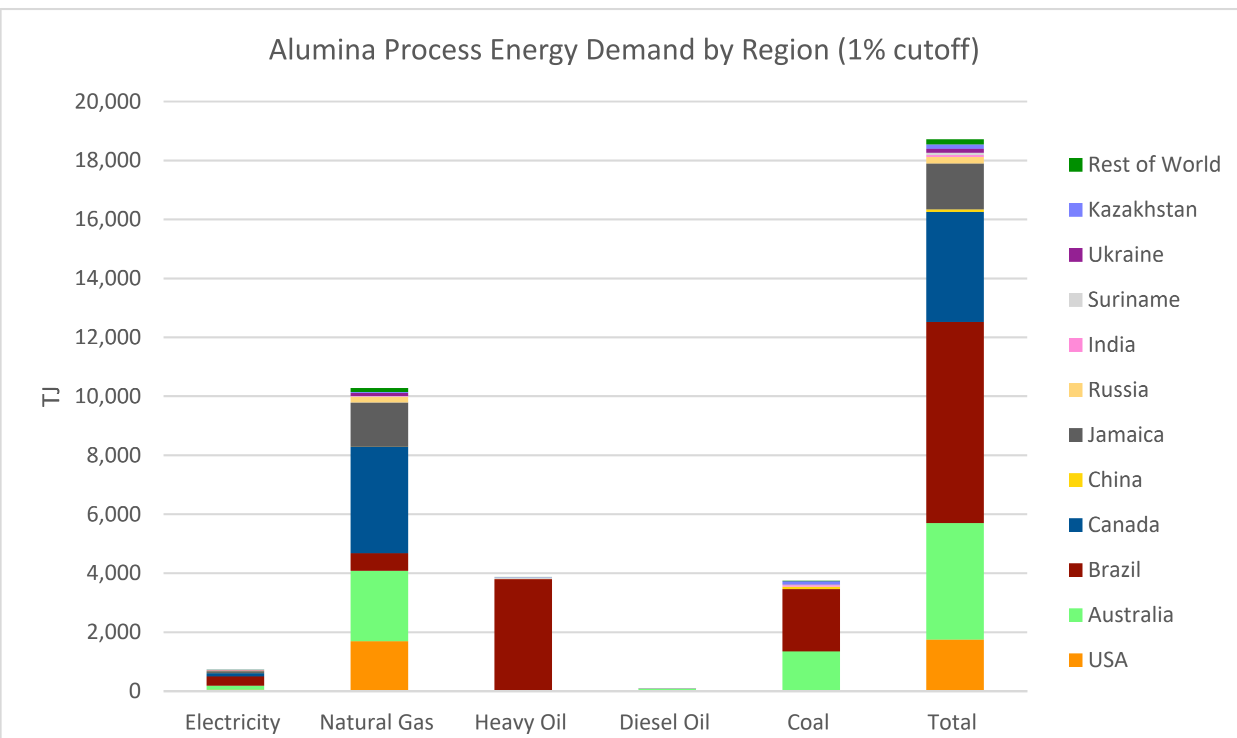

Figure 11: Regional distributions of alumina process energy demand by energy input. Regions are listed by either country or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

3.2.4 BAUXITE REGIONALITY

Countries responsible for over 1% of the bauxite entering the American automotive industry are shown in Figure 12 and represent 95% of the total amount of bauxite. Similar to the results for alumina, the supply of bauxite is dominated by Brazil (57%), with Australia (20%) and Jamaica (14%) each also representing over 10% of the total supply. The large supply shares of these countries follow the distribution of global bauxite reserves. The distribution of energy demand for bauxite mining follows the same pattern as the material's mass flows and energy inputs are largely fossil based as shown in Figure 13.

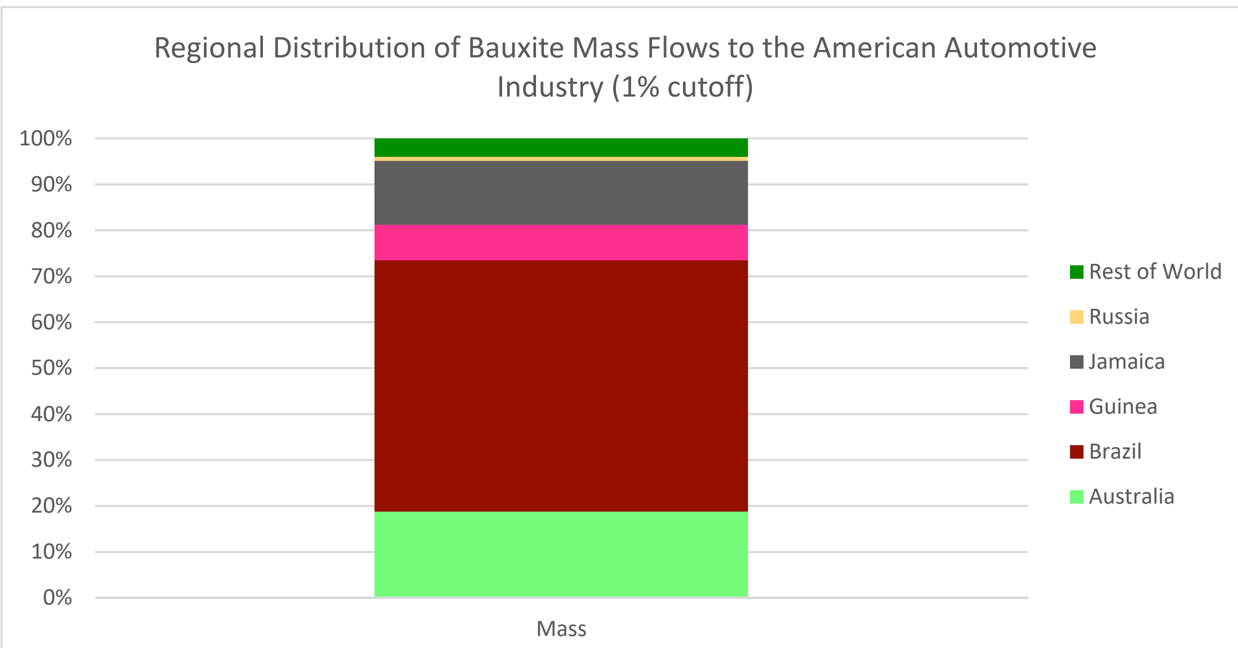

Figure 12: Regional distribution of mass flows for bauxite that enters the American automotive industry. Only regions contributing over 1% of the total mass flow are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

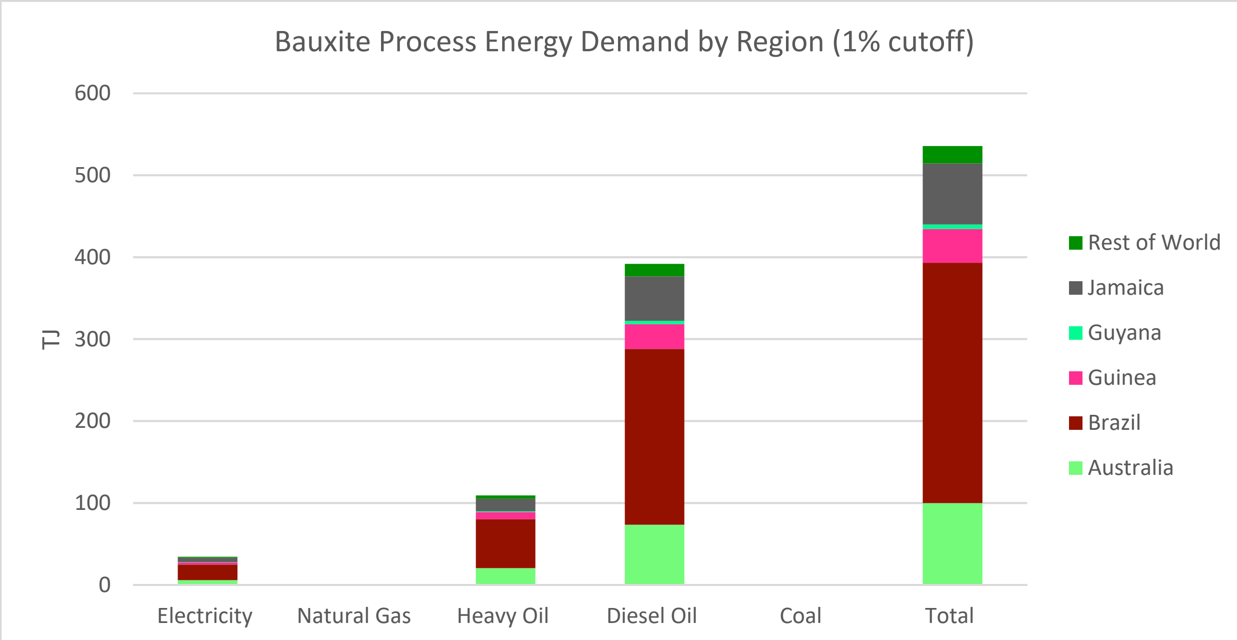

Figure 13: Regional distributions of bauxite process energy demand by energy input. Regions are listed by either country or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

3.2.5 TOTAL ENERGY DEMAND REGIONALITY

The total process energy demand embodied in automotive aluminum is 88,220 TJ. The regional distribution of total process energy demand (Figure *14*), largely follows the primary aluminum regional energy demand distribution for since the production of primary aluminum accounts for 70% of automotive aluminum's total energy inputs (Figure 15). Electricity accounts for over 70% of the total energy embodied in automotive aluminum (Figure 16).

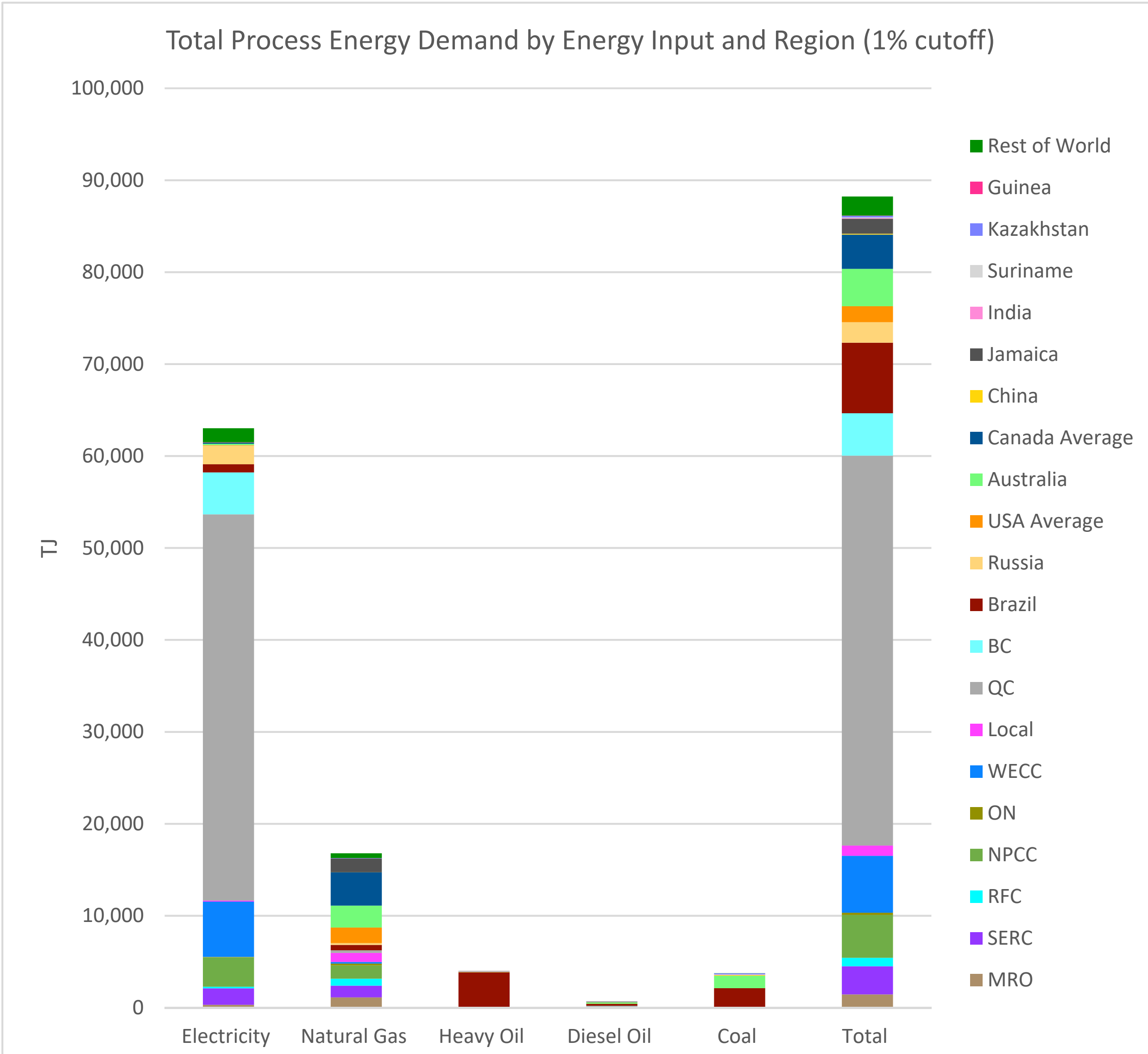

Figure 14: Regional distribution of total process energy embodied in aluminum entering the American automotive industry by energy input. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

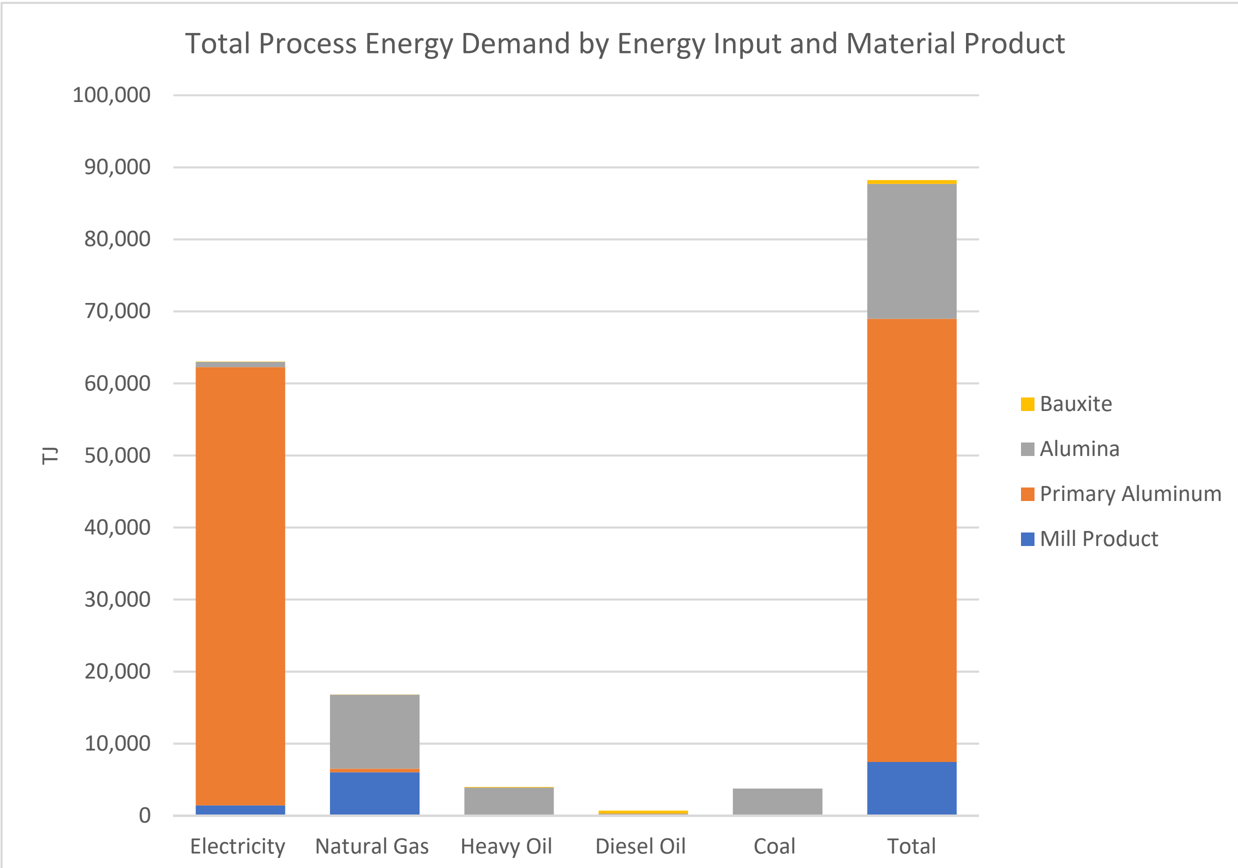

Figure 15: Total process energy embodied in aluminum entering the American automotive industry by energy input and material product along the aluminum product cycle.

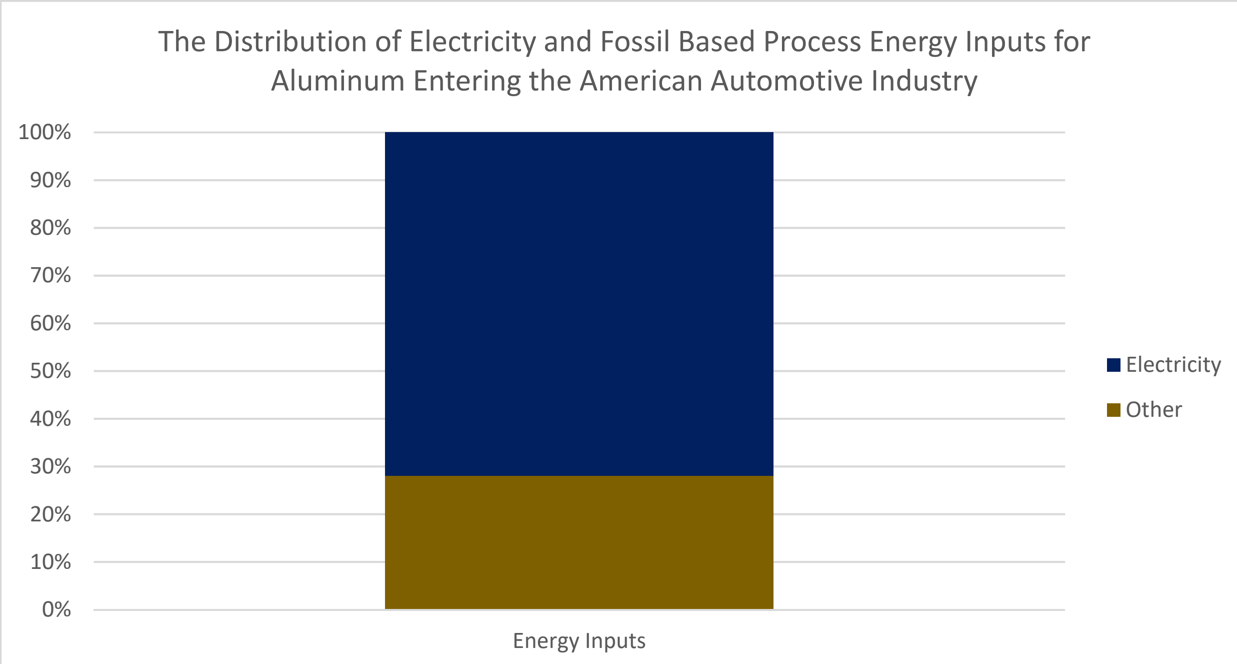

Figure 16: Total process energy embodied in aluminum entering the American automotive industry by energy input.

3.2.6 RESULTS OF SCENARIO AND SENSITIVITY ANALYSES

3.2.6.1 FIRST ALTERNATIVE PRIMARY ALUMINUM SOURCING SCENARIO

By sourcing all primary aluminum for automotive aluminum mill product producers from the primary aluminum supply mix in Table 4, the combined USA and Canada supply share of primary aluminum decreased 13% from the base scenario to 81%. Consequently, the supply shares of alumina and bauxite from American continents decreased, allowing additional countries to meet the 1% cutoff. Detailed mass distributions by region are shown in Figure 17, Figure 19, and Figure 21, where this scenario is indicated by "Alt Scenario 1." Since the scenario analysis occurred upstream of automotive aluminum mill products, their regional distribution remained unchanged.

The energy demand for primary aluminum, alumina, and bauxite entering the American automotive industry follow the changes in mass flows, as shown in Figure 18, Figure 20, and Figure 22. Although the total mass of primary aluminum remains constant, the energy demand increases as more primary aluminum is internationally sourced due to lower efficiency of international primary aluminum production. The increase of international primary aluminum sourcing by automotive aluminum mill product producers increases total process energy demand embodied by automotive aluminum by 1.4%. Figure 23 shows the effect of regional changes to total process energy demand.

3.2.6.2 SECOND ALTERNATIVE PRIMARY ALUMINUM SOURCING SCENARIO

The second alternative scenario also assumes that all automotive aluminum mill product producers source primary aluminum from a single supply mix. The primary aluminum supply mix for this alternative scenario assumes a greater share of primary aluminum imports and is shown in Table 7. In this scenario, the USA and Canada account for 67% of the total primary aluminum supply mix. This decreases the supply shares of alumina and bauxite from North and South America and allows for additional countries to meet the 1% cutoff relative to the base scenario. Detailed changes in regional mass flows of primary aluminum, alumina, and bauxite are shown in Figure 17, Figure 19, and Figure 21.

Changes in regional energy demand follow the changes in mass flows for primary aluminum, alumina, and bauxite. The increase of international primary aluminum sourcing by automotive aluminum mill product producers results in a 1.8% increase of total process energy demand embodied in automotive aluminum. Figure 23 shows the regional changes in total energy demand between the scenarios.

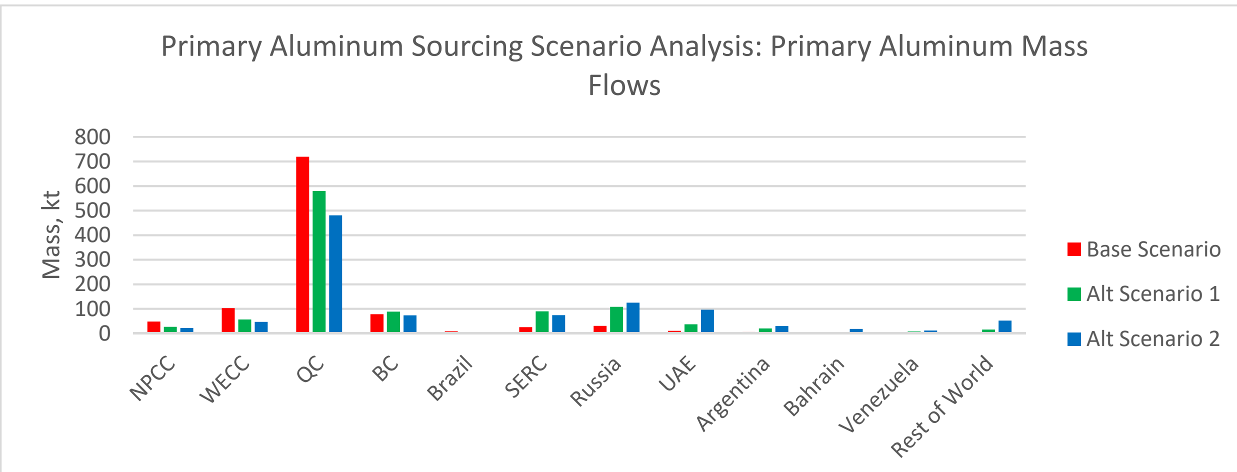

Figure 17: The effect of changing the American primary aluminum mix and sourcing patterns of automotive aluminum mill product producers on regional mass flows of primary aluminum.

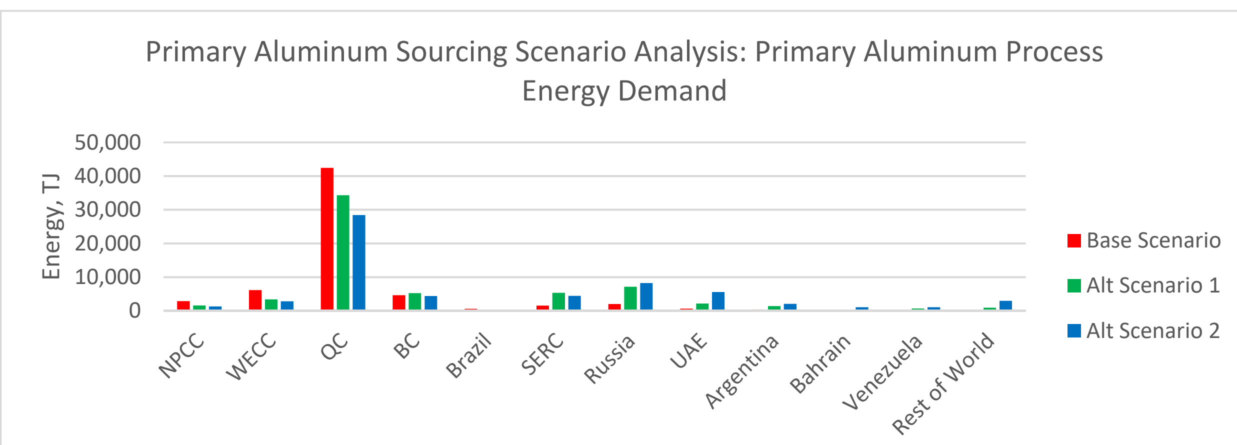

Figure 18: The effect of changing the American primary aluminum mix and sourcing patterns of automotive aluminum mill product producers on the regional distribution of primary aluminum process energy demand. Process energy demand is not separated by energy input here but rather aggregated.

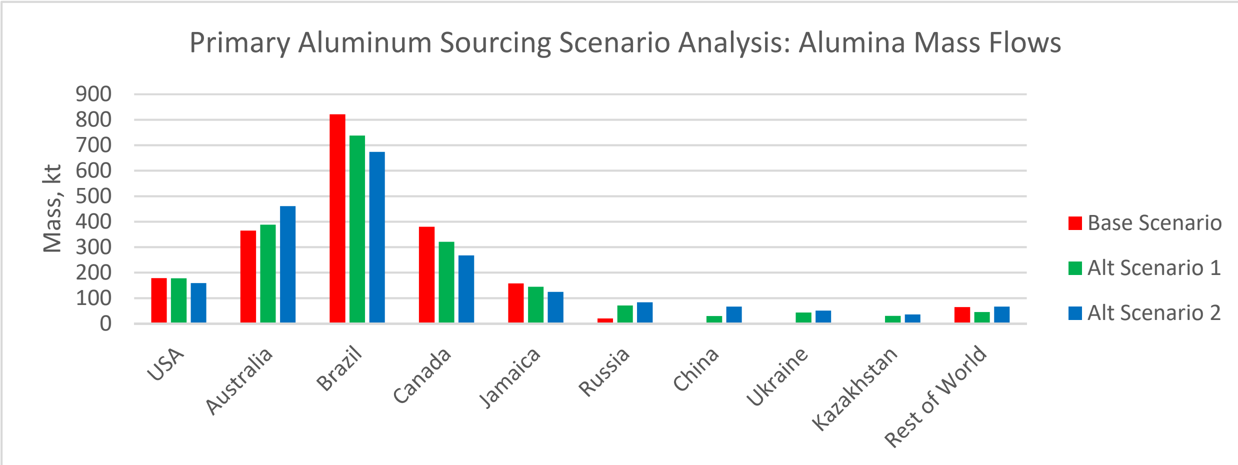

Figure 19: The effect of changing the American primary aluminum mix and sourcing patterns of automotive aluminum mill product producers on regional mass flows of alumina.

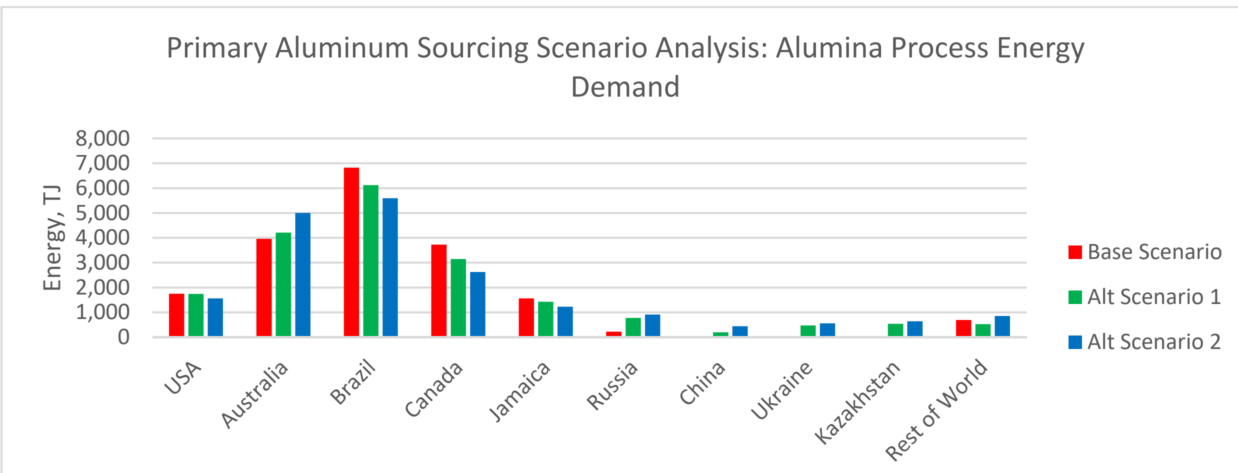

Figure 20: The effect of changing the American primary aluminum mix and sourcing patterns of automotive aluminum mill product producers on the regional distribution of alumina process energy demand. Process energy demand is not separated by energy input here but rather aggregated.

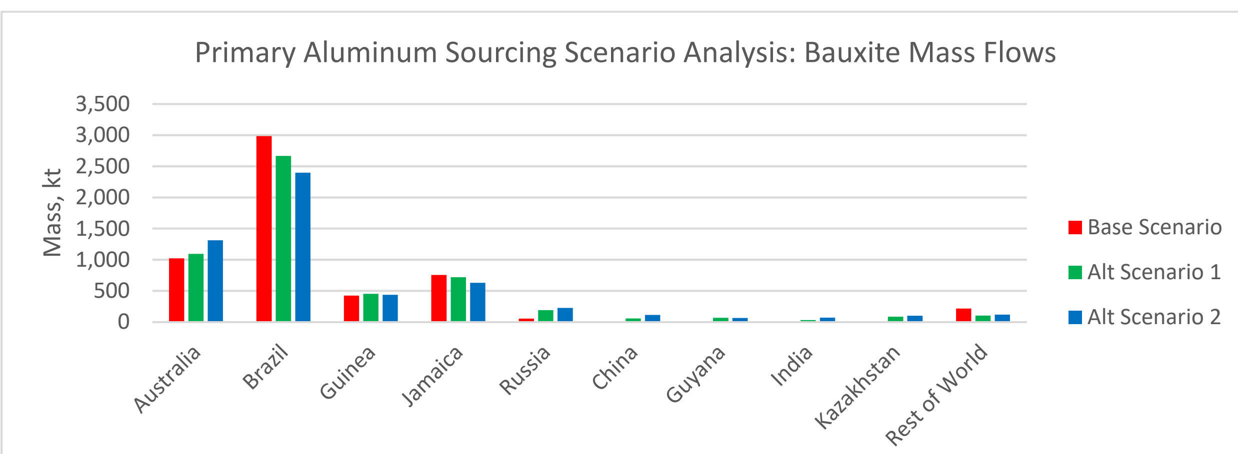

Figure 21: The effect of changing the American primary aluminum mix and sourcing patterns of automotive aluminum mill product producers on regional mass flows of bauxite.

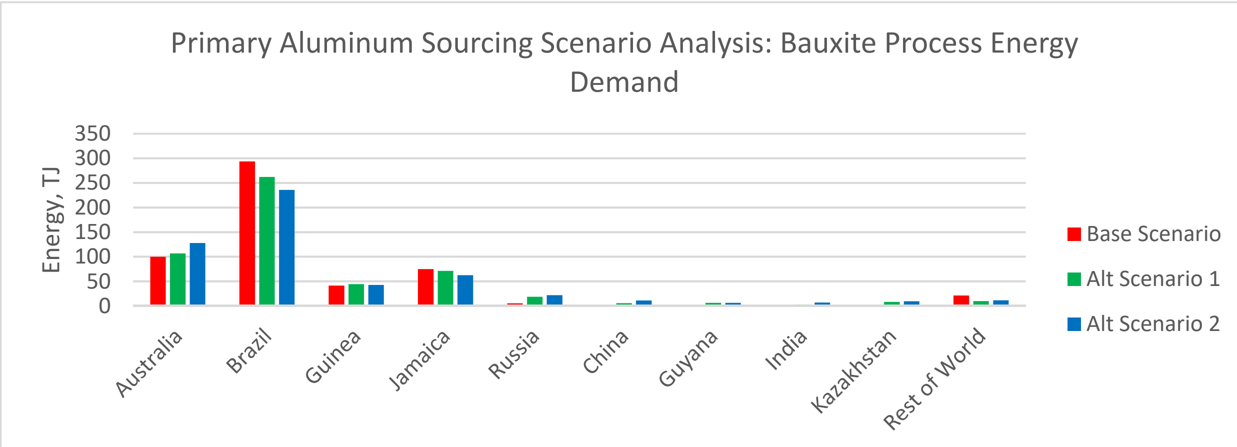

Figure 22: The effect of changing the American primary aluminum mix and sourcing patterns of automotive aluminum mill product producers on the regional distribution of bauxite process energy demand. Process energy demand is not separated by energy input here but rather aggregated.

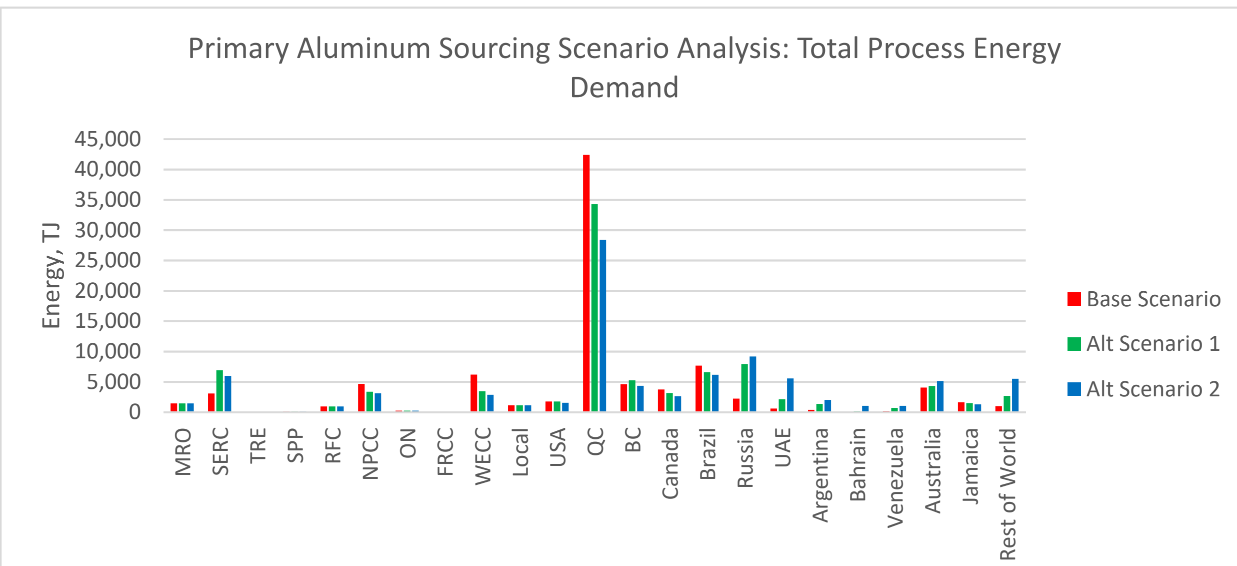

Figure 23: The effect of changing the American primary aluminum mix and sourcing patterns of automotive aluminum mill product producers on the regional distribution of total process energy demand for aluminum entering the American automotive industry. Process energy demand is not separated by energy input here but rather aggregated.

3.2.6.3 ALUMINUM MILL PRODUCT REGIONALITY SCENARIO AND SENSITIVITY

Uniformly distributing both the automotive aluminum mill product producer market shares by mill product and the supply shares of automotive aluminum mill product producer locations resulted in notable decreases in mass flows from the MRO, NPCC, and "Local" regions and significant increase in mass flows from the TRE, SPP, RFC and ON regions (Figure 24).

Changes in the regional distributions of primary aluminum, alumina, and bauxite entering the American automotive industry also occur, though to a lesser degree, as shown in Figure 26, Figure 28, and Figure 30. Regional changes in energy demand follow the same pattern as mass flows.

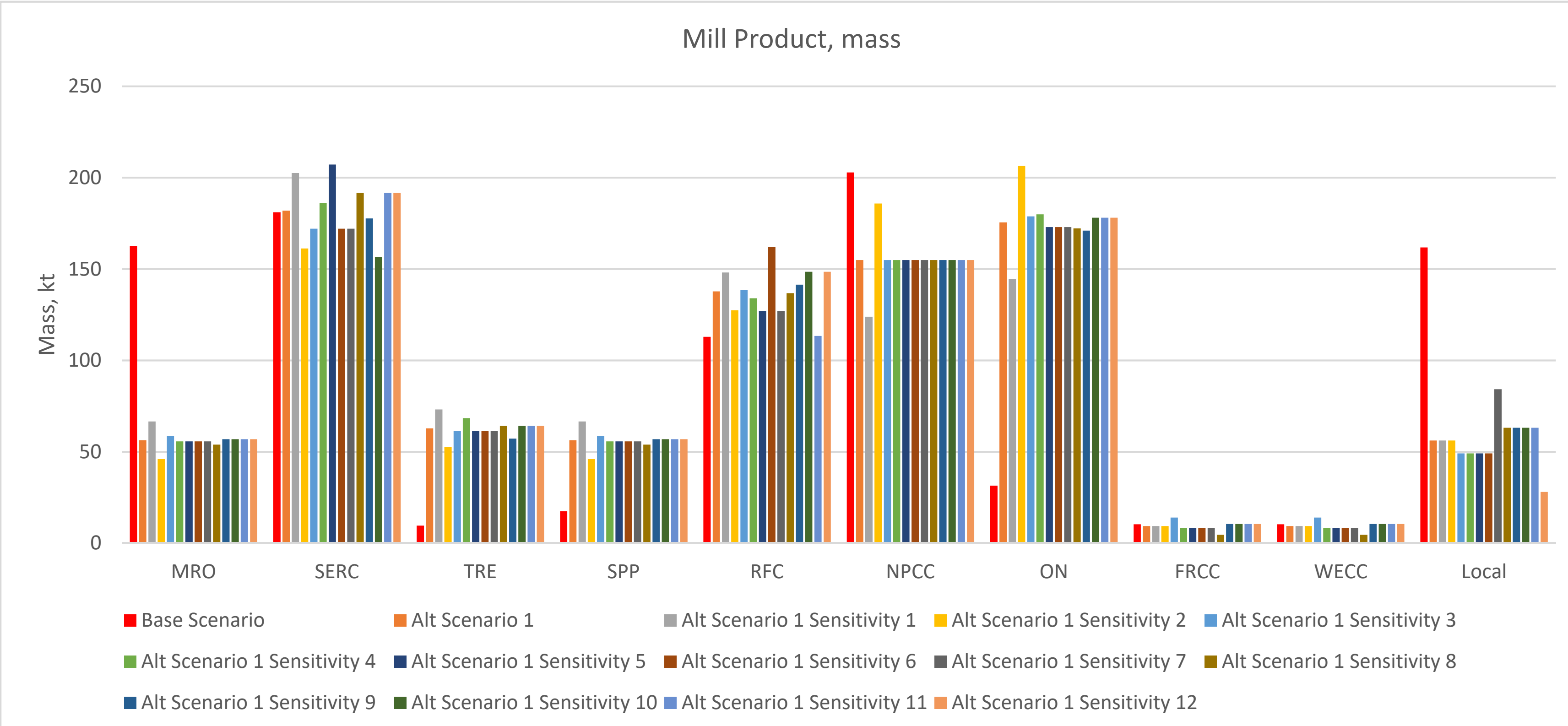

Figure 24: Effects on regional mass flows of automotive aluminum mill products from (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Descriptions of scenario labels can be found in Table 10.

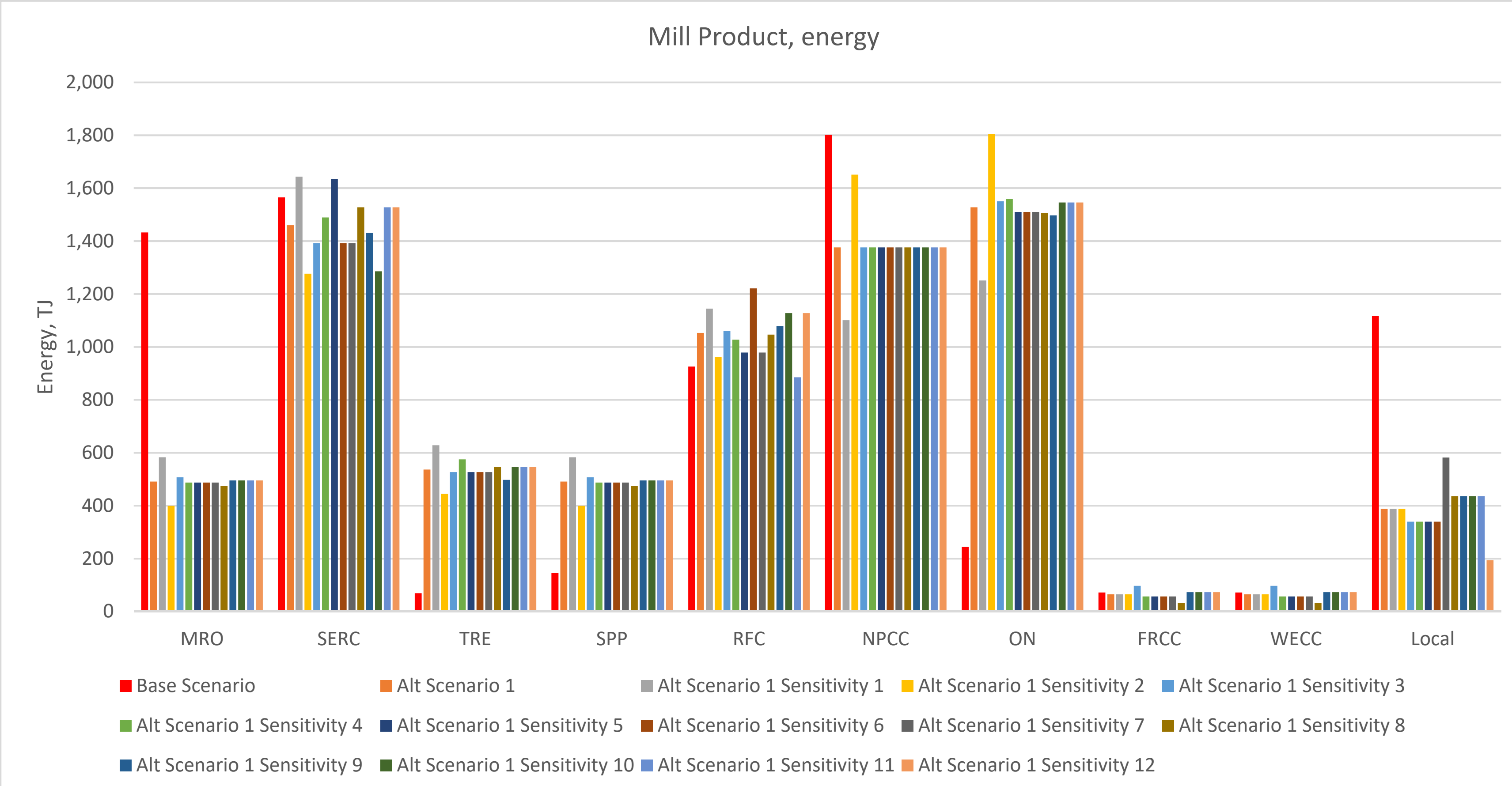

Figure 25: Effects on the regional process energy demand of automotive aluminum mill products from (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Descriptions of scenario labels can be found in Table 10. Process energy demand is not separated by energy input here but rather aggregated.

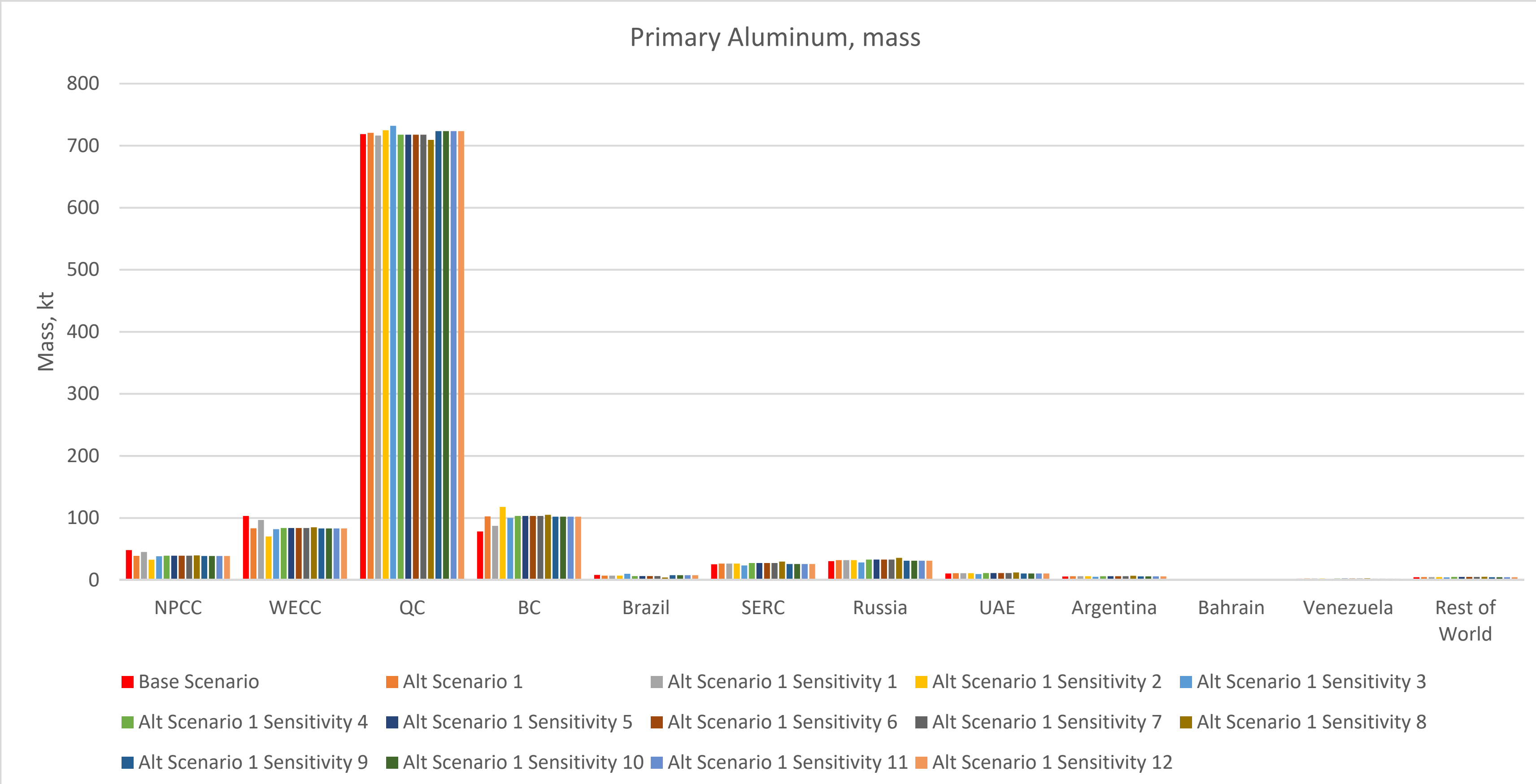

Figure 26: Effects on the regional mass flows of primary aluminum from (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Descriptions of scenario labels can be found in Table 10.

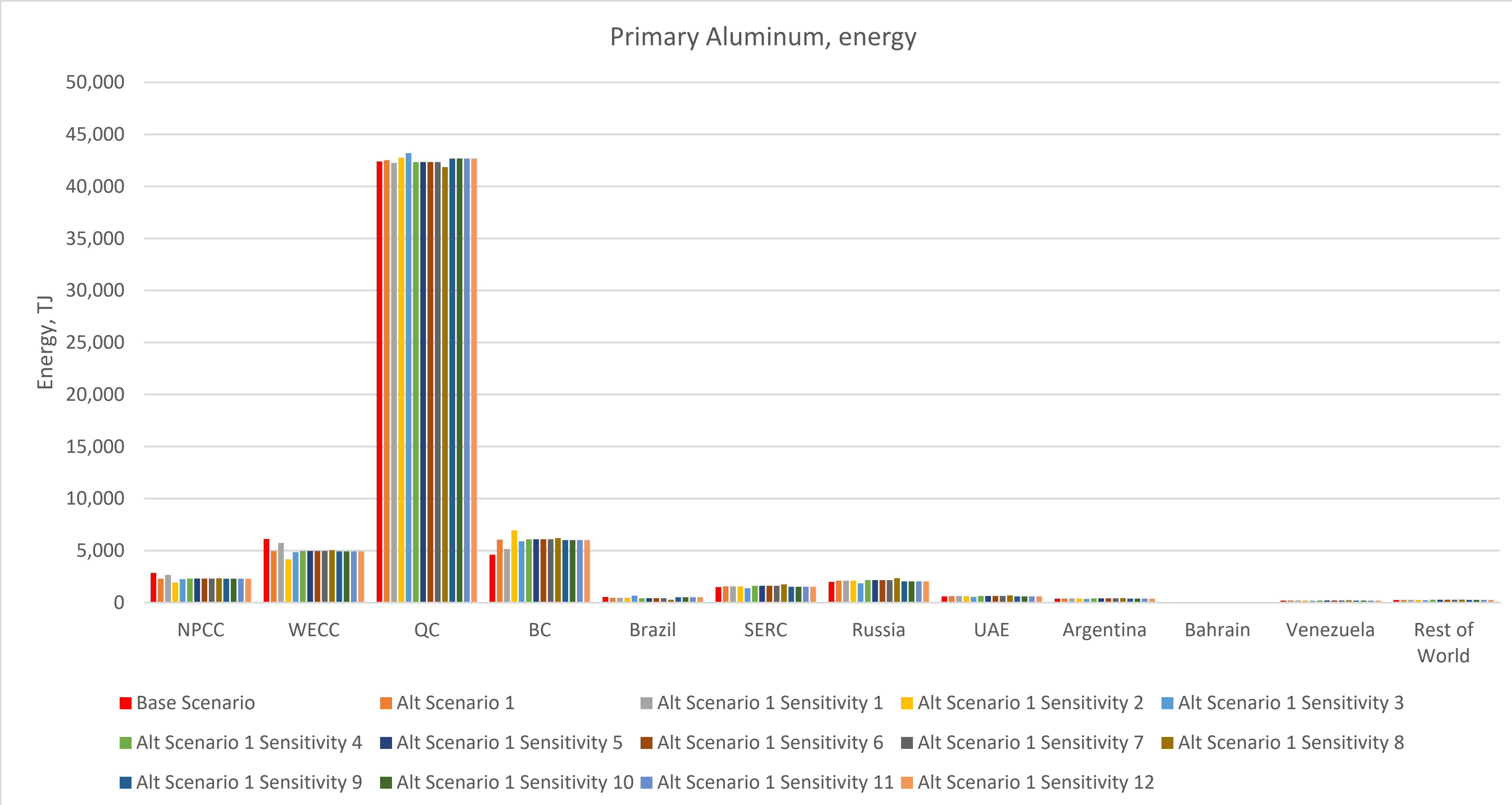

Figure 27: Effects on the regional process energy demand of primary aluminum from (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Descriptions of scenario labels can be found in Table 10. Process energy demand is not separated by energy input here but rather aggregated.

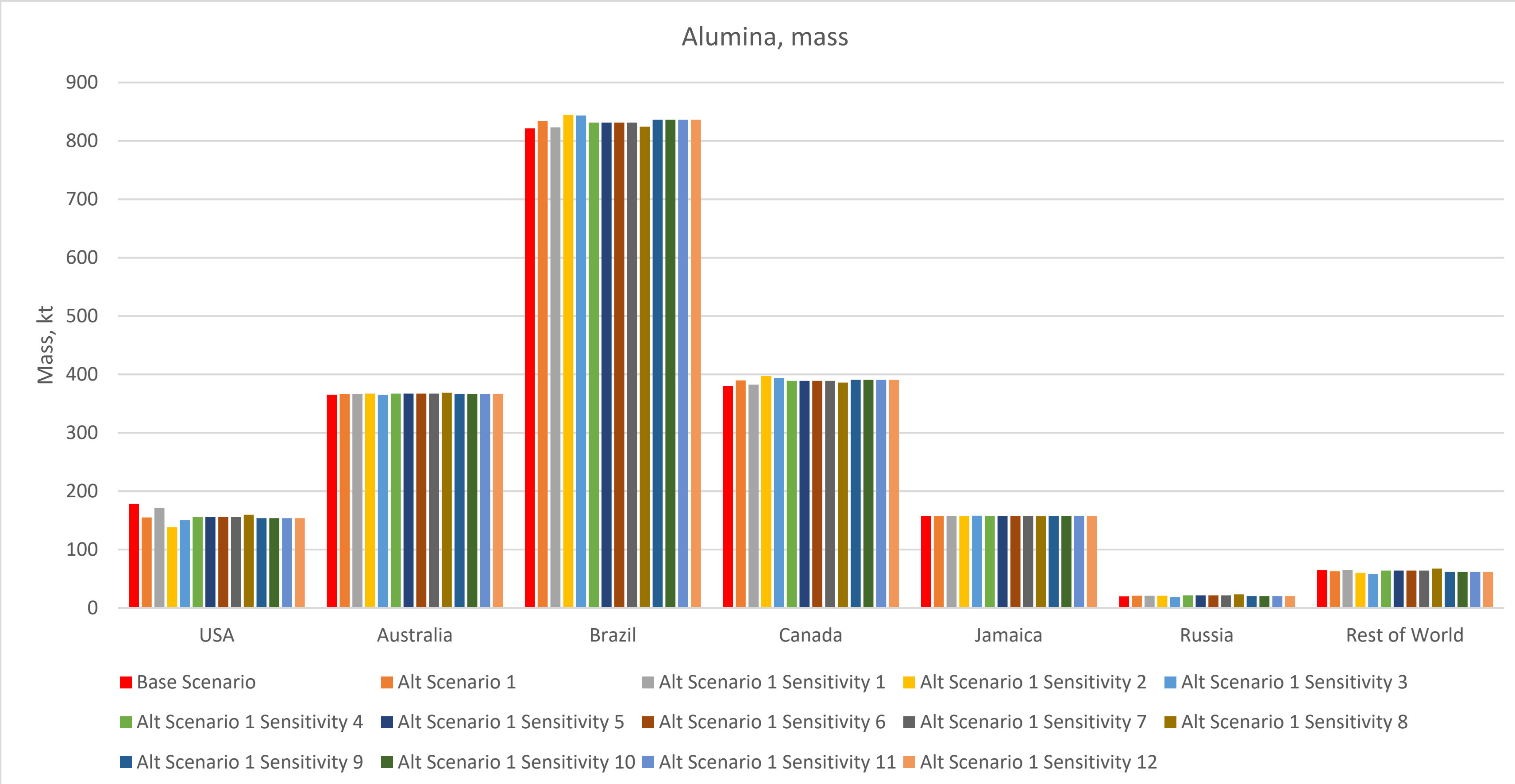

Figure 28: Effects on the regional mass flows of alumina from (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Descriptions of scenario labels can be found in Table 10.

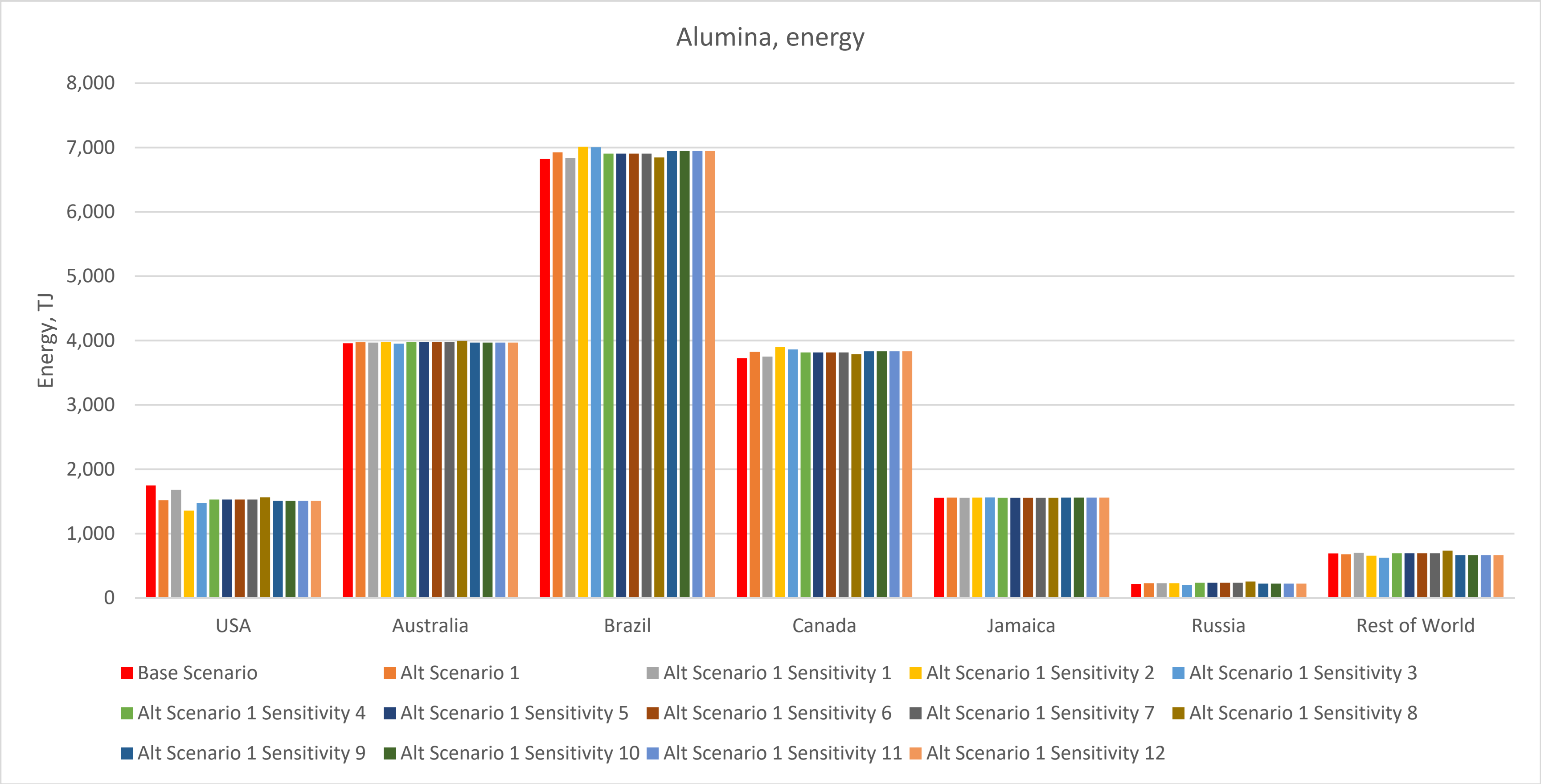

Figure 29: Effects on the regional process energy demand of alumina from (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Descriptions of scenario labels can be found in Table 10. Process energy demand is not separated by energy input here but rather aggregated.

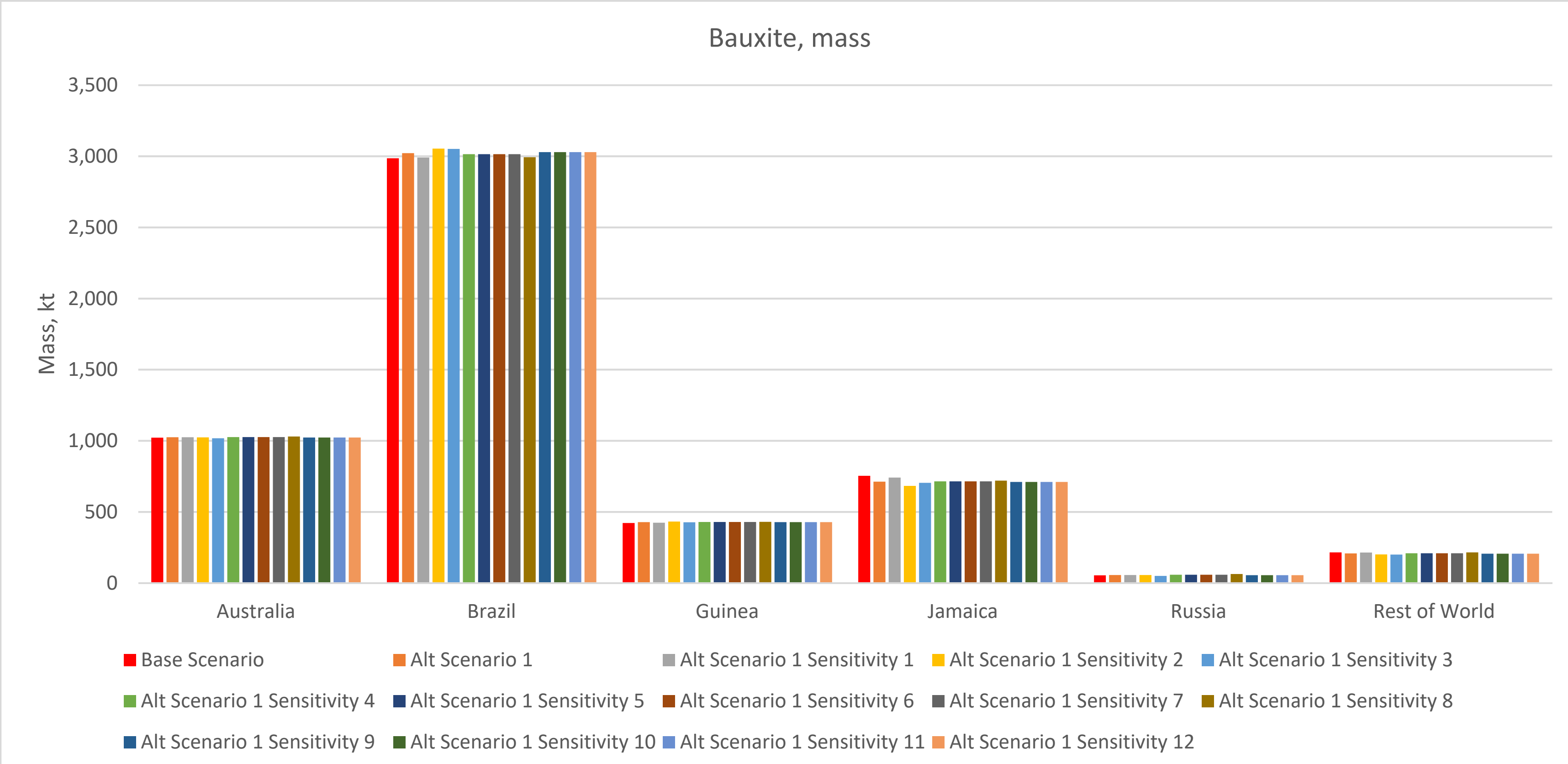

Figure 30: Effects on the regional mass flows of bauxite from (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Descriptions of scenario labels can be found in Table 10.

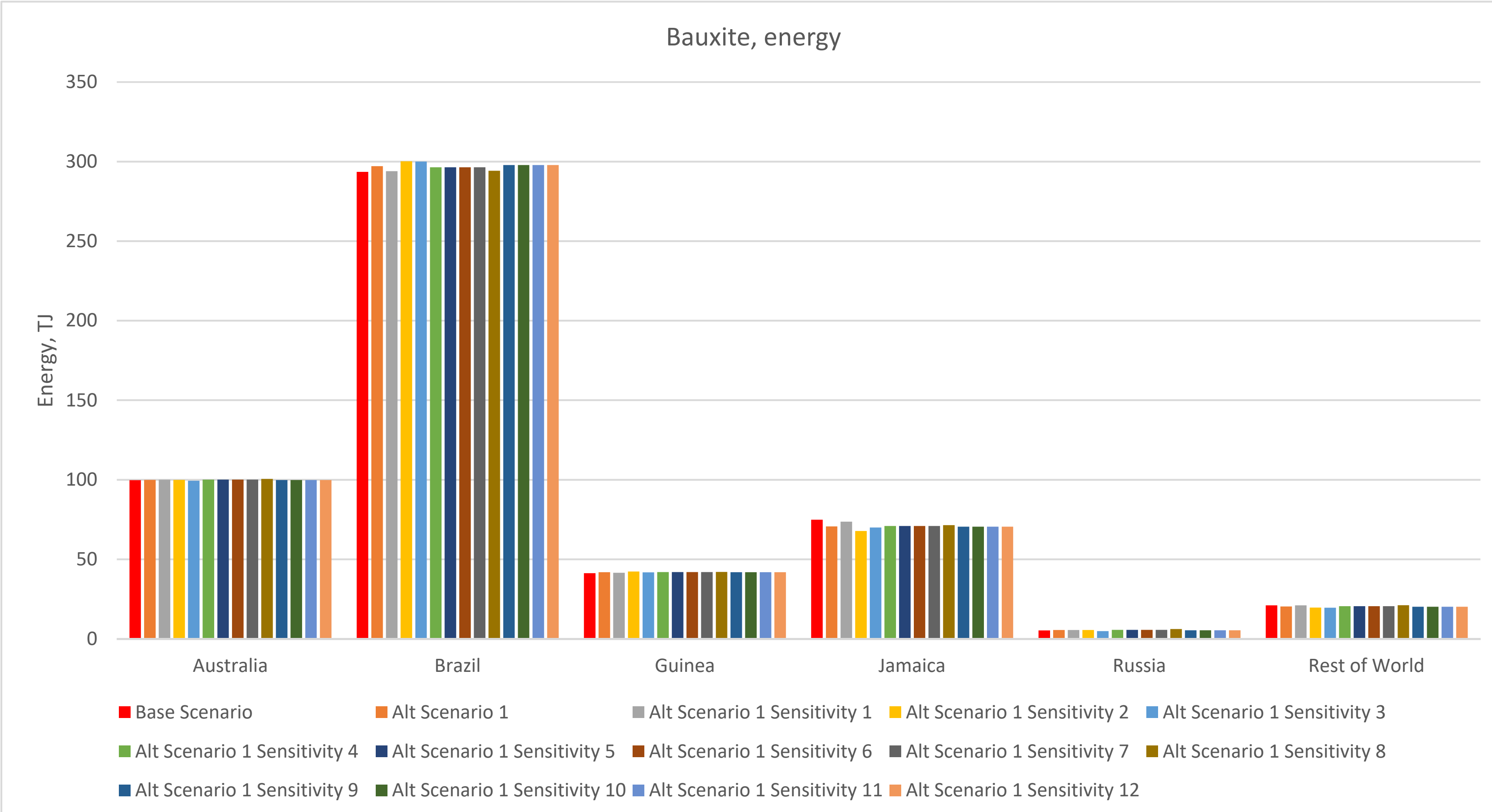

Figure 31: Effects on the regional process energy demand of bauxite from (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Descriptions of scenario labels can be found in Table 10. Process energy demand is not separated by energy input here but rather aggregated.

Table 10: Scenario label descriptions for Figure 22-Figure 29.

Scenario	Description
Base Scenario	Model Case
Alt Scenario 1	Uniform distribution market shares and location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 1	10% market share increase for Company A / uniform distribution market share decrease for other sheet producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 2	10% market share increase for Company B / uniform distribution market share decrease for other sheet producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 3	10% market share increase for Company C / uniform distribution market share decrease for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 4	10% market share increase for Company D / uniform distribution market share decrease for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 5	10% market share increase for Company E / uniform distribution market share decrease for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 6	10% market share increase for Company F / uniform distribution market share decrease for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 7	10% market share increase for Local / uniform distribution market share decrease for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 8	10% market share decrease for Company C / uniform distribution market share increase for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 9	10% market share decrease for Company D / uniform distribution market share increase for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 10	10% market share decrease for Company E / uniform distribution market share increase for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 11	10% market share decrease for Company F / uniform distribution market share increase for other extrusion producers / uniform distribution location supply shares for all mill product producers
Alt Scenario 1 Sensitivity 12	10% market share decrease for Local / uniform distribution market share increase for other extrusion producers / uniform distribution location supply shares for all mill product producers

The application of a ±10% sensitivity to automotive aluminum mill product producer market shares results in slight changes to the regional distribution of mass flows at each material stage along automotive aluminum's life cycle. Change in the regional energy demand distribution follows the same pattern as mass flow.

Compared to the effect of changing primary aluminum sourcing patterns and weights, changing the sourcing weights of automotive aluminum mill products has a minor effect on the regional mass flows of all upstream materials and overall distribution of process energy demand associated with automotive aluminum (Figure 32).

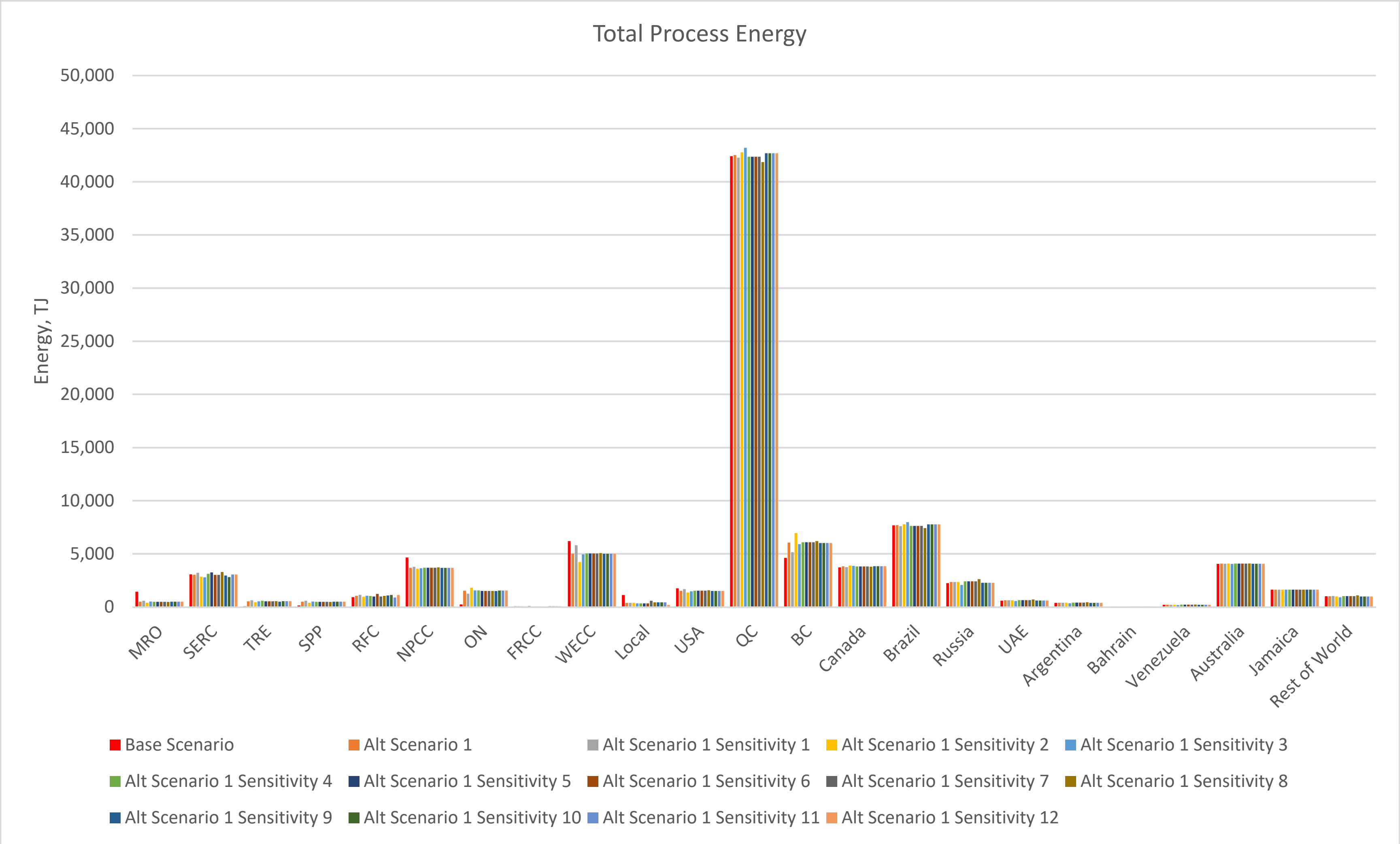

Figure 32: Regional changes in contribution towards the total process energy demand embodied by automotive aluminum due to (1) uniformly distributing the automotive aluminum mill product producer market shares and producer location shares and (2) performing a ±10% sensitivity analysis on the uniformly distributed automotive aluminum mill product producer market shares. Process energy demand is not separated by energy input here but rather aggregated.

3.3 DISCUSSION

We have identified several major insights worthy of discussing. First, the inability to resolve the Local region for automotive aluminum extrusions acts as a pain point in our analysis since it prevents complete NERC level disaggregaton of automotive aluminum extrusions. Additional research into disaggregating the Local region is necessary to add further regional detail the aluminum extrusions entering the American automotive industry. A potential strategy could weight American automotive OEM assembly facilities, tier 1 and tier 2 supplier facilities by NERC region and apply those weights to the Local region. This strategy relies on the assumption that production of automotive aluminum is uniform across different facilities and is directly related to the distribution of American automotive facilities.

Second, if sourcing of primary aluminum, which is highly electricity intensive, becomes increasingly globalized and American primary aluminum sourcing decreases, a large increase in GHG emissions will occur. Since the bulk of American primary aluminum comes from Quebec, which has an electrical grid powered primarily by hydroelectric sources, decreasing the relative sourcing of primary aluminum from Quebec will dramatically increase GHG emissions, since other countries in the American primary aluminum mix have GHG emission factors two orders of magnitude greater than Quebec's. Research to identify primary energy embodied by automotive aluminum, regional energy intensities of automotive aluminum, and regional GHG intensities of automotive aluminum is recommended to further explore the environmental burdens of regional aluminum sourcing by the American automotive industry.

A consequence of decreasing American primary aluminum use is the decrease in alumina and bauxite sourcing from American continents. We found that the share of alumina and bauxite from Brazil and Jamaica decreased while Australia's share increased, indicating that proximity between bauxite and alumina supplying countries and primary aluminum producing countries maintains a role in the sourcing of alumina and bauxite.

Since primary aluminum accounts for 70% of the total energy embodied in automotive aluminum, its regionalization is the largest determinant of environmental effects. Increased efforts to integrate scrap into automotive aluminum sheet and extrusions could result in major changes in regional aluminum raw material flows and total primary energy demand. Secondary aluminum ingot production is nearly 20 times less energy intensive than primary aluminum ingot production (GARC, 2009). Efforts to increase the recovery of new scrap from automotive sheet stamping processes have already begun to be operationalized (Ford, 2017), and if utilized by automotive aluminum mill product producers, could dramatically reduce the need for aluminum raw materials and decrease energy consumption. In this vein, we recognize that the primary aluminum content of automotive aluminum mill products assumed by GREET and used by this study is outdated and recommend it be updated once new and reliable information is made available. If the utilization rate for aluminum scrap increases in automotive aluminum mill product production, the sourcing patterns of aluminum scrap would influence the regional supply chain associated with automotive aluminum, and alumina and bauxite intensity for automotive aluminum mill products would decrease. We recognize that identifying and quantifying the flows of aluminum scrap are important in further detailing the geography of the automotive aluminum supply chain and recommend further research as this was beyond the scope of this work.

4. REGIONALLY LINKED AUTOMOTIVE STEEL MFA

4.1 METHODS

4.1.1 SYSTEM BOUNDARIES, SCOPE, AND DESIRED REGIONALITY

The system boundary for the automotive steel system is presented in Figure 33. The spatial boundary of the American automotive industry was defined by the geographic boundary of the USA and the temporal boundary was 2017. OEMs and tier 1 and 2 suppliers are assumed to be included in the definition of the American automotive industry.

The scope of the automotive steel system includes automotive steel mill products as well as the steel contained in finished automotive parts entering the American automotive industry. Automotive steel mill products were disaggregated following the framework of the American Iron and Steel Institute's annual statistical review into hot-rolled sheet, cold-rolled sheet, galvanized sheet, other coated sheet, hot-rolled bar, and other steel (AISI 2018). Each automotive steel mill product category was then disaggregated by crude steel production method, either BOF or EAF. Steel contained in finished automotive parts is often found in the drivetrain and components that attach to a vehicle's body-in-white (BIW). This steel was disaggregated by BOF or EAF crude steel production method. Upstream materials including coke, coking coal, iron ore, lime, scrap, DRI, and pig iron were also analyzed.

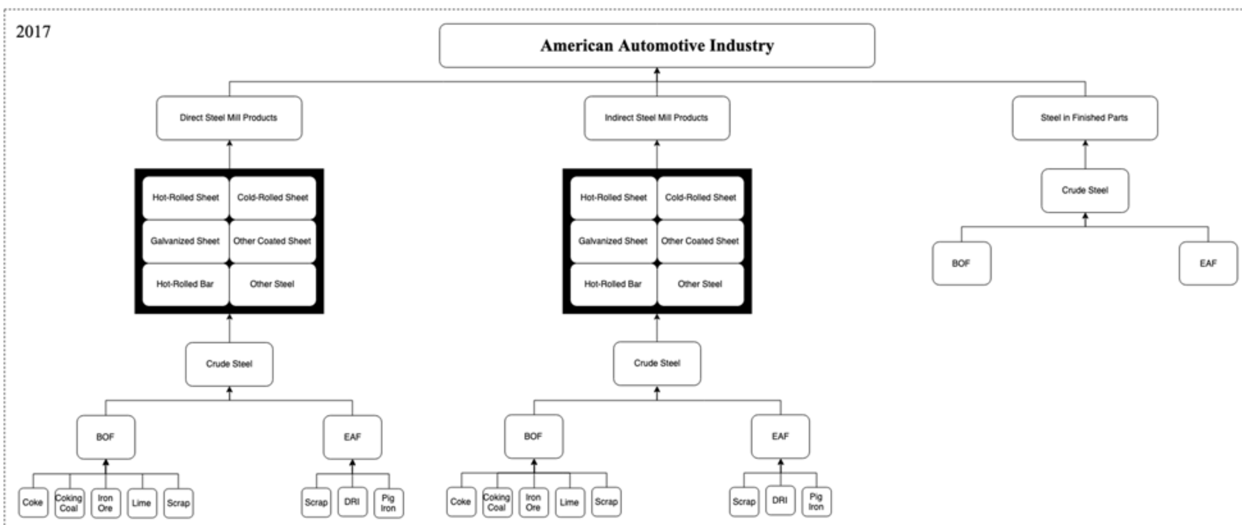

Figure 33: System boundaries for the automotive steel MFA. Automotive steel mill products are boxed in black.

The levels of regional disaggregation for the automotive steel system were NERC regions for the USA and country-level for all other countries. These levels were chosen so that meaningful energy demand results could be extracted. NERC regions allow investigation into electricity differences, which have more regional variance from a GHG emissions perspective than other energy sources.

4.1.2 RESOLVING STEEL MILL PRODUCTS AND STEEL IN FINISHED PARTS ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

Finished steel in LDVs enters via two major pathways, either through steel mill products or through steel contained in finished automotive parts. Ratios of vehicular steel originating from steel mill products or contained in finished parts are difficult to determine, with vehicle teardowns being the primary method to do so. Estimates for the percentage of steel in a vehicle from steel mill products and steel in finished parts for this study were extracted from previous studies conducted by MEGA Associates (Schnatterly, 2010; Schnatterly, 2012; MEGA Associates Ltd, n.d.). Flows of steel mill products and steel in finished parts to the North American automotive industry were averaged and used as a proxy for the spatial boundary of the American automotive industry.

Steel mill products entering the American automotive industry may further be disaggregated by direct and indirect shipments. Automotive steel mill product producers ship steel mill products directly to the American automotive industry, while the indirect route involves automotive steel mill product producers shipping steel mill products to steel service centers or converters for further processing before ultimately entering the American automotive industry. The direct-to-indirect ratio of steel mill shipments to the American automotive industry were estimated by extracting information from the MEGA Associates studies and averaging.

4.1.3 REGIONALIZING THE STEEL IN FINISHED PARTS ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

USA and other country shares of finished automotive parts supplied to the American automotive industry were obtained using an industry report from IBISWorld (Miles, 2017). Due to the supply chain complexity of the automotive parts industry, inability to isolate flows of specific automotive parts, and major uncertainties in steel content of automotive parts, we assumed that regional flows of steel in finished automotive parts directly follow those of finished automotive parts themselves.

In order to obtain NERC region estimates for the steel in finished automotive parts from the USA entering the American automotive industry, we assumed that steel was produced from either BOF or EAF crude steel in the same ratio as the country's overall crude steel production (AISI, 2018). Steel produced via BOF and EAF crude steel was assigned to the NERC regions of BOF and EAF crude steelmakers respectively (Table *13* and Table *14*). BOF crude steelmaker locations were identified by first isolating the total number of companies and facilities from USGS (Fenton, 2018a) and then using company websites and annual reports to identify specific facility locations. NERC region aggregation was then applied. EAF crude steelmaker locations were identified by consulting USGS to identify the total number of facilities (Fenton, 2018a) and then using a state level facility distribution map of EAF crude steelmakers from IBISWorld (Hadad, 2017) to determine the number of EAF crude steelmaker locations by state. If the majority of a state was within the boundaries of a NERC region, then all of the EAF crude steelmaker locations within that state were attributed to that NERC region. We assumed that the NERC region distribution of EAF crude steelmakers was predicated on facility number and not facility production due to inability to obtain facility production data.

Data for countries supplying steel in finished automotive parts to the American automotive industry were kept at country level regionality but split by BOF and EAF crude steel production (World Steel Association, 2018) in order to trace raw materials by proxy. Regional distribution percentages were applied to the mass flows of steel in finished automotive parts following Equation 10 in order to obtain regional mass flows.

The energy input for steel in finished automotive parts differs by type of crude steel input. If BOF crude steel is the input, an averaged value based on GREET 2 energy inputs for steel sheet products is used and in the case of EAF crude input, the GREET 2 energy input for hot-rolled bar is used (ANL, 2018b). The energy inputs for steel in finished automotive parts do not account for any additional processing from mill product to finished part. Regional energy demands associated with the steel in finished automotive parts were calculated following Equation 11.

Equation 10:

$$M(sfp)_i = M_T * W * A_j * B_k * C_i$$

Where:
$M(sfp)_i$ = mass of steel in finished parts from location i
M_T = total mass of steel entering the American automotive industry
W = estimated percentage of steel in finished parts entering the American automotive industry
A_j = estimated American or international share of steel in finished parts
B_k = estimated share of American steel in finished parts produced via BOF or EAF (ignore if j = international)
C_i = estimated supply share of steel in finished parts from location i (within BOF or EAF if j= American or within international countries if j= international)

Equation 11:

$$ED(sfp)_i = M(sfp)_i * EI(sfp)_i$$

Where:
$ED(sfp)_i$ = energy demand of steel in finished parts from location i
$M(sfp)_I$ = mass of steel in finished parts from location i
$EI(sfp)_i$ = energy input per unit mass of steel in finished parts from location i

4.1.4 REGIONALIZING AUTOMOTIVE STEEL MILL PRODUCTS

Due to a lack of supply information regarding indirect shipments of steel mill products to the American automotive industry, the regionalization scheme for direct shipments of automotive steel mill products described in this section was applied to both direct and indirect steel mill products entering the American automotive industry.

In this model we used the American Automotive Policy Council's (AAPC) conservative estimate of the USA versus international supply share of steel mill products to the American automotive industry (85% USA and 15% international) (AAPC, 2017). Industry data from AISI (AISI, 2018) on shipment of USA steel mill products to the American automotive industry were consulted and disaggregated by product. Hot-rolled sheet, galvanized sheet, other coated sheet, and hot-rolled bar are stand-alone products. Cold-rolled sheet and cold-rolled strip were attributed to the "cold-rolled sheet" product category. All other listed steel mill products constituted the "other steel" product category. All steel mill product categories were disaggregated by type of crude steel input. Steel sheet products followed a 94/6 BOF/EAF ratio detailed by SRI (Sebastian & Thimons, 2017). Hot-rolled bar and other steel were assumed to follow a 50/50 BOF/EAF split due to lack of data or a proxy method.

USA automotive steel sheet producers were identified through consultation with industry professionals (Sebastian, Thimons, & Hall, 2019), steel industry reports and presentations, steel sheet producer websites, steel sheet producer annual reports and 10-K SEC filings, steel industry news articles, and automotive industry news articles. Specific sources employed and findings are contained in Table 11. Automotive steel sheet producers, their locations and associated NERC regions by sheet product are shown in Table 12.

Table 11: Specific references used in the regionalization of steel mill products and steel in finished automotive parts entering the American automotive industry.

Parameter	Method	Source(s)
Automotive Steel Mill Products vs Steel in Finished Automotive Parts	Proxy	• (Schnatterly, 2010) • (Schnatterly, 2012) • (MEGA Associates Ltd, n.d.)
American vs International Steel in Finished Automotive Parts	Proxy	• (Miles, 2017)
Steel in Finished Automotive Parts Produced via BOF and EAF crude steel	Proxy	• (AISI, 2018) • (World Steel Association 2018)
Direct vs Indirect Automotive Steel Mill Products	Proxy	• (Schnatterly, 2010) • (Schnatterly, 2012) • (MEGA Associates Ltd, n.d.)
American vs International Automotive Steel Mill Products	-	• (AAPC, 2017)
Direct, American Automotive Steel Mill Product Shipment Weights	-	• (AISI, 2018)
Indirect Steel Mill Product Shipment Weights	Proxy	• (AISI, 2018)
Automotive Steel Sheet Produced via BOF and EAF crude steel	-	• (Sebastian & Thimons, 2017)
American Automotive Steel Sheet Producers and Producer Locations	-	• (Sebastian, Thimons, & Hall, 2019) • (United States Steel Corporation [US Steel], 2018) • (AK Steel Holding Corporation [AK Steel], 2018) • (ArcelorMittal, 2018) • (Tolomeo et al., 2019) • (NLMK USA, 2016) • (NLMK USA, 2019) • (Nucor, 2019) • (Steel Dynamics, Inc. [SDI], 2019a) • (Cowden, 2018) • (BlueScope, 2019)

American Automotive Steel Sheet Producer Market Shares	Proxy	• (AISI, 2018) • (US Steel, 2018) • (AK Steel, 2018) • (ArcelorMittal, 2018) • (Nucor, 2018) • (SDI, 2018) • (NLMK, 2018) • (BlueScope, 2017) • (Cowden, 2018)
American Automotive Steel Sheet Producer Location Supply Shares	Proxy and Uniform Distribution	• (ArcelorMittal, 2018) • (SDI, 2019) • (NLMK USA, 2019)
International Automotive Steel Sheet Suppliers and Weights	Proxy	• (AISI, 2018)
Automotive Steel Bar Produced via BOF and EAF crude steel	Uniform Distribution	-
American Automotive Steel Bar Producer Locations and Weights	Proxy	• (US Steel, 2018) • (AK Steel, 2018) • (ArcelorMittal, 2018) • (Fenton, 2018a) • (Hadad, 2017)
International Automotive Steel Bar Suppliers and Weights	Proxy	• (AISI, 2018)
Automotive Other Steel Produced via BOF and EAF crude steel	Uniform Distribution	-
American Automotive Other Steel Producer Locations and Weights	Proxy	• (US Steel, 2018) • (AK Steel, 2018) • (ArcelorMittal, 2018) • (Fenton, 2018a) • (Hadad, 2017)
International Automotive Other Steel Suppliers and Weights	Proxy	• (AISI, 2018)

Table 12: Automotive steel sheet producers by company, location, region, crude steel source, and sheet product type.

Producer	Location	Appropriate Region	BOF/EAF Crude Steel	Hot-Rolled Sheet	Cold-Rolled Sheet	Galvanized Sheet	Other Coated Sheet
K	K1	SERC	BOF			x	
K	K2	RFC	BOF	x	x	x	
K	K3	RFC	BOF	x	x	x	x
K	K4	RFC	BOF		x	x	x
K	K5	RFC	BOF				x
L	L1	RFC	BOF	x	x	x	
L	L2	RFC	BOF	x	x	x	
L	L3	RFC	BOF	x	x	x	x
L	L4	RFC	BOF			x	
L	L5	RFC	BOF	x			
L	L6	SERC	BOF	x	x	x	
L	L7	RFC	BOF		x	x	
M	M1	SERC	BOF			x	
M	M2	RFC	BOF	x	x	x	
M	M3	SERC	BOF	x	x	x	
M	M4	RFC	BOF	x	x	x	
M	M5	RFC	BOF			x	
M	M6	RFC	BOF		x	x	
M	M7	RFC	BOF	x	x	x	x
M	M8	RFC	BOF		x	x	
K	K6	RFC	EAF	x	x		x
N	N1	SERC	EAF	x	x	x	
N	N2	RFC	EAF	x	x	x	
N	N3	SERC	EAF	x	x	x	
N	N4	SERC	EAF	x	x	x	
N	N5	SERC	EAF	x	x		
O	O1	RFC	EAF	x	x	x	
O	O2	SERC	EAF	x		x	
O	O3	RFC	EAF			x	
O	O4	RFC	EAF			x	
P	P1	RFC	EAF	x			
P	P2	RFC	EAF	x	x		
P	P3	RFC	EAF			x	
Q	Q1	RFC	EAF	x			
R	R1	SERC	EAF	x	x	x	

For American hot-rolled bar and other steel entering the American automotive industry, regional distributions are assumed to be the same as the distributions for BOF and EAF crude steel production shown in Table *13* and Table *14*. BOF crude steel production occurs exclusively in the RFC NERC region. The NERC region distribution of EAF crude steel production was determined using facility distribution (Hadad, 2017) and total facility (Fenton, 2018a) data as described in section 4.1.3.

Weighted mass flows for automotive steel mill product producers and producer locations were calculated through proxy methods that leveraged sources of data which could be related to production and uniform distributions. Descriptions of proxy methods used and sample calculations can be found in Appendix C. Weight estimates are withheld to acknowledge their uncertainty and preserve producer anonymity.

The weights for international automotive steel mill products by product were assumed to be the same as those for USA automotive steel mill products. At the country level, international distributions of automotive steel mill product sources by mill product were extracted from AISI's industry statistics (AISI, 2018) by weighting countries based on USA import volume. A Rest of World region was also included in the industry statistics. The BOF/EAF ratios for each automotive steel mill product were assumed to be the same as previously mentioned for USA automotive steel mill products. Regional mass flows were then calculated via Equation 12.

Equation 12:

$$M_{l,m} = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m}$$

Where:
$M_{l,m}$ = mass of steel mill product l from location m
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q's location m if produced via BOF (ignore if produced via BOF)

Energy inputs for each steel mill product were obtained from the GREET 2 model (ANL, 2018b). Other coated steel sheet was assumed to have the same energy input as galvanized sheet and other steel was assumed to have the same energy input as hot-rolled bar. Regional energy demands were then calculated using Equation 13.

Equation 13:

$$ED_{l,m} = M_{l,m} * EI_{l,m}$$

Where:
$ED_{l,m}$ = energy demand of steel mill product l from location m
$M_{l,m}$ = mass of steel mill product l from location m
$EI_{l,m}$ = energy input per unit mass of steel mill product l from location m

4.1.5 REGIONALIZING THE CRUDE STEEL ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

Fabrication efficiencies from crude steel to automotive hot-rolled sheet, cold-rolled sheet, galvanized sheet, and hot-rolled bars are taken from GREET 2 (ANL, 2018b) while the fabrication efficiency for other coated sheet was assumed to be the same as galvanized sheet. The material input of crude steel for other steel mill products and steel in finished automotive parts was assumed to be 1.05 based on an informed estimate from GREET 2 values for other steel mill products. This assumption necessarily omits loss factors during conversion of steel mill products into finished automotive parts. Resulting crude steel masses were then regionalized within each production type.

Since USA BOF automotive steel mill products are produced by integrated steelmakers, they are assumed to source their BOF crude steel from the same company and from the crude steelmaking locations within that company—shown in Table *13*—except for Producer L's L6 location which is a 50/50 joint venture between Producer L and a crude steel producer in Japan and assumed to source half its crude steel from Company L and half from Japan. All BOF crude steel producing locations within the USA are in the RFC NERC region and so USA automotive steel mill products produced via BOF are assumed to source crude steel from RFC.

Table 13: USA BOF crude steel producers by company, location, and NERC region.

Producer	Producer Location	Region
K	K2	RFC
K	K3	RFC
L	L1	RFC
L	L2	RFC
L	L3	RFC
L	L5	RFC
M	M2	RFC
M	M4	RFC
M	M7	RFC

Table 14: USA EAF crude steel production by NERC region.

Region	Estimated Region Weights (%)
RFC	31
SERC	48
WECC	7
TRE	6
MRO	3
NPCC	1
SPP	1

FRCC	3

Regionalizing the supply of crude steel to USA automotive steel sheet producers that utilize EAF crude steel also assumed company level vertical integration. For USA hot-rolled bar and other steel that utilize EAF crude steel, sourcing was assumed to be from the same NERC region as mill product production. The regional distribution of EAF crude steel production in the USA was described in section 4.1.4 and was based off of a facility locations proxy.

Both BOF and EAF crude steel supplies for international automotive steel mill product producers were assumed to be from the same country that the automotive steel mill product was produced in. Crude steel regional flows were calculated via Equation 14.

Equation 14:

$$M(crude)_s = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m} * Y_l * J_r * K_s$$

Where:
$M(crude)_s$ = mass of crude steel from location s
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q's location m if produced via BOF (ignore if produced via EAF)
Y_l = crude steel required for steel mill product l
J_r = estimated market share of crude steel supplier r
K_s = estimated supply share of crude steel supplier r's location s

Energy inputs for crude steel production were obtained from GREET 2. BOF energy inputs accounted for sintering, the blast furnace, the basic oxygen furnace, and on-site generation and other steam uses and losses. The EAF energy input was defined exclusively by the electric arc furnace. Regional energy demand associated with crude steel production were determined through Equation 15.

Equation 15:

$$ED(crude)_s = M(crude)_s * EI(crude)_s$$

Where:
$ED(crude)_s$ = energy demand of crude steel from location s
$M(crude)_s$ = mass of crude steel from location s
$EI(crude)_s$ = energy input per unit mass of crude steel from location s

4.1.6 REGIONALIZING THE COKE ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

Using data from World Steel (World Steel Association, 2019) and the Industrial Efficiency Technology Database (IETD) (Institute for Industrial Productivity [IPP], 2019a), the material input of coke to produce crude BOF steel was applied to all crude BOF steel mass flows. A weighted and regionalized coke supply mix was then produced for each crude BOF steel supplying country to calculate coke mass flows.

The regionalized USA coke supply was determined by first using the production, export, and imports data from EIA (USA EIA, 2018a) to create a country level supply mix. The USA share was then disaggregated further by first identifying USA coke producer locations in 2016 (American Coke and Coal Chemicals Institute [ACCCI], 2016) and assuming the same locations for 2017. Production for specific USA coke facilities was then estimated by two methods. The first method consisted of marrying facility data from producer websites (SunCoke Energy Inc., 2017; USA EPA, 2019b) and census bureau coke production statistics from EIA. The second method used a production to number of coke ovens ratio (Haryanto, Hein, and Kaiser, 2012). Through a combination of location production capacity identification and subtraction of identified production capacities from reported census division values, coke production was able to be identified and weighted by NERC region.

The regionality for coke supplies of all countries was kept at the country level. UN Data (UN, 2019b) were used to identify country level coke production, export, and import data for the year 2017. If 2017 data were unavailable, 2016 production data from UN Data were used and combined with 2017 export and import data from UN Comtrade. The principles for determining a country’s coke supply mix is given by Equation 5. If a country lacked coke import and export data, a Rest of World supply mix was used. The coke supply for the Rest of World was determined by weighting country-level coke exports. By applying the country-level coke supply mixes to crude steel mass flows, regional distributions of coke entering the American automotive industry were determined with Equation 16.

Equation 16:

$$M(coke)_u = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m} * Y_l * J_r * K_s * L * M_t * N_u$$

Where:
$M(coke)_u$ = mass of coke from location u
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q’s location m if produced via BOF (ignore if produced via EAF)
Y_l = crude steel required for steel mill product l
J_r = estimated market share of crude steel supplier r
K_s = estimated supply share of crude steel supplier r’s location s
L = coke required for crude steel if produced via BOF (ignore if produced via EAF)
M_t = estimated market share of coke supplier t if produced via BOF (ignore if produced via EAF)
N_u = estimated supply share of coke supplier t’s location u if produced via BOF (ignore if produced via EAF)

Energy inputs for coke production were taken from GREET 2 and applied to the regional distribution of coke mass flows using Equation 17 to create a regionally resolved energy demand distribution.

Equation 17:

$$ED(coke)_u = M(coke)_u * EI(coke)_u$$

Where:
$ED(coke)_u$ = energy demand of coke from location u
$M(coke)_u$ = mass of coke from location u
$EI(coke)_u$ = energy input per unit mass of coke from location u

4.1.7 REGIONALIZING THE COKING COAL ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

The material input of coking coal required to produce coke (IPP, 2019a) was applied to each coke material flow and for each coke supplying country, a country level coking coal supply mix was constructed to trace the material flows of coking coal.

USA coking coal exports and imports by country were obtained from EIA (USA EIA, 2018b) while USA coking coal production was estimated by taking total coking coal consumption, subtracting total imports, and adding total exports. The supply mix was then generated by combining USA coking coal net production and imports.

Coking coal supply mixes for other countries were generated by combining coking coal production, exports, and imports data taken from UN Data and following the rules of Equation 5. UN Comtrade data were then used to resolve the country level regionality of imports. If UN Data did not have 2017 data, IEA data (IEA, 2019) from 2016 were used while using 2017 UN Comtrade data to resolve country level regionality of imports. If a country lacked coking coal import and export data, a Rest of World supply mix was used. The Rest of World coking coal supply mix was determined by weighting country level coking coal exports. The determined country level supply mixes were then used to calculate the regional distribution of coking coal using Equation 18.

Equation 18:

$$M(cokingcoal)_w = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m} * Y_l * J_r * K_s * L * M_t * N_u * O * P_v * Q_w$$

Where:
$M(cokingcoal)_w$ = mass of coking coal from location w
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q's location m if produced via BOF (ignore if produced via EAF)

Y_l = crude steel required for steel mill product l
J_r = estimated market share of crude steel supplier r
K_s = estimated supply share of crude steel supplier r's location s
L = coke required for crude steel if produced via BOF (ignore if produced via EAF)
M_t = estimated market share of coke supplier t if produced via BOF (ignore if produced via EAF)
N_u = estimated supply share of coke supplier t's location u if produced via BOF (ignore if produced via EAF)
O = coking coal required for coke if produced via BOF (ignore if produced via EAF)
P_v = estimated market share of coking coal supplier v if produced via BOF (ignore if produced via EAF)
Q_w = estimated supply share of coking coal supplier v's location w if produced via BOF (ignore if produced via EAF)

Energy inputs for coking coal were taken from the GREET 1 model (ANL, 2018a) and regional energy demand associated with getting coking coal to the coking plant were calculated with Equation 19.

Equation 19:

$$ED(cokingcoal)_w = M(cokingcoal)_w * EI(cokingcoal)_w$$

Where:
$ED(cokingcoal)_w$ = energy demand of coking coal from location w
$M(cokingcoal)_w$ = mass of coking coal from location w
$EI(cokingcoal)_w$ = energy input per unit mass of coking coal from location w

4.1.8 REGIONALIZING THE IRON ORE ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

The total amount of iron ore required for BOF crude steel entering the American automotive industry was identified by applying a material input ratio from World Steel (World Steel Association, 2019). Regionalizing the mass flows of iron ore required the construction of country level iron ore supply mixes in the same manner as for coke in section 4.1.6.

The USA iron ore supply mix was determined by first disaggregating the total amount of iron ore produced by NERC region. Using an annual report from iron ore mining company Cleveland-Cliffs (Cleveland-Cliffs Inc., 2018), a USGS minerals yearbook identifying iron mine locations (Tuck, 2018a) and a USGS commodity report (Tuck, 2018b), USA iron ore sources by NERC region were identified and weighted by production. The regionalized production of USA iron ore was combined with export and import data from UN Comtrade to create the iron ore supply mix for the USA.

Country iron ore supply mixes were kept at country-level regionality and constructed following the rules of Equation 5. Production data were obtained from USGS and if 2017 production data were unavailable, 2016 production statistics were used (USGS, 2018). Import and export data were obtained via UN Comtrade. If a given country lacked iron ore import and export data, a Rest of World supply mix was used. The Rest of World iron ore supply mix was determined by weighting country-level iron ore exports relative to total world iron ore exports. Country level supply mixes were then used to calculate the regional distribution of iron ore using Equation 20.

Equation 20:

$$M(ironore)_y = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m} * Y_l * J_r * K_s * R * S_x * T_y$$

Where:
$M(ironore)_y$ = mass of iron ore from location y
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q's location m if produced via BOF (ignore if produced via EAF)
Y_l = crude steel required for steel mill product l
J_r = estimated market share of crude steel supplier r
K_s = estimated supply share of crude steel supplier r's location s
R = iron ore required for crude steel if produced via BOF (ignore if produced via EAF)
S_x = estimated market share of iron ore supplier x if produced via BOF (ignore if produced via EAF)
T_y = estimated supply share of iron ore supplier x's location y if produced via BOF (ignore if produced via EAF)

Energy inputs for iron ore were obtained from GREET 2 and used with regional mass flows of iron ore (Equation 21) to determine regional energy demand.

Equation 21:

$$ED(ironore)_y = M(ironore)_y * EI(ironore)_y$$

Where:
$ED(ironore)_y$ = energy demand of iron ore from location y
$M(ironore)_y$ = mass of iron ore from location y
$EI(ironore)_y$ = energy input per unit mass of iron ore from location y

4.1.9 REGIONALIZING THE LIME ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

The regionalization of country-level lime supplies was performed in a similar manner to the regionalization of coke and iron ore described in previous sections. The material input of lime required for BOF crude steel was obtained from World Steel (World Steel Association, 2019).

The lime supply mix for the USA was determined by using the rules from Equation 5, with production data coming from USGS (Corathers, 2018a) and export and import data from UN Comtrade. Although other USA raw material supplies were regionalized at the NERC level, lime was regionalized by census regions and divisions since that was the smallest unit possible.

International supply mixes of lime for each country were produced at the country level by using production data from USGS and export and import data from UN Comtrade. 2015 production data (Corathers, 2018b) were used where 2017 data were unavailable (at the time of this study, the most recent USGS minerals yearbook for lime was 2015). The Rest of World lime supply mix was determined following the same procedure as for previous raw materials. If a country lacked lime import and export data, the Rest of World supply was used. Country-level supply mixes were used to calculate the regional distribution of lime using Equation 22.

Equation 22:

$$M(lime)_a = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m} * Y_l * J_r * K_s * U * V_z * W_\alpha$$

Where:
$M(lime)_\alpha$ = mass of lime from location α
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q's location m if produced via BOF (ignore if produced via EAF)
Y_l = crude steel required for steel mill product l
J_r = estimated market share of crude steel supplier r
K_s = estimated supply share of crude steel supplier r's location s
U = lime required for crude steel if produced via BOF (ignore if produced via EAF)
V_z = estimated market share of lime supplier z if produced via BOF (ignore if produced via EAF)
W_α = estimated supply share of lime supplier z's location α if produced via BOF (ignore if produced via EAF)

Energy inputs for lime were obtained from GREET 2 and combined with regional mass flows (Equation 23) in order to determine regional energy demand.

Equation 23:

$$ED(lime)_\alpha = M(lime)_\alpha * EI(lime)_\alpha$$

Where:
$ED(lime)_\alpha$ = energy demand of lime from location α
$M(lime)_\alpha$ = mass of lime from location α
$EI(lime)_\alpha$ = energy input per unit mass of lime from location α

4.1.10 REGIONALIZING THE STEEL SCRAP ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

Regionalizing material flows of steel scrap entering the American automotive industry required different analysis for steel produced via BOF and EAF due to differing amounts of steel scrap input required for these two types of furnace. Within EAF steel entering the American automotive industry, steel scrap input also varies by mill product. Applying particular material input values of steel scrap to crude steel mass flows using World Steel data (World Steel Association, 2019) and informed estimates, the total amount of steel scrap entering the American automotive industry was determined. Regionalized steel scrap supply mixes for each crude steel supplying country were then produced.

The USA steel scrap supply mix was determined using methods previously described for other raw materials, using USGS (Fenton, 2018b) for production data and UN Comtrade for export and import data.

International steel scrap production statistics are not well documented, so steel scrap supply mixes for crude steel supplying countries were constructed following the rules in Equation 5. Countries with reported steel scrap consumption (Bureau of International Recycling [BIR], 2018) follow a production back-calculation and export and import data analysis method while countries that lack reported steel scrap consumption follow simple wholly integrated or wholly imported steel scrap supply mixes. The Rest of World steel scrap supply mix was determined by weighting country level steel scrap exports relative to total world steel scrap exports. Lacking steel scrap import and export data, countries with such deficits were assigned the Rest of World supply mix. The regional distribution of steel scrap was then determined by Equation 24.

Equation 24:

$$M(scrap)_{\chi} = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m} * Y_l * J_r * K_s * Z * \alpha_{\beta} * \beta_{\chi}$$

Where:
$M(scrap)_{\chi}$ = mass of steel scrap from location χ
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q's location m if produced via BOF (ignore if produced via EAF)
Y_l = crude steel required for steel mill product l
J_r = estimated market share of crude steel supplier r
K_s = estimated supply share of crude steel supplier r's location s
Z = steel scrap required for crude steel
α_{β} = estimated market share of steel scrap supplier β
β_{χ} = estimated supply share of steel scrap supplier β's location χ

The energy input for steel scrap was assumed to be the same as for iron scrap and was obtained from the Ecoinvent database (Althaus, 2007). The energy input data and regional mass flows of steel scrap were used in Equation 25 to calculate regional energy demand.

Equation 25:

$$ED(scrap)_{\chi} = M(scrap)_{\chi} * EI(scrap)_{\chi}$$

Where:
$ED(scrap)_{\chi}$ = energy demand of steel scrap from location χ
$M(scrap)_{\chi}$ = mass of steel scrap from location χ
$EI(scrap)_{\chi}$ = energy input per unit mass of steel scrap from location χ

4.1.11 REGIONALIZING THE DRI ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

DRI is an alternative to steel scrap for high quality EAF crude steel production. Due to its variable utilization in producing different mill products, the material input of DRI for EAF crude steel is uncertain. We assumed DRI constitutes 25% of the material composition of steel mill products other than hot-rolled bar, which was assumed to be made wholly from steel scrap. Fabrication loss factors between mill products and EAF crude steel were not considered. Regional supply mixes of DRI for each EAF crude steel producing country were estimated to regionalize the material flows of DRI.

USA total DRI production was estimated by supplementing the reported DRI production in the USA (Midrex Technologies, Inc., 2018) with additional known DRI production that was excluded (SDI, 2019b). The total reported USA DRI production from MIDREX was disaggregated by NERC region by consulting websites of the production companies (Voestlapine Texas LLC, 2019; Nucor, 2018). Exports and imports of DRI were obtained through UN Comtrade. The USA supply mix was then determined following the rules in Equation 5.

DRI supply mixes for international EAF crude steel supplying countries were determined using the same procedures for other raw materials, with production data obtained from MIDREX (Midrex Technologies, Inc., 2018) and export and import data from UN Comtrade. The Rest of World DRI supply mix was created using country-level export data and was used for countries that lacked DRI import and export data. Country-level DRI supply mixes were then combined with crude steel mass flows using Equation 26 to regionalize the mass flows of DRI.

Equation 26:

$$M(DRI)_{\varepsilon} = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m} * Y_l * J_r * K_s * \chi * \delta_{\delta} * \varepsilon_{\varepsilon}$$

Where:
$M(DRI)_{\varepsilon}$ = mass of DRI from location ε
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q's location m if produced via BOF (ignore if produced via EAF)
Y_l = crude steel required for steel mill product l
J_r = estimated market share of crude steel supplier r
K_s = estimated supply share of crude steel supplier r's location s
χ = DRI required for crude steel if produced via EAF (ignore if produced via BOF)
δ_{δ} = estimated market share of DRI supplier δ if produced via EAF (ignore if produced via BOF)
$\varepsilon_{\varepsilon}$ = estimated supply share of DRI supplier δ's location ε if produced via EAF (ignore if produced via BOF)

The energy input for DRI was obtained from the IETD (IPP, 2019b) and was combined with regional DRI mass flows to calculate energy demands in Equation 27.

Equation 27:

$$ED(DRI)_{\varepsilon} = M(DRI)_{\varepsilon} * EI(DRI)_{\varepsilon}$$

Where:
$ED(DRI)_{\varepsilon}$ = energy demand of DRI from location ε
$M(DRI)_{\varepsilon}$ = mass of DRI from location ε
$EI(DRI)_{\varepsilon}$ = energy input per unit mass of DRI from location ε

4.1.12 REGIONALIZING THE PIG IRON ENTERING THE AMERICAN AUTOMOTIVE INDUSTRY

Similar to DRI, pig iron is also an alternative to steel scrap for high quality EAF crude steel production. Pig iron utilization also varies with mill product type and application, creating uncertainty in quantifying it as a material input for EAF crude steel production. A 25% steel material composition of pig iron was assumed for all steel mill products produced via EAF other than hot-rolled bar. Material loss factors were not considered. After determining the total amount of pig iron required, flow regionalization was conducted.

The regionalized supply mix for USA-sourced pig iron was constructed by assuming that 5% of the reported pig iron production (Fenton, 2018a) was available for non-BOF crude steelmaking. Since pig iron is produced at the same locations as BOF crude steel, all USA pig iron was assumed to be sourced from the RFC NERC region. Combining the disaggregated USA pig iron production with export and import statistics from UN Comtrade results in the regionalized supply mix of pig iron for EAF crude steel production.

International supply mixes of pig iron for EAF crude steel production used the same 5% availability rule of reported pig iron production used for the USA to identify country-level production. If 2017 USGS pig iron production data were unavailable, 2016 data (Fenton & Tuck, 2019) were substituted. Supply mixes were then generated following the rules in Equation 5 after obtaining export and import data from UN Comtrade. Country-level export data were used to determine the Rest of World pig iron supply and were also used for countries that lacked import and export data. Regional flows of pig iron were then determined using the country-level supply mixes in Equation 28.

Equation 28:

$$M(pigiron)_{\gamma} = M_T * X * D_n * E_o * F_l * G_{l,p} * H_{l,q} * I_{l,p,q,m} * Y_l * J_r * K_s * \phi * \gamma_{\phi} * \eta_{\gamma}$$

Where:
$M(pigiron)_{\gamma}$ = mass of DRI from location ε
M_T = total mass of steel entering the American automotive industry
X = estimated percentage of steel mill products entering the American automotive industry
D_n = estimated direct or indirect share of steel mill products
E_o = estimated share of American or International steel mill products
F_l = estimated share of steel mill product l
$G_{l,p}$ = estimated share of steel mill product l produced via BOF or EAF
$H_{l,q}$ = estimated market share of steel mill product l from producer q
$I_{l,p,q,m}$ = estimated supply share of steel mill product l from producer q's location m if produced via BOF (ignore if produced via EAF)
Y_l = crude steel required for steel mill product l
J_r = estimated market share of crude steel supplier r
K_s = estimated supply share of crude steel supplier r's location s

ϕ = pig iron required for crude steel if produced via EAF (ignore if produced via BOF)
γ_ϕ = estimated market share of pig iron supplier ϕ if produced via EAF (ignore if produced via BOF)
η_γ = estimated supply share of pig iron supplier ϕ's location γ if produced via EAF (ignore if produced via BOF)

Energy inputs for pig iron were obtained from GREET and included coke production, sintering, and blast furnace processes. Equation 29 was used to calculate regionalized energy demands for pig iron from pig iron energy inputs and regional mass flows .

Equation 29:

$$ED(pigiron)_\gamma = M(pigiron)_\gamma * EI(pigiron)_\gamma$$

Where:
$ED(pigiron)_\gamma$ = energy demand of pig iron from location γ
$M(pigiron)_\gamma$ = mass of pig iron from location γ
$EI(pigiron)_\gamma$ = energy input per unit mass of pig iron from location γ

4.1.13 TOTAL STEEL TO LDV

Since our model accounted for both the steel mill products and steel in finished parts entering the American automotive industry, we were able to calculate the total amount of steel entering the American automotive industry. The ratio of American to international steel mill product shipments, the ratio of direct to indirect steel mill product shipments, and the ratio of steel mill products to steel in finished automotive parts were used to calculate the total amount of steel entering the American automotive industry. By analyzing the ratio of steel entering LDVs and heavy duty vehicles (HDVs) using a bottom-up approach, we were able to estimate the total amount of steel entering the American LDV industry. The calculated result of total steel to LDVs from our model (Equation 30) was compared to a bottom-up calculation of the same value. The bottom-up calculation (Equation 31) included an average LDV steel content, estimated steel mill product shares of steel in LDVs, and steel mill product fabrication efficiencies.

Vehicle production data were obtained from the International Organization of Motor Vehicle Manufacturers (OICA) (OICA, 2018a; OICA, 2018b; OICA, 2018c), average steel content of LDVs was obtained from American Chemistry Council (ACC) (American Chemistry Council [ACC], 2018), average steel content of HDVs was obtained by consulting previous work done by MEGA Associates (Schnatterly, 2012), and estimated steel mill product shares of steel in LDVs were identified through previous work conducted by Ducker (Ducker, 2017a). Sheet stamping efficiency was assumed to be 55% (Sebastian & Thimons, 2017) while the fabrication efficiency for all other mill products was assumed to be 80%, as suggested by MEGA Associates (Schnatterly, 2012).

Equation 30:

$$M(steeltoLDVs) = \frac{M_T\left(\varphi_{LDV} * \kappa_{LDV}\right)}{\left(\left(\varphi_{LDV} * \kappa_{LDV}\right) + \left(\varphi_{HDV} * \kappa_{HDV}\right)\right)}$$

Where:
$M(steeltoLDVs)$ = mass of steel to American LDVs

M_T = mass of steel entering the American automotive industry
φ_{LDV} = total number of American LDVs produced
κ_{LDV} = average steel content of an American LDV
φ_{HDV} = total number of American HDVs produced
κ_{HDV} = average steel content of an American HDV

Equation 31:

$$M(steeltoLDVs) = \frac{(\varphi_{LDV} * \kappa_{LDV} * \lambda)}{\mu} + \frac{(\varphi_{LDV} * \kappa_{LDV} * \nu)}{\sigma}$$

Where:
M(steeltoLDVs) = mass of steel in American LDVs
φ_{LDV} = total number of American LDVs produced
κ_{LDV} = average steel content of American LDVs
λ = share of steel in American LDVs that is sheet
μ = stamping efficiency of steel sheet
ν = share of steel in American LDVs that is all other steel mill product
σ = fabrication efficiency of all other steel mill product

4.1.14 SCENARIO AND SENSITIVITY ANALYSES

To assess how different parameters in our model influence the regional material flows and energy demand of steel and its upstream materials entering the American automotive industry, the scenario and sensitivity analyses listed in Table 15 were conducted.

Table 15: Scenario and sensitivity analyses conducted on the automotive steel model.

Parameter	Lower Value	Model Value	Upper Value
Direct Shipments of Automotive Steel Mill Products	65%	75%	85%
American Share of Automotive Steel Mill Products	-	85%	95%
Automotive Steel Sheet Produced via BOF Crude Steel	85%	94%	-
Automotive Steel Bar and Other Steel Produced via BOF Crude Steel	-	50%	90%

A ± 10% sensitivity analysis was performed on the ratio between direct and indirect shipments of steel mill products to the American automotive industry to identify regional effects as well as effects on the model-calculated total steel in American LDVs. The USA supply of steel mill products to the American automotive industry was increased by 10% to analyze the same effects. Only an increase was selected since the 85/15 split used in the model was a conservative estimate (American Automotive Policy Council [AAPC], 2017) and conversations with industry professionals provided evidence that the actual USA supply was about 95%.

The BOF/EAF production base for automotive steel mill products was also subject to scenario analysis. For steel sheet products, an 85/15 split scenario between sheet produced via BOF/EAF was utilized due to the steel industry having used this scenario before (Sebastian & Thimons, 2017). For all other steel mill products, a 10/90 split scenario between products produced via BOF/EAF was utilized since steel mill products other than sheet are largely produced via EAF in the USA.

A ± 5% sensitivity analysis on steel sheet stamping efficiency was performed on our bottom-up calculation of total steel going to American LDVs.

4.2 RESULTS

4.2.1 STEEL IN FINISHED AUTOMOTIVE PARTS REGIONALITY

The sources of steel in finished automotive parts are shown in Figure 34. The split between the USA supply and international supply is nearly 50/50. Within the USA supply, the RFC and SERC regions dominate, representing 27% and 17% of the total supply respectively. Mexico is the dominant international source of steel in finished automotive parts, providing 19% of the total supply. Since energy efficiencies did not differ by region, the regional distribution of energy exactly follows that of mass.

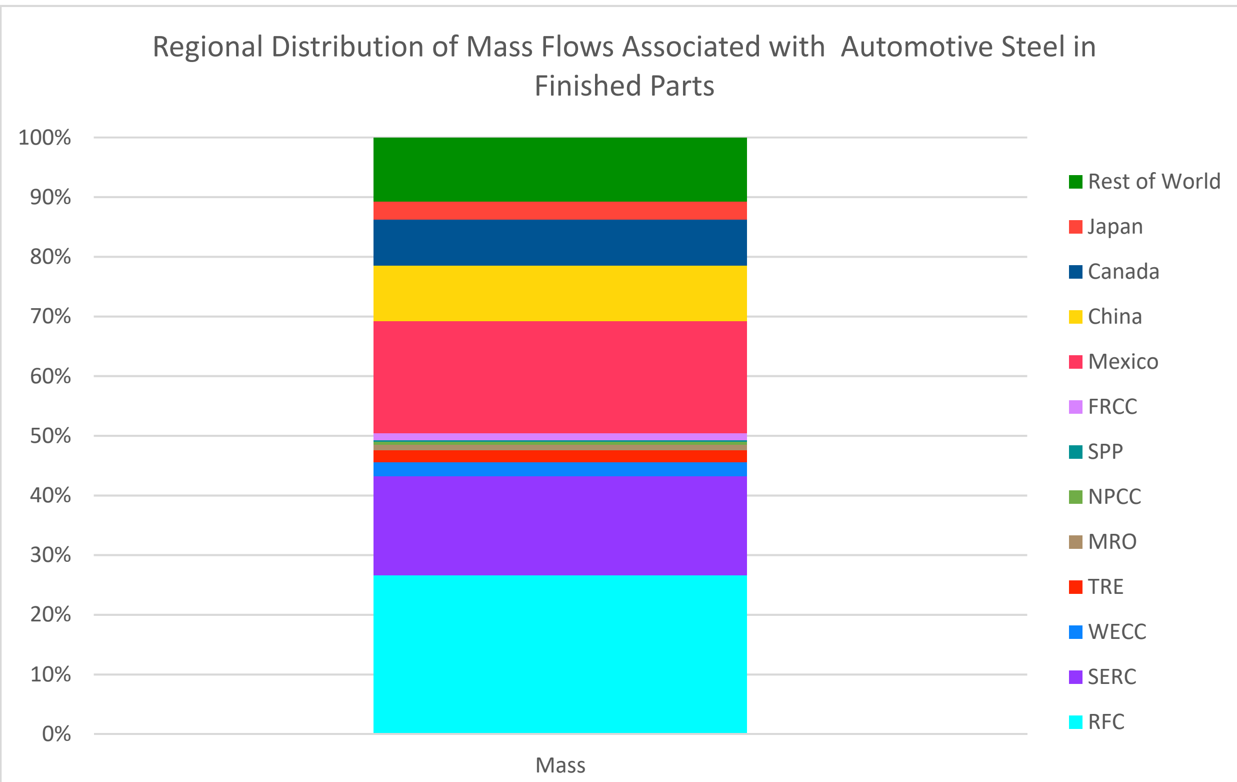

Figure 34: Regional distribution of mass flows associated with steel in finished automotive parts.

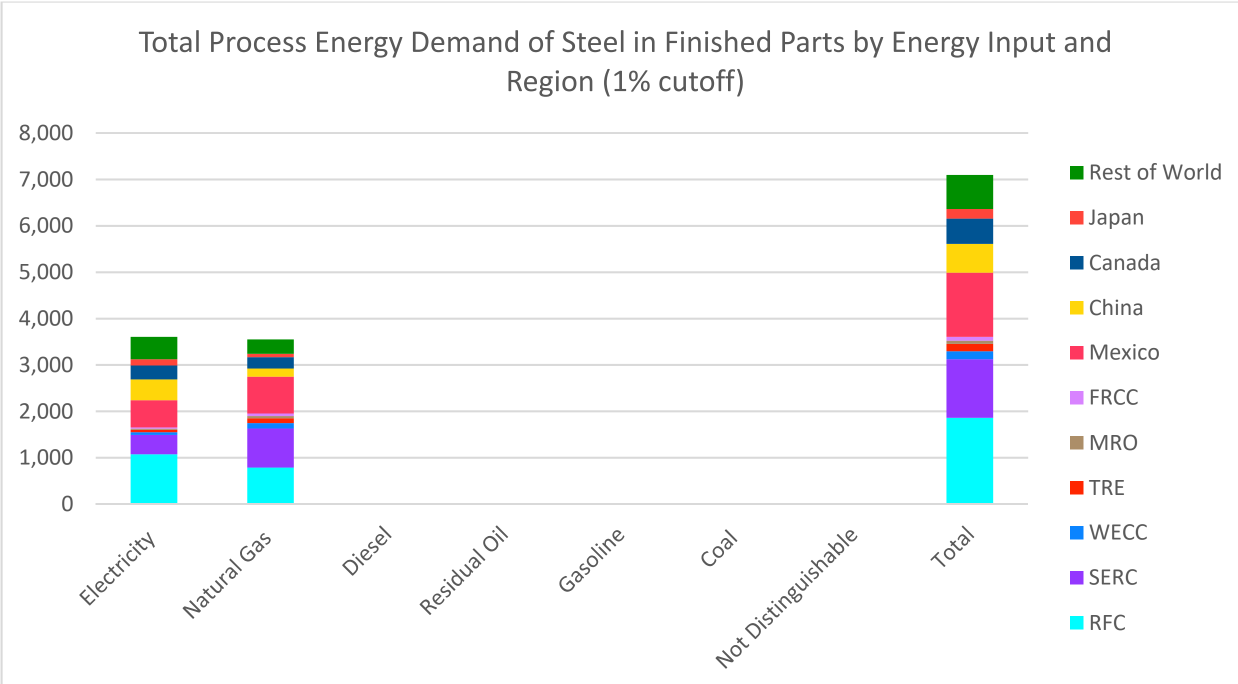

Figure 35: Regional distributions of the process energy demand associated with steel in finished automotive parts automotive by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.2 AUTOMOTIVE STEEL MILL PRODUCT REGIONALITY

The regional mix of automotive steel mill products is dominated by the RFC (63%) and SERC (20%) regions (Figure 36). The only other regions that supply over 1% of the total are Canada (4.5%) and Turkey (1.1%). Separating automotive steel sheet products, we show in the even figures between Figure 38-Figure 44 that the RFC and SERC regions dominate the supply for each product. The countries that supply over 1% of the total amount of each sheet product vary, but the total combined supply of countries for each sheet product never exceeds 20%. Similar findings are observed for the hot-rolled bar and other steel product categories. While the RFC and SERC regions provide the majority of both hot-rolled bar and other steel supply, other NERC regions—WECC, TRE, MRO, and FRCC—exceed 1% of the supply since half of these products are produced via EAF crude steel. The regional distribution of energy demands, shown in the odd figures between Figure 37-Figure 49, for each individual automotive steel mill product exactly follow their regional mass flow distributions.

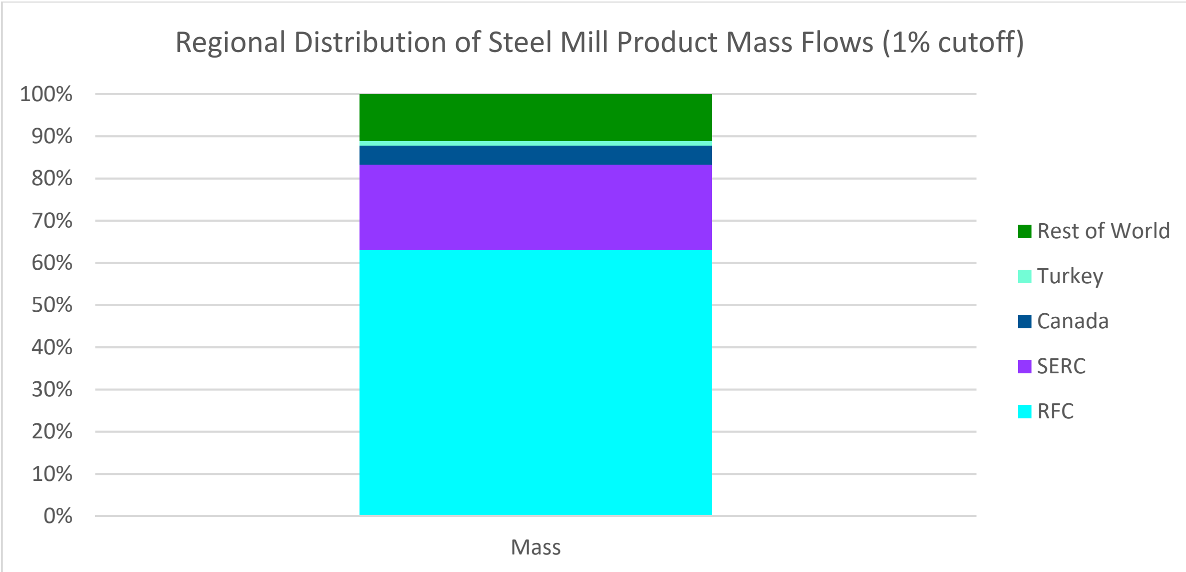

Figure 36: Regional distribution of mass flows for automotive steel mill products. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

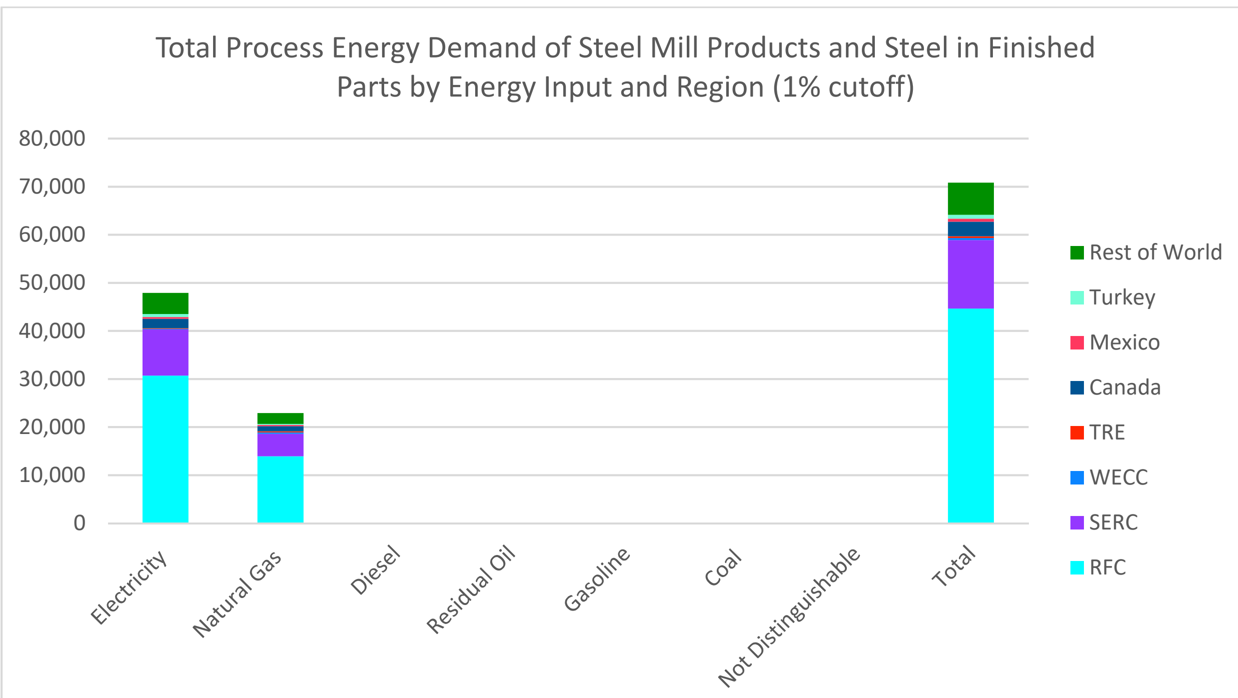

Figure 37: Regional distributions of steel mill product process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

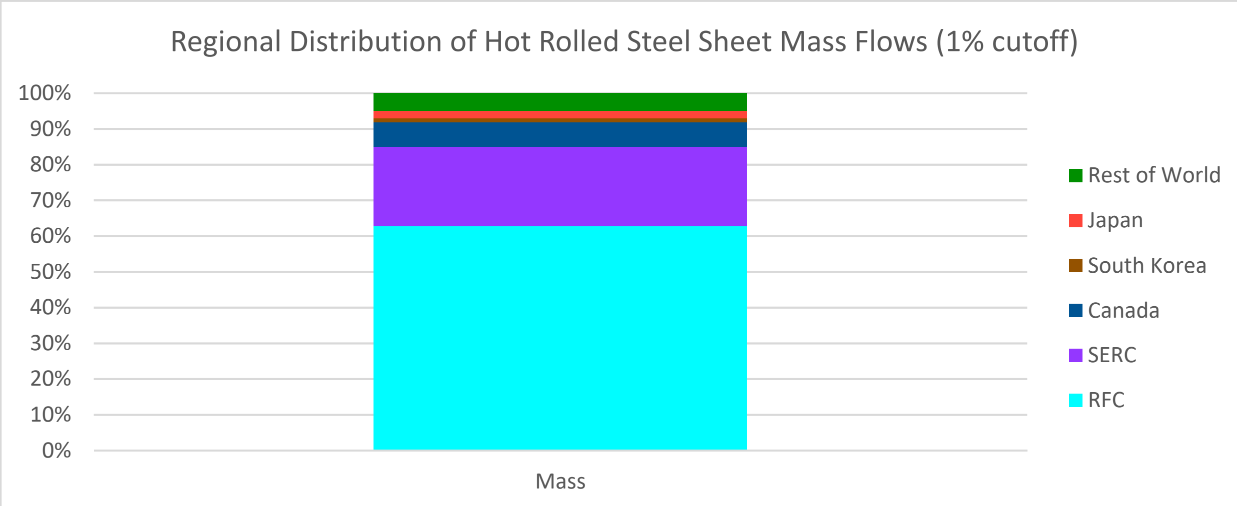

Figure 38: Regional distribution of mass flows of hot-rolled steel sheet entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

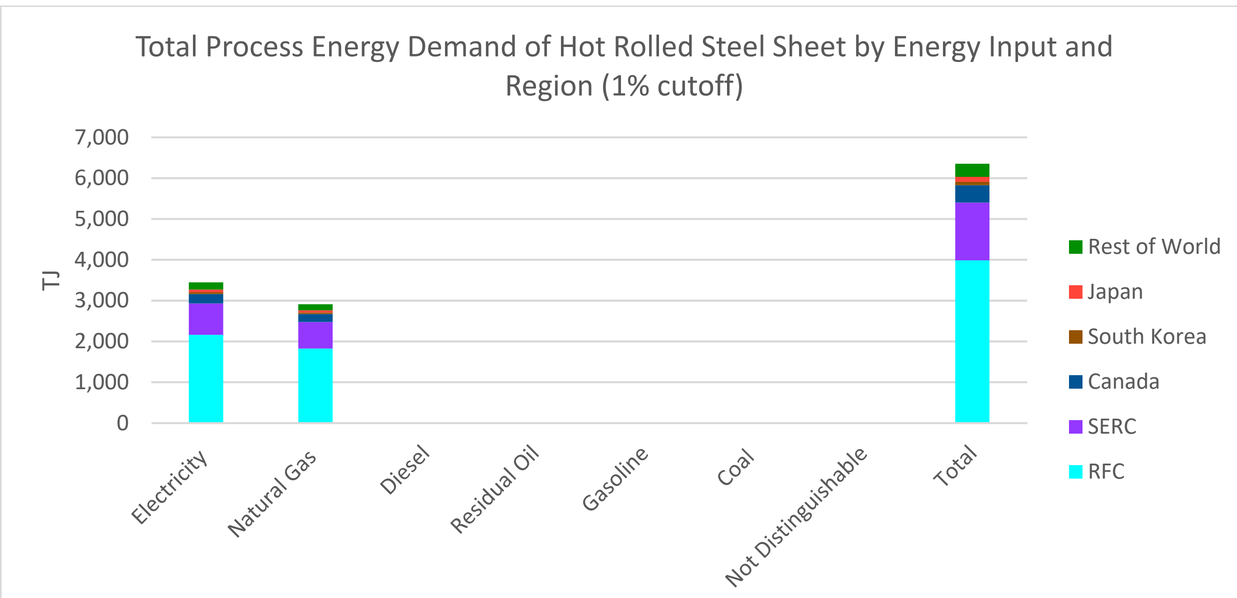

Figure 39: Regional distributions of hot rolled steel sheet process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

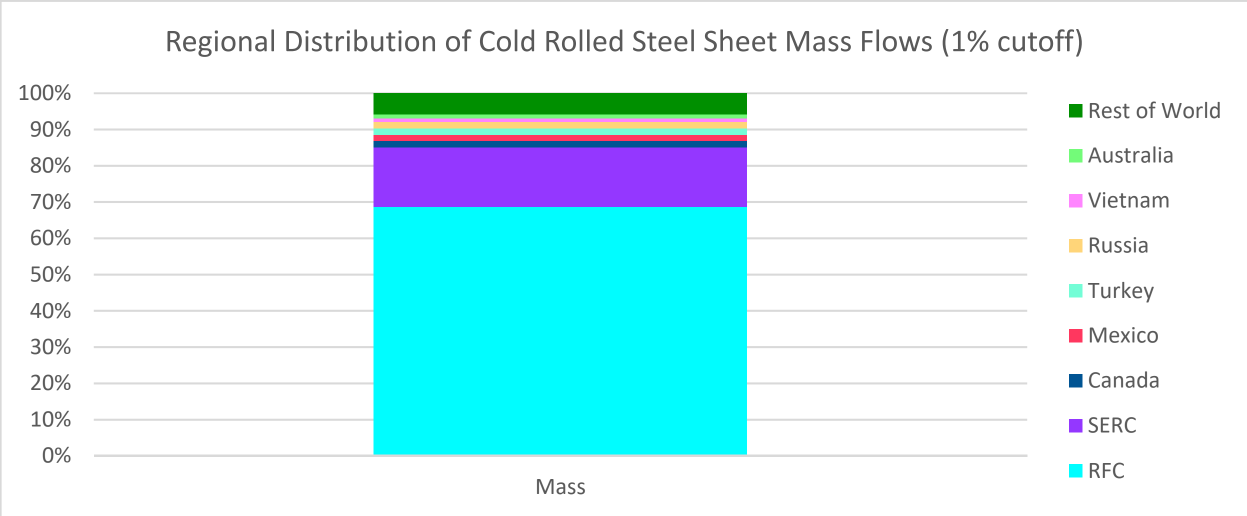

Figure 40: Regional distribution of mass flows of cold-rolled steel sheet entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

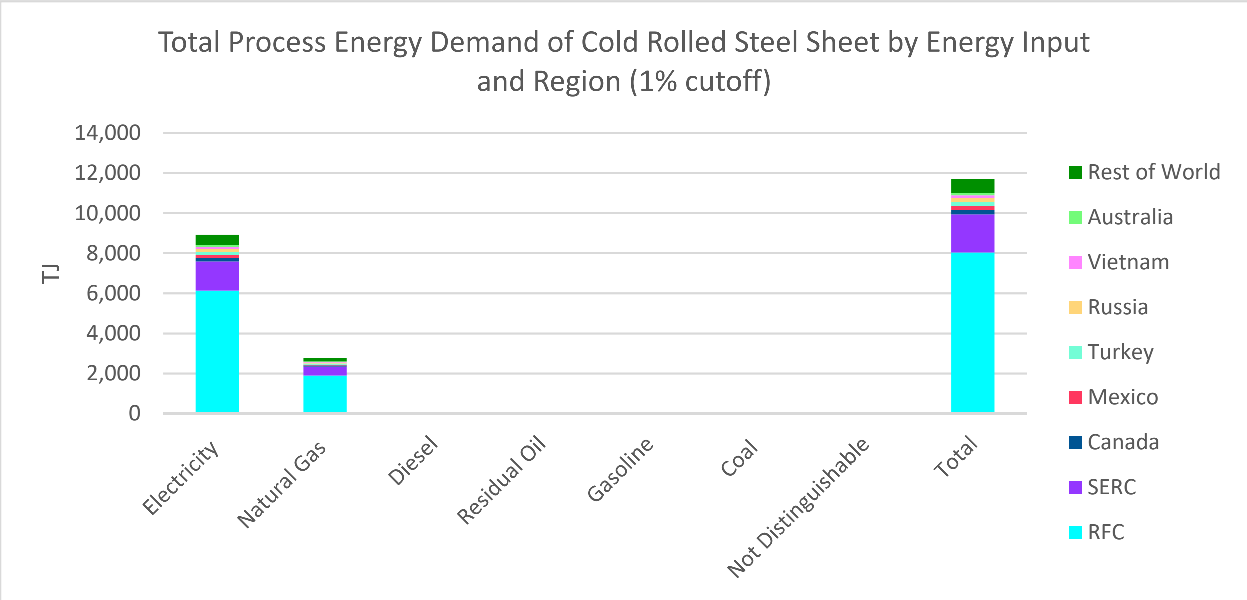

Figure 41: Regional distributions of cold rolled steel sheet process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

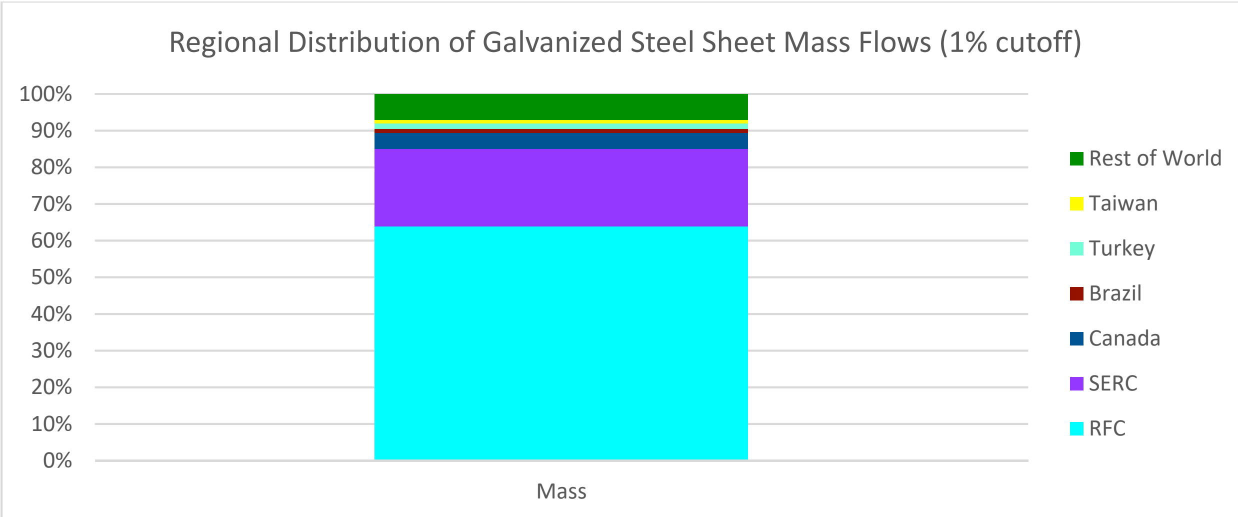

Figure 42: Regional distribution of mass flows of galvanized steel sheet entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

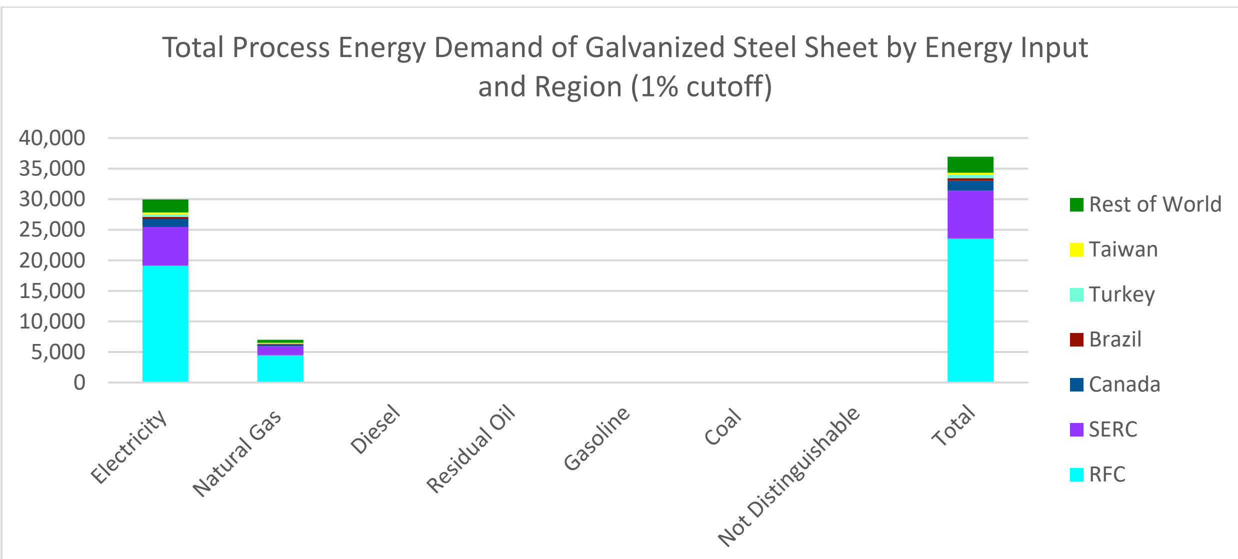

Figure 43: Regional distributions of galvanized steel sheet process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

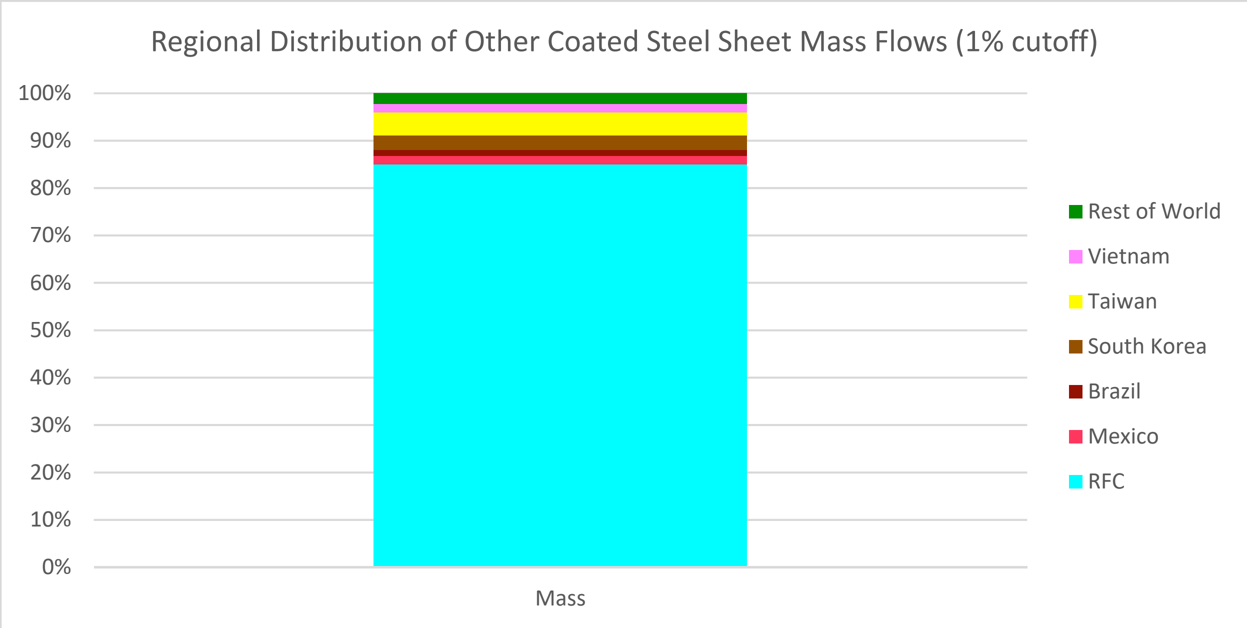

Figure 44: Regional distribution of mass flows of other coated steel sheet entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

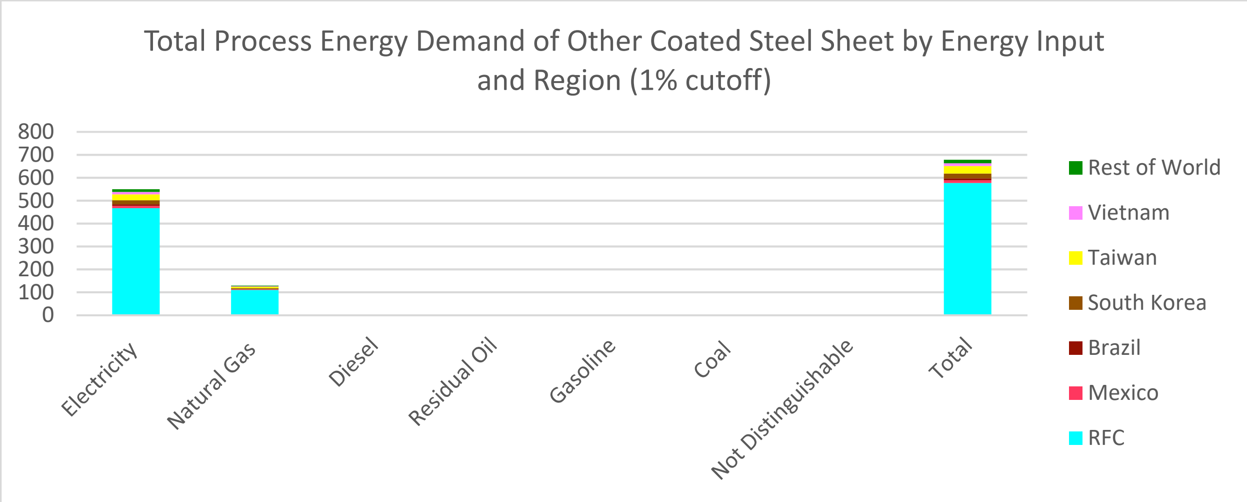

Figure 45: Regional distributions of other coated steel sheet process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

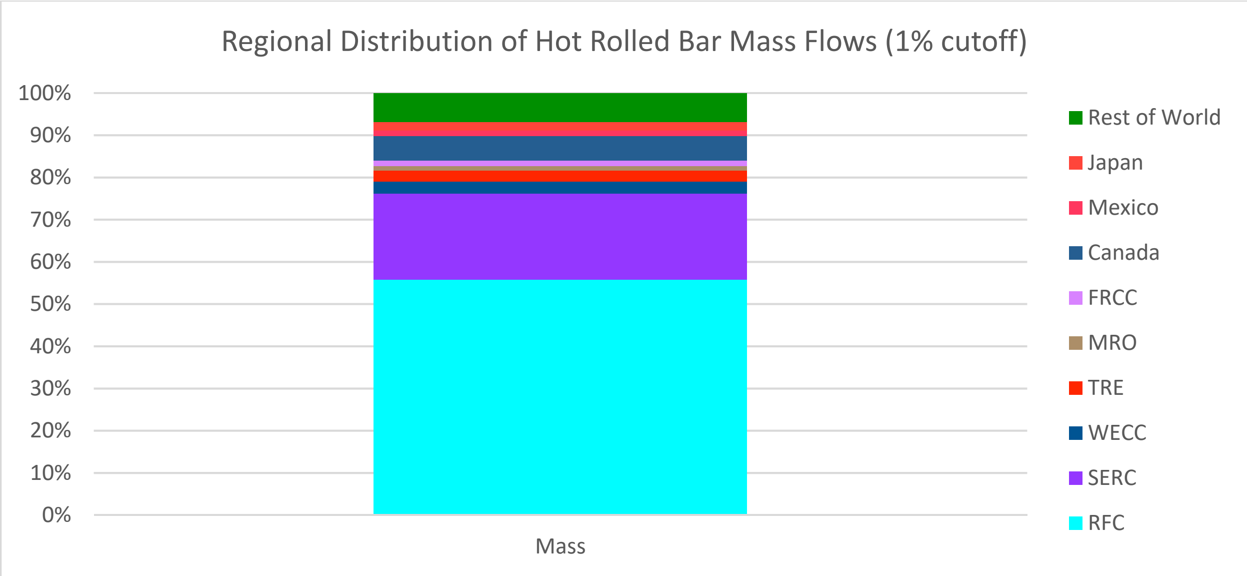

Figure 46: Regional distribution of mass flows of hot-rolled bar entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

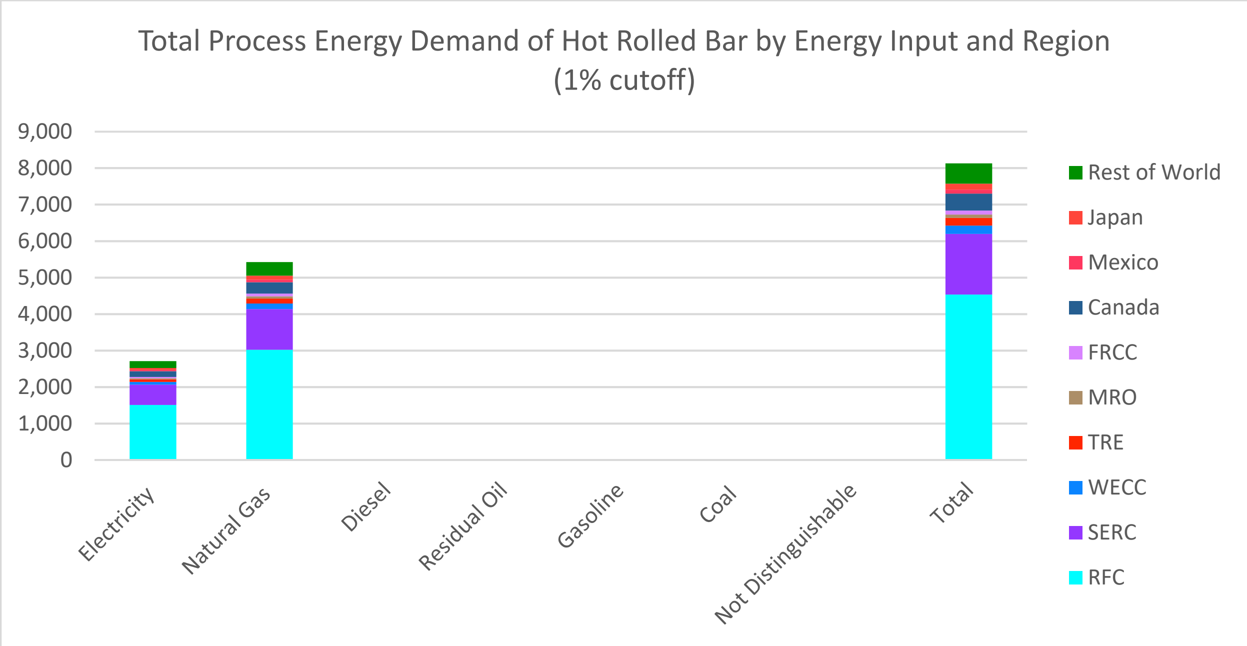

Figure 47: Regional distributions of hot rolled bar process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

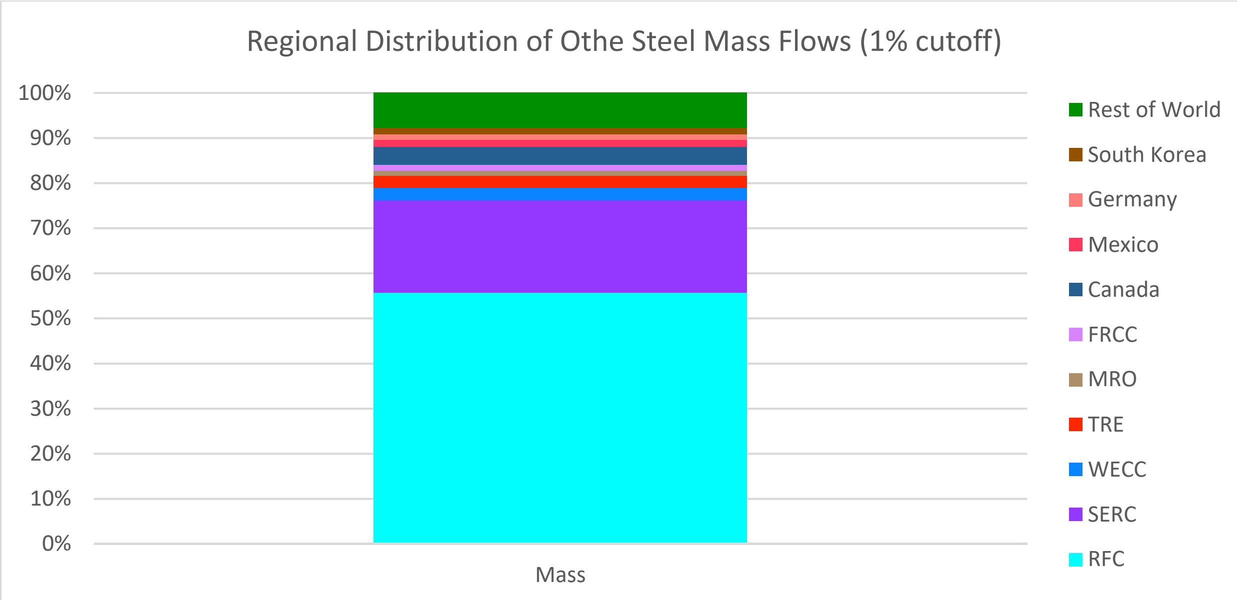

Figure 48: Regional distribution of mass flows of other steel entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

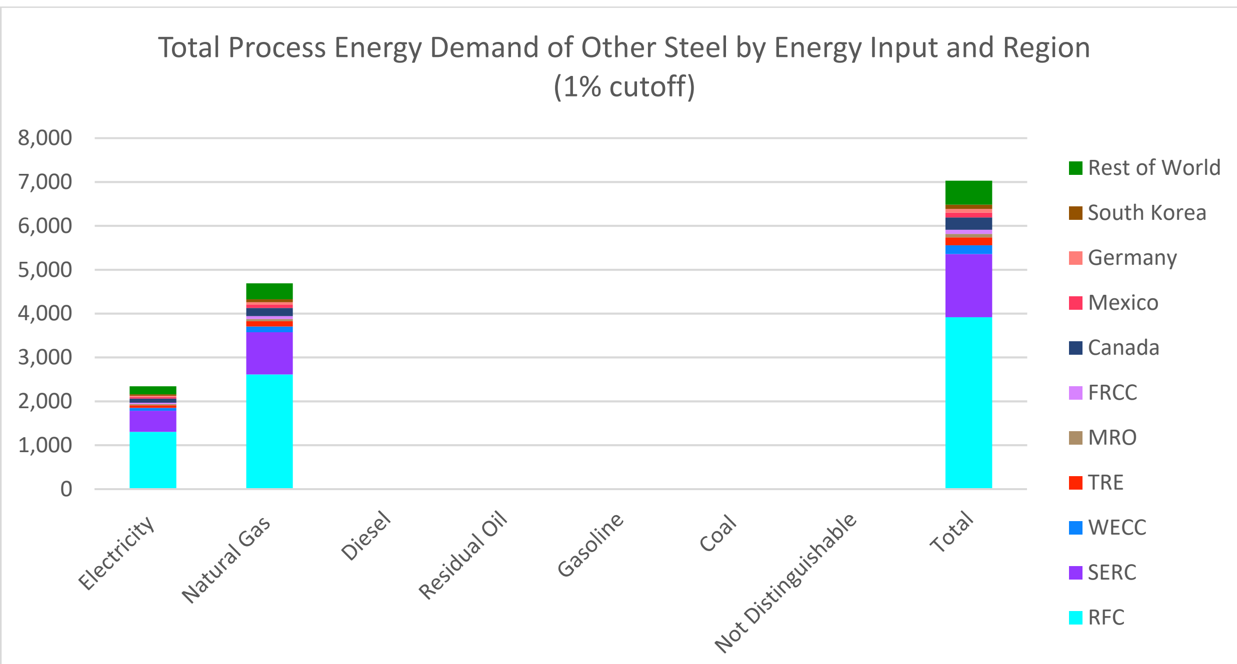

Figure 49: Regional distributions of other steel process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.3 CRUDE STEEL REGIONALITY

Like with automotive steel mill products, the supply of crude steel is largely dominated by the RFC (62%) and SERC (14%) regions (Figure 40). The only international crude steel producers that provide over 1% of the total mass supply are Japan (5.0%), Canada (4.7%) Mexico (2.5%), and Turkey (1.0%). The regional distribution of energy demand differs from that of mass flows for crude steel due to differences in energy requirements between BOF and EAF production of crude steel (Figure 51). Relative mass flows and process energy demands of crude steel by production type are shown in Figure 52. Remember that coke production was separated from BOF crude steel production in our analysis of crude steel regional energy demands. By separating coke production from BOF crude steel production, we find that EAF crude steel production (7.19 TJ/kt) has a higher energy intensity than BOF crude steel production (2.90 TJ/kt) (ANL, 2018b). If the energy demand for coke production were included in BOF crude steel production, BOF energy intensity would be 23.9 TJ/kt (ANL, 2018b). Additionally, while EAF crude steel only accounts for 18% of the total crude steel entering the American automotive industry, it accounts for 52% of the electricity required for the total amount of crude steel, highlighting the process' electricity intensity relative to BOF crude steel.

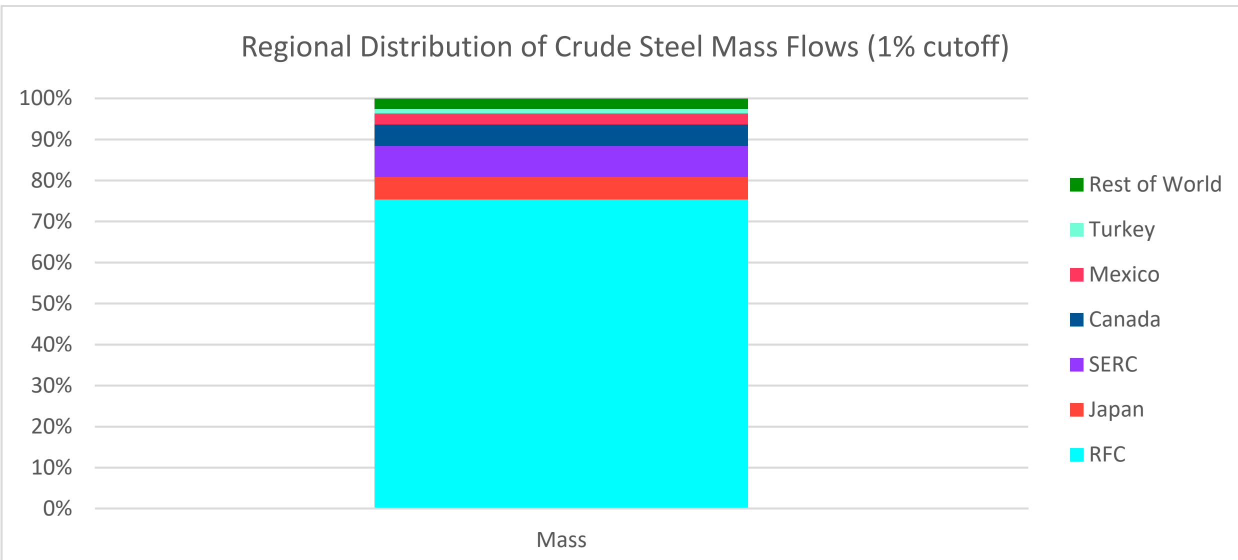

Figure 50: Regional distribution of mass flow for crude steel entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

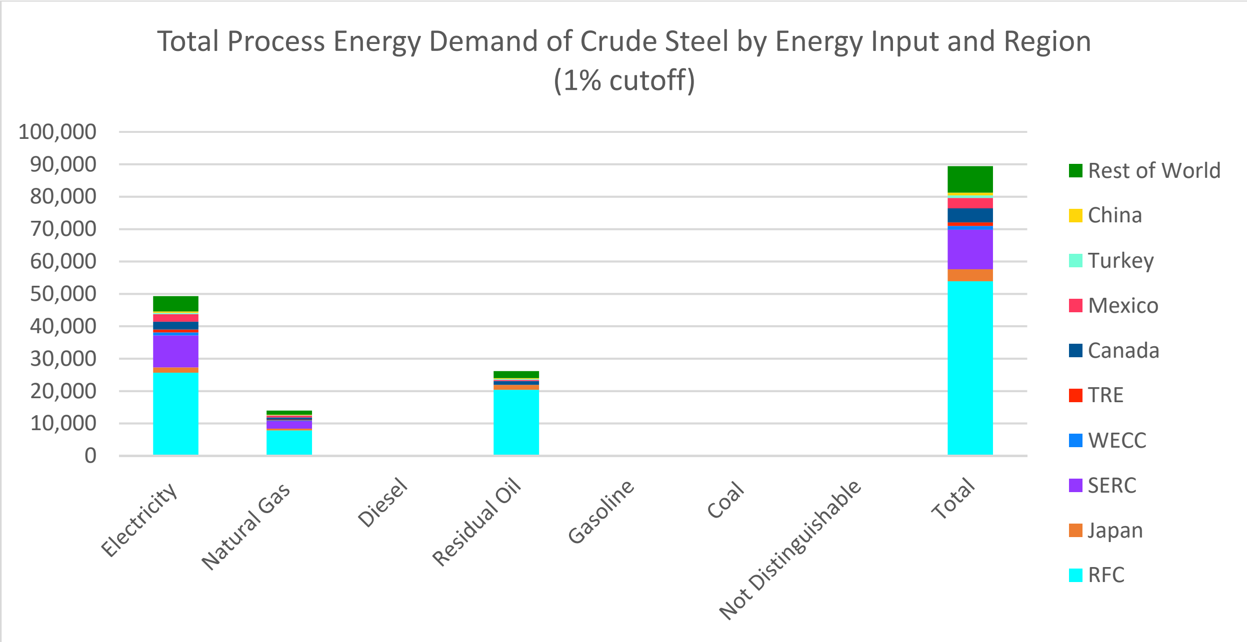

Figure 51: Regional distributions of crude steel process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

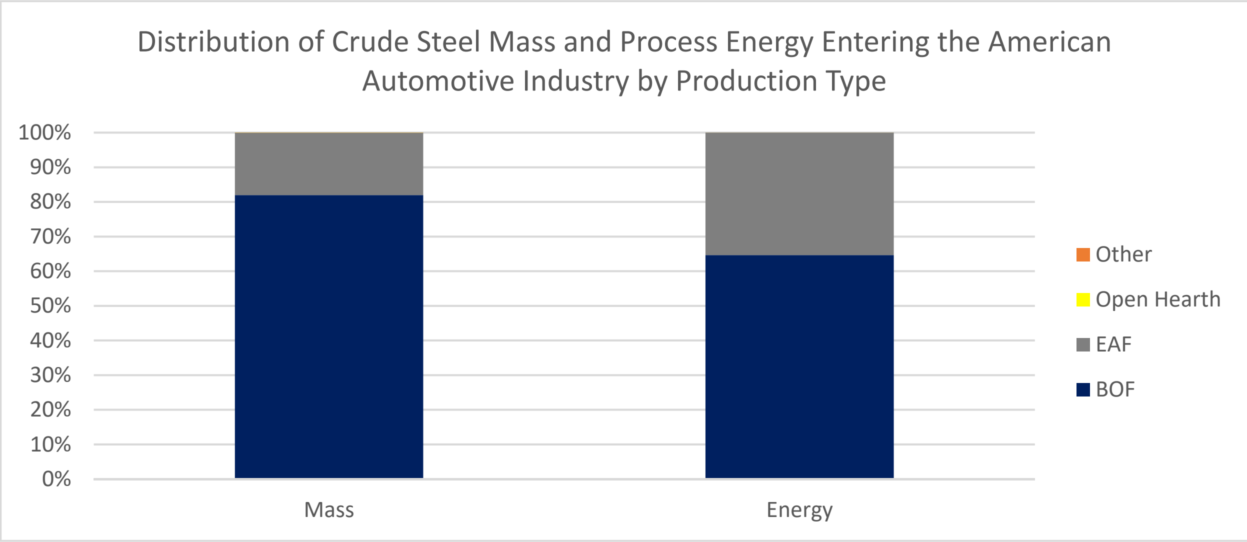

Figure 52: Mass flow and process energy demand of crude steel entering the American automotive industry by production type.

4.2.4 COKE REGIONALITY

Applying a 1% supply cutoff to the coke that enters the American automotive industry results in the regional supply distribution shown in Figure 53, with the RFC and SERC regions dominating supply. In practice, much of the coke that BOF crude steel producers use is produced on-site, correlating the production of coke with the production of BOF crude steel. A general USA region appears because the USA exports coke to other crude steel producing countries that then export crude steel back to the USA. Regional energy demand for coke follows its regionalized mass flows because the energy in coke production is dominated by coal as a heat source (Figure 54).

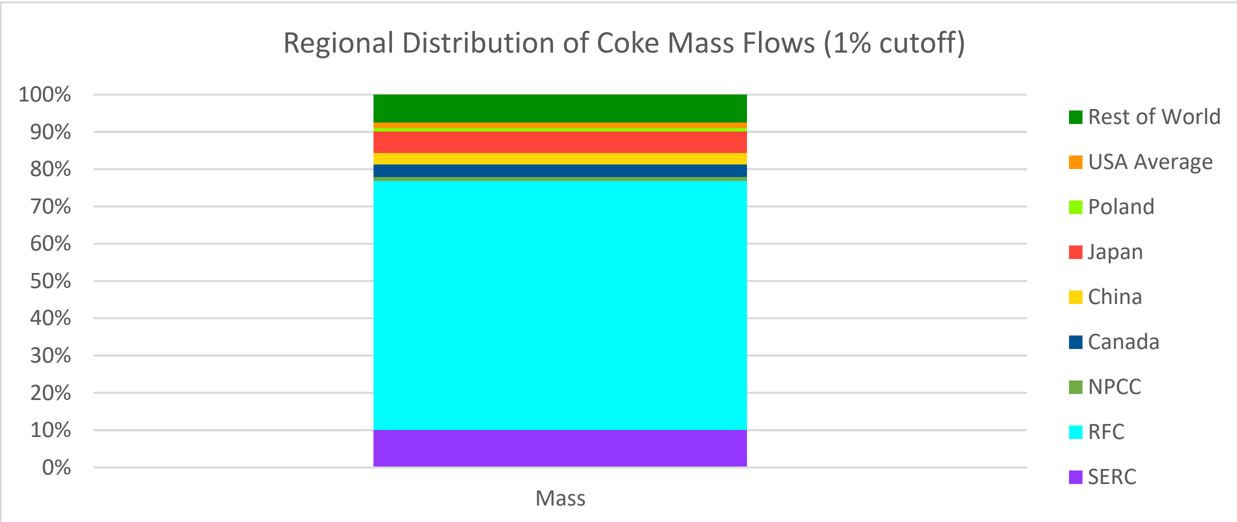

Figure 53: Regional distribution of mass flows for coke that enters the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

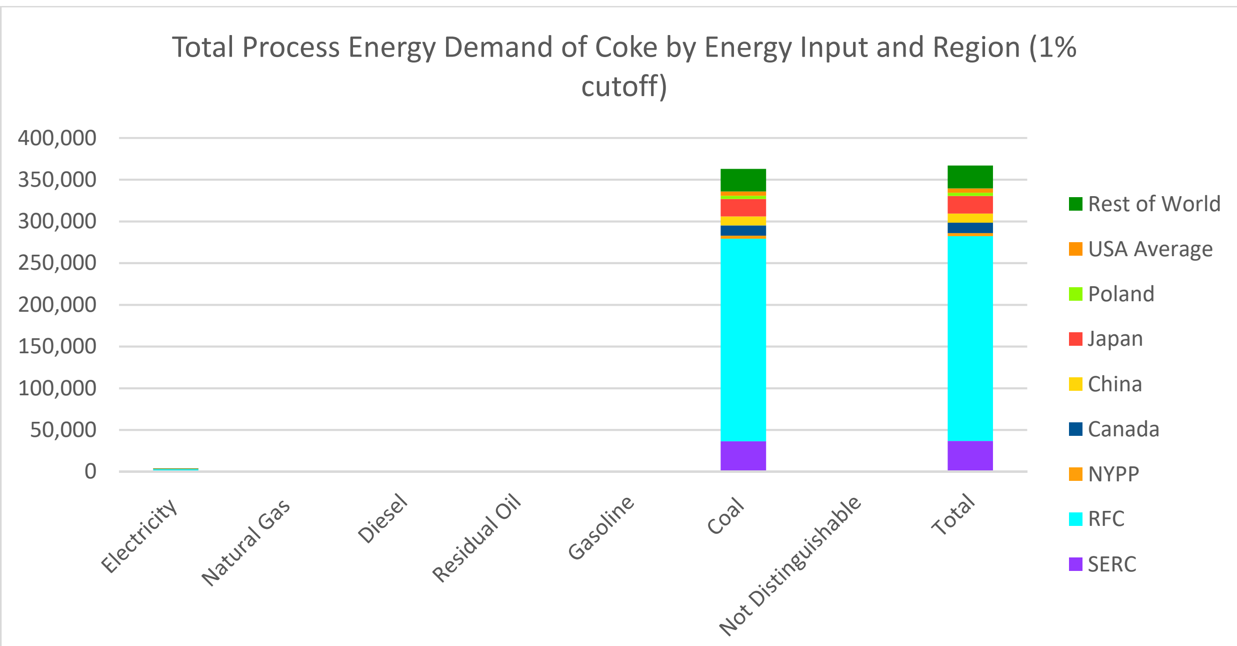

Figure 54: Regional distributions of coke process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.5 COKING COAL REGIONALITY

The regional supply of coking coal is dominated by the USA as seen in Figure 55. Using a 1% supply cutoff narrows the supply of coking coal to six suppliers while still accounting for 97% of the total supply. Energy demand associated with supplying coking coal to coke facilities follows the same regional distribution as mass.

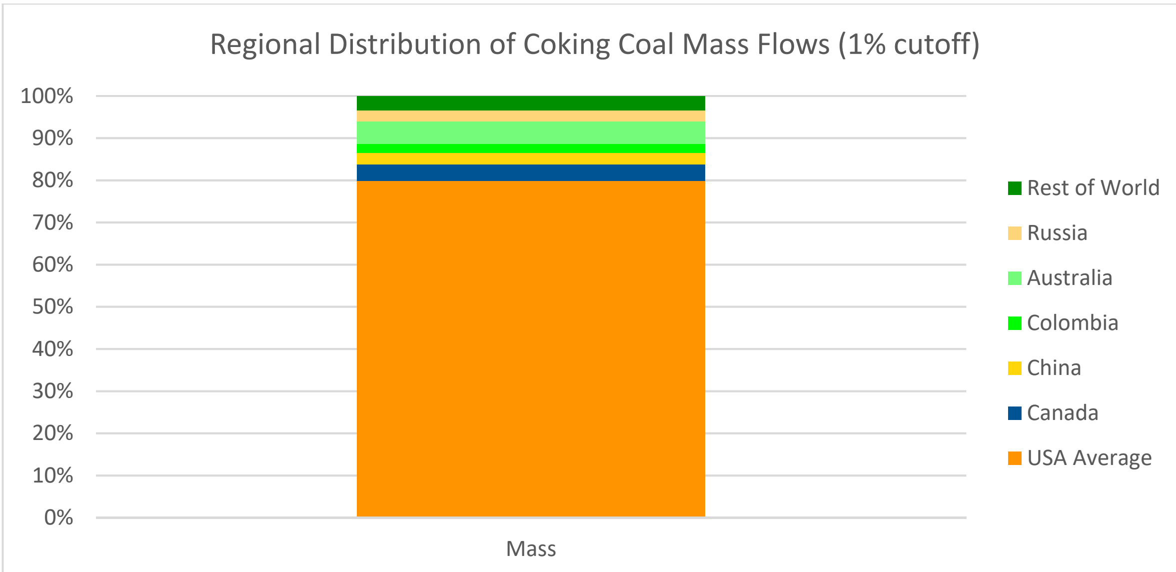

Figure 55: Regional distribution of mass flows associated with coking coal entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

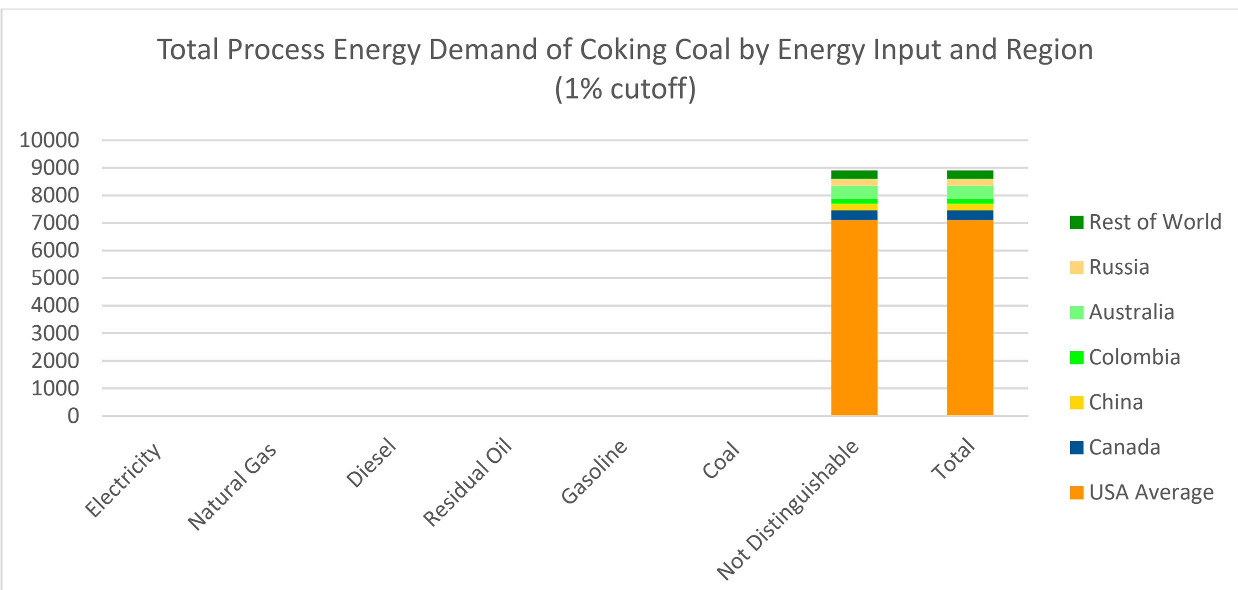

Figure 56: Regional distributions of coking coal process energy demand by energy input. Regions are listed by either country or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.6 IRON ORE REGIONALITY

Iron ore entering the American automotive industry is heavily dominated by the MRO and RFC regions as shown in Figure 57. The relative supply of iron ore coming from the USA is less than for other raw materials, with international supplies of iron ore entering the American automotive industry from ore-rich countries like Brazil. A general USA region appears here because the USA is a major iron ore exporter, and some crude steel producing countries that export crude steel to the USA import iron ore from the USA. The regional distribution of energy demand associated with iron ore follows that of mass.

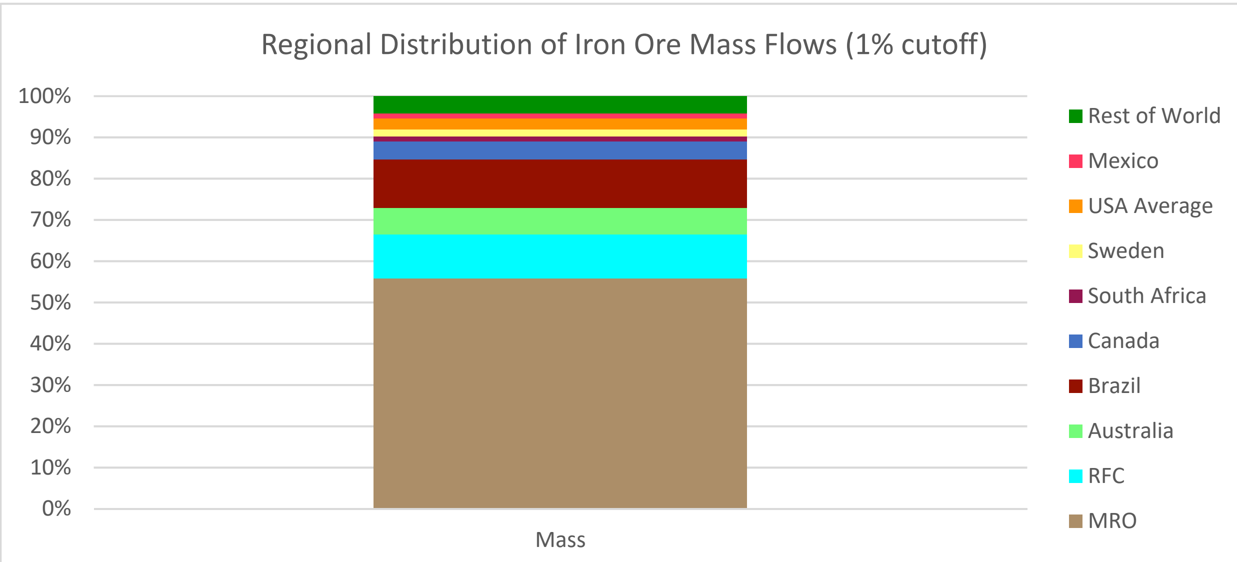

Figure 57: Regional distribution of mass flows associated with iron ore entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

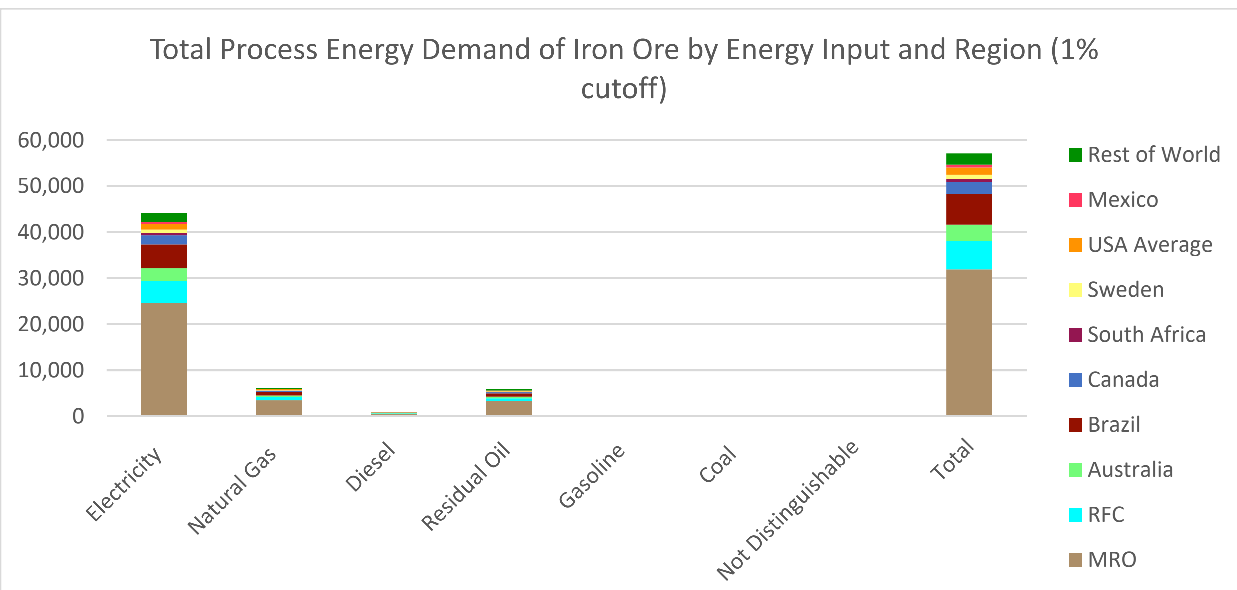

Figure 58: Regional distributions of iron ore process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.7 LIME REGIONALITY

The regional characterization of the lime supply entering the American automotive industry utilizes different USA regions than other raw materials. Supplies of lime by census regions and divisions within the USA were the smallest achievable given the data available. The Midwest, East South Central, and West census regions and divisions within the USA are the three most dominant sources of lime supply to the American automotive industry, each representing over 10% of the total supply (Figure 59). The energy demand distribution directly follows the regional distribution of mass flows.

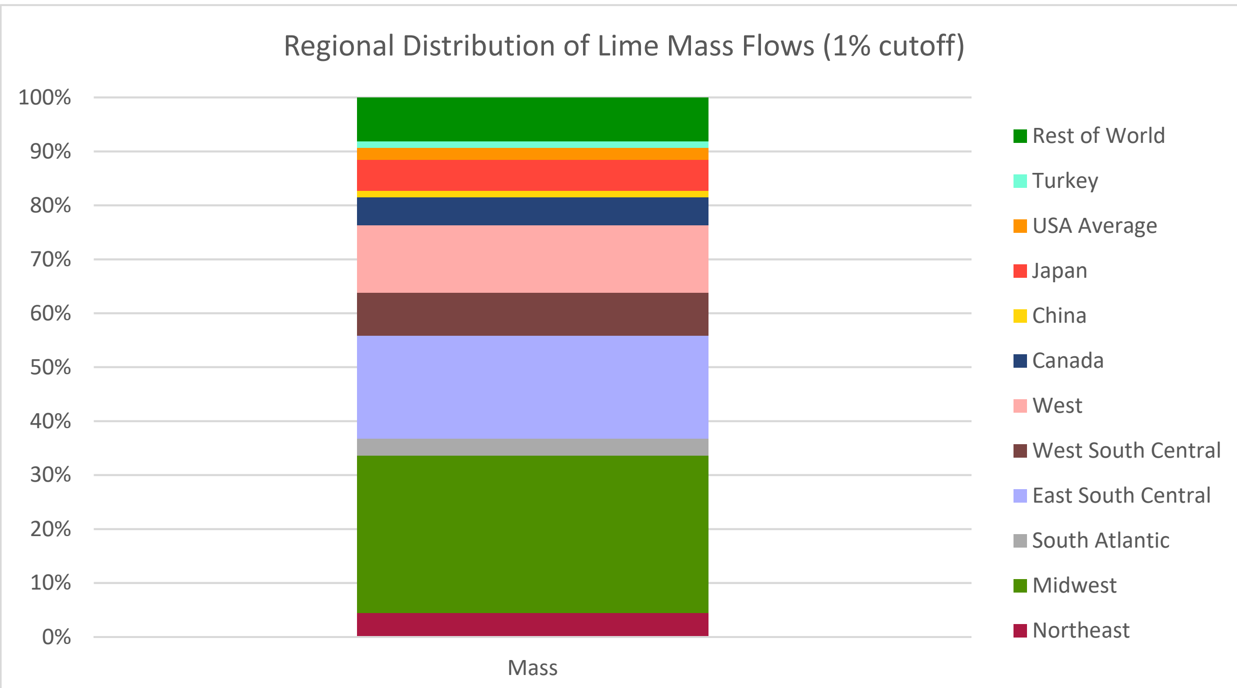

Figure 59: Regional distribution of mass flows associated with lime entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

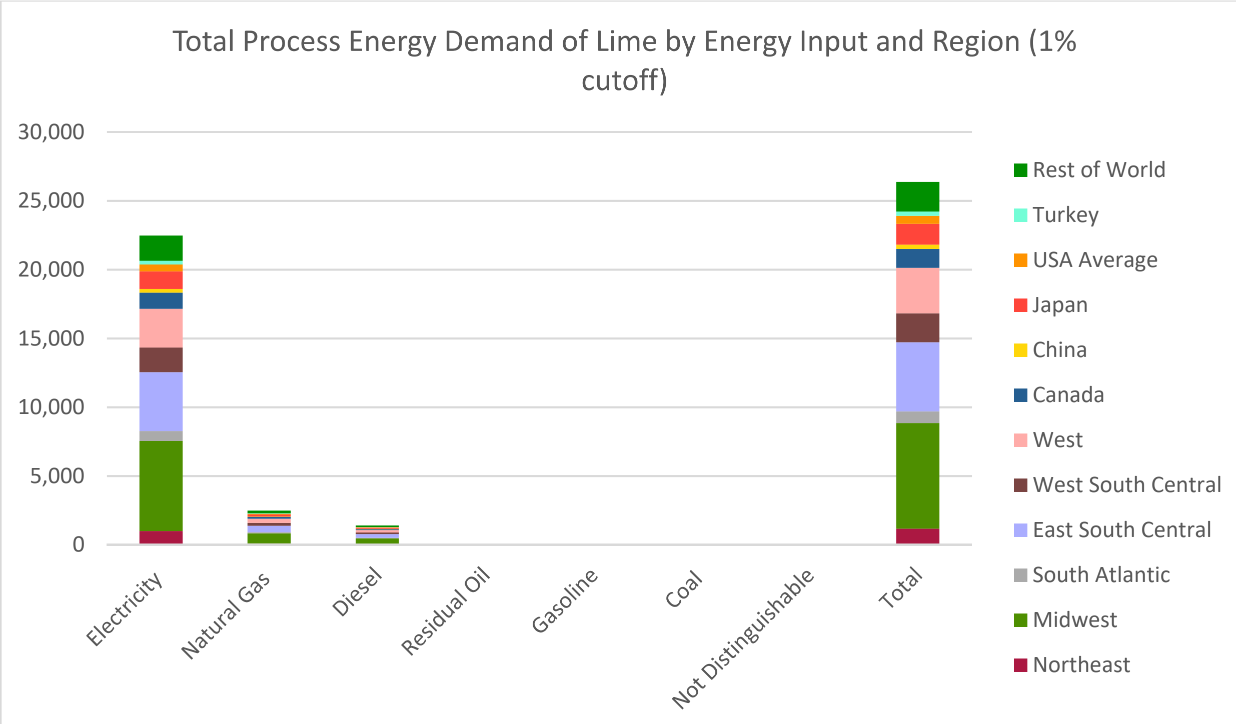

Figure 60: Regional distributions of lime process energy demand by energy input. Regions are listed by either USA census regions and divisions, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.8 STEEL SCRAP REGIONALITY

The USA dominates the supply of steel scrap to the American automotive industry, but Canada, Japan, and the UK also contribute over 1% of the total steel scrap supply (Figure 61). The distribution of energy demand follows the regional distribution of mass flows.

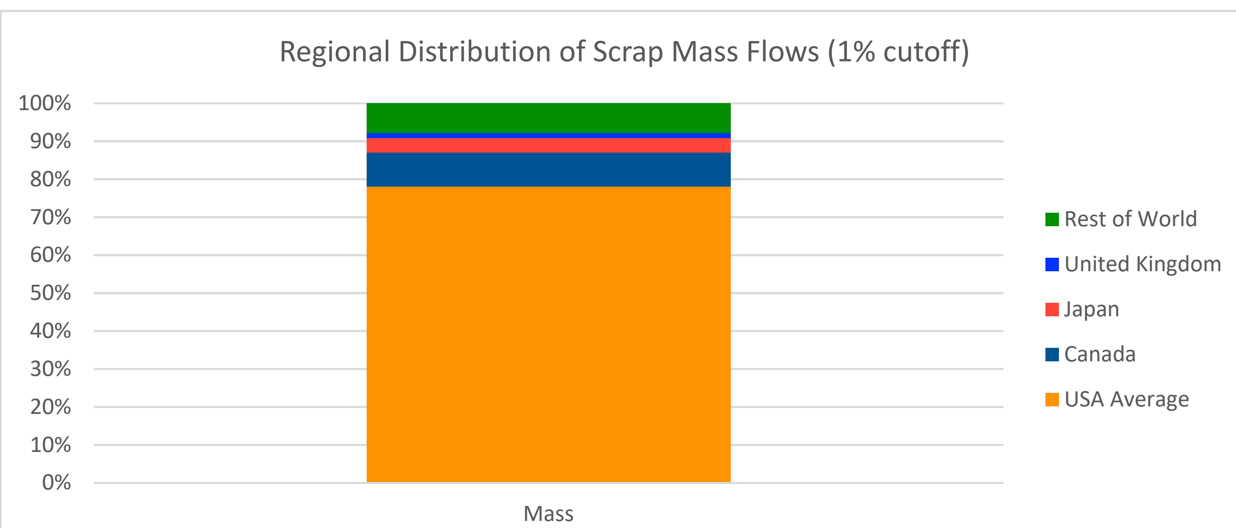

Figure 61: Regional distribution of mass flows associated with steel scrap entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

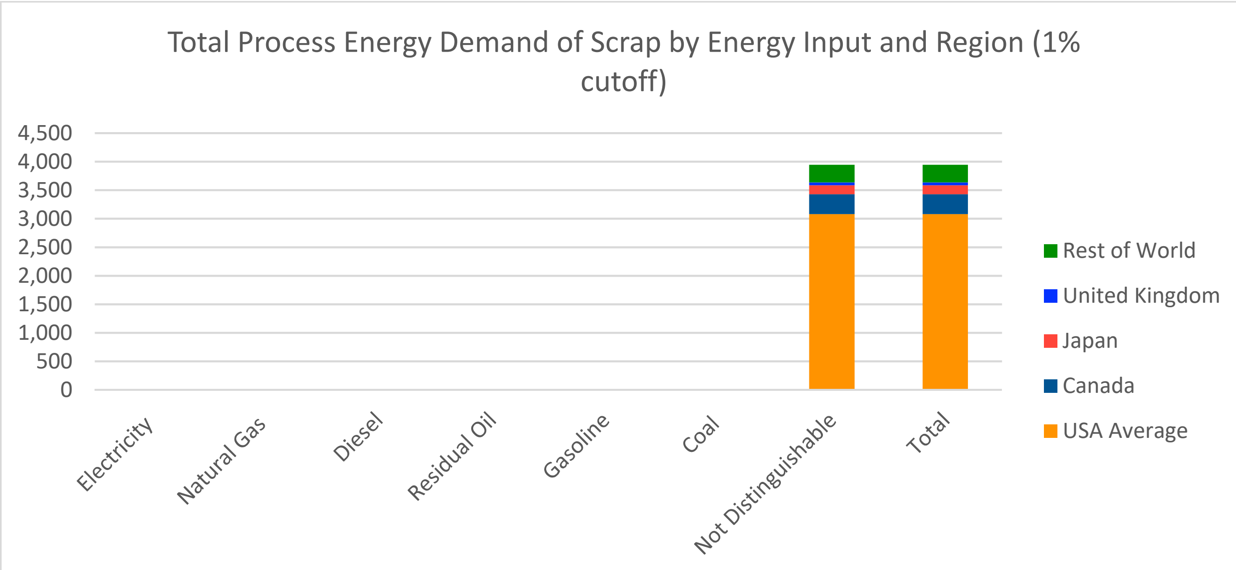

Figure 62: Regional distributions of scrap process energy demand by energy input. Regions are listed by either country or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.9 DRI REGIONALITY

The supply of DRI entering the American automotive industry is dominated by international suppliers. Trinidad and Tobago is the major international source of DRI entering the American automotive industry, providing 30% of the total supply, with the SERC (24%) and TRE (16%) regions dominating supply within the USA (Figure 63). The regional distribution of energy demands associated with DRI production follows the regional distribution of mass flows.

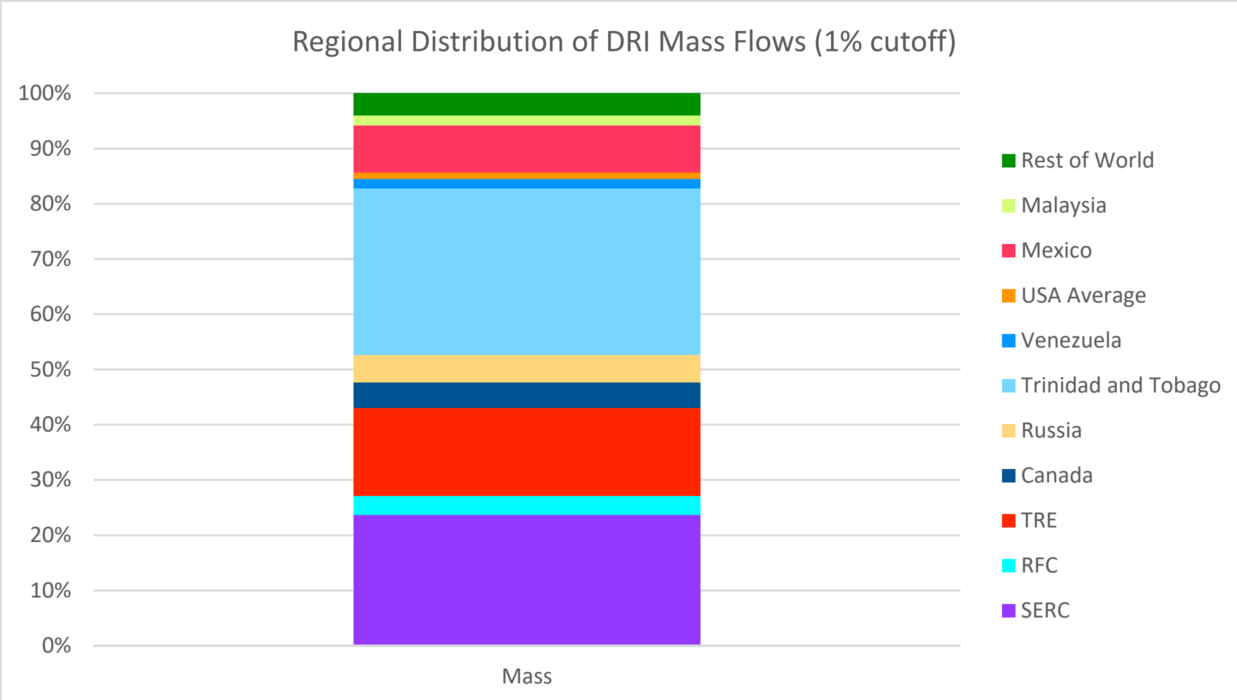

Figure 63: Regional distribution of mass flows associated with DRI entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

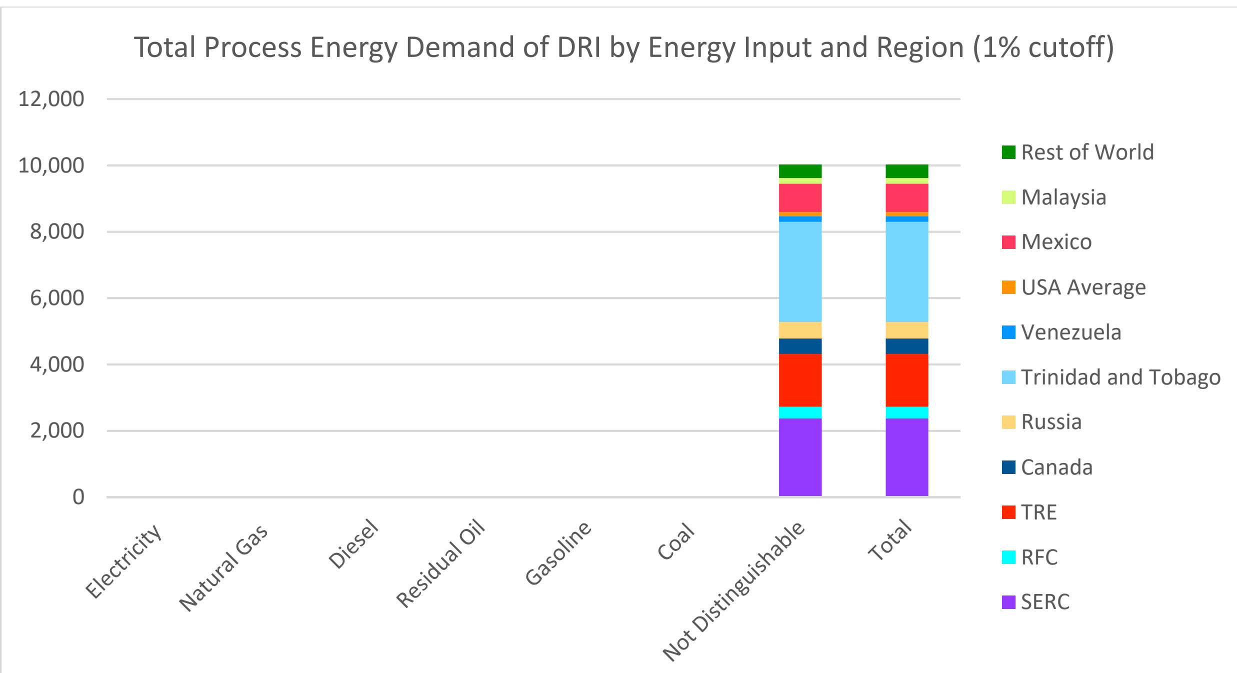

Figure 64: Regional distributions of DRI process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.10 PIG IRON REGIONALITY

Pig iron entering the American automotive industry via EAF production is heavily dominated by international sources (Figure 65). Russia (38%), Ukraine (16%), and Brazil (16%) are the three largest sources of pig iron. Combined they supply 67% of the total while the RFC region within the USA accounts for 13%. Energy demand regionalization produces a regional distribution following that of mass flows.

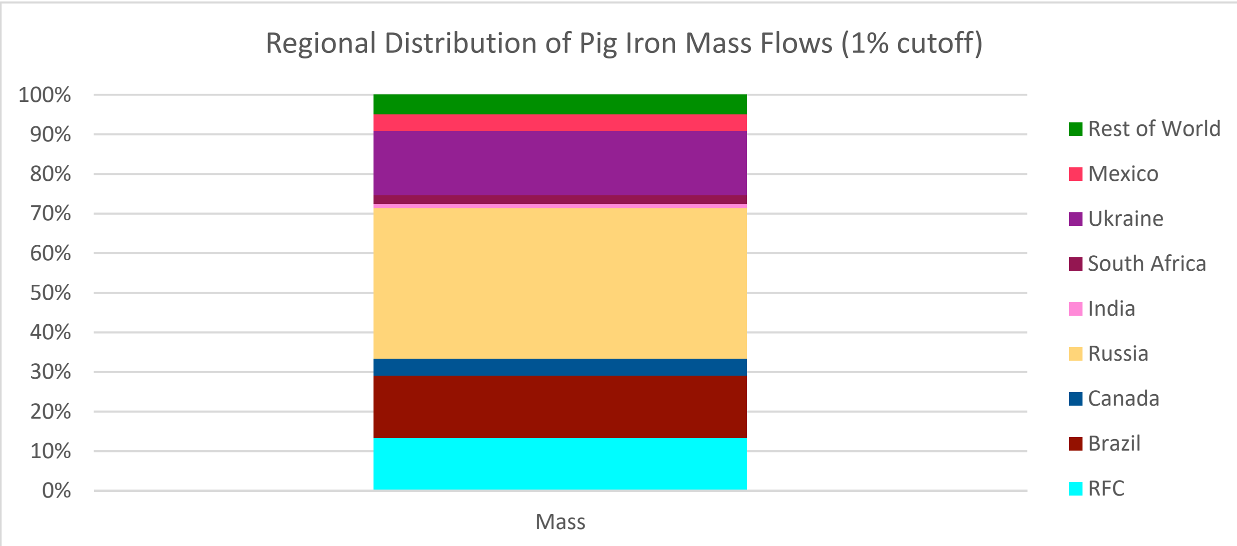

Figure 65: Regional distribution of mass flows associated with pig iron entering the American automotive industry. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

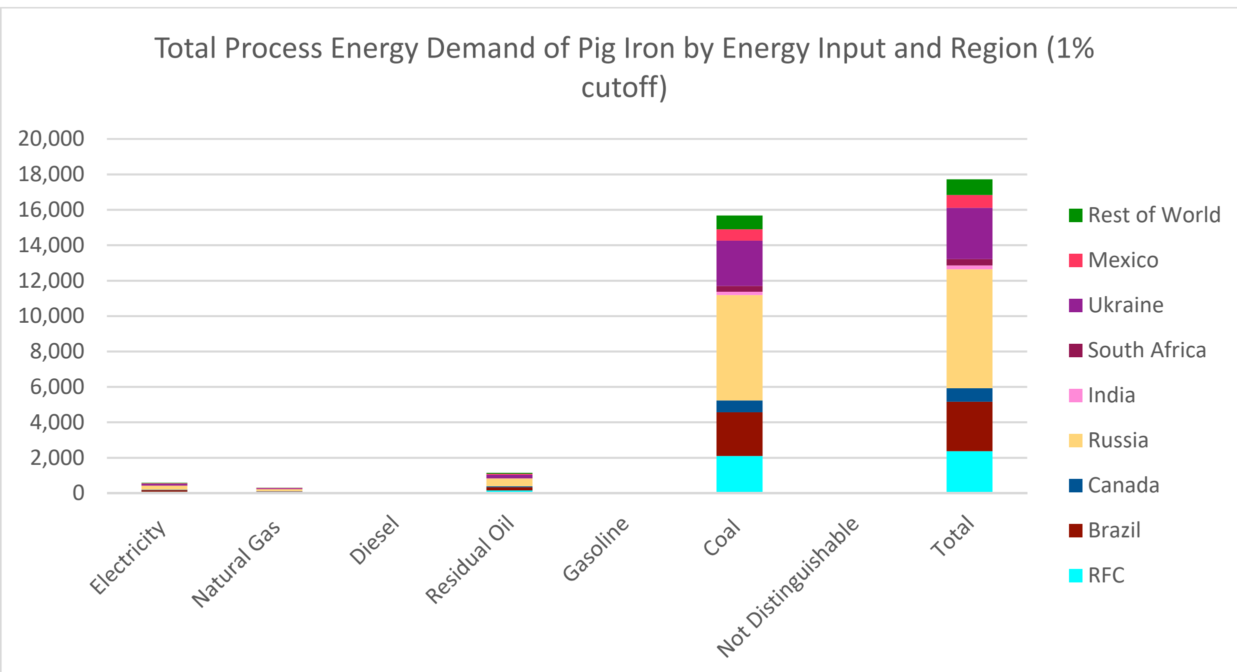

Figure 66: Regional distributions of pig iron process energy demand by energy input. Regions are listed by either NERC region, country, or Rest of World. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

4.2.11 TOTAL STEEL IN LDVS

We estimated that 20,947 kt of steel entered the American LDV industry in 2017 with our model. Using a separate bottom-up analysis we estimated 17,136 kt of steel entered the American LDV industry in 2017, resulting in a 22% difference between our modeling approach and our bottom-up results where the bottom-up is the reference (Figure 67). To examine factors impacting our model and bottom-up analysis, we conducted a sensitivity analysis and present those findings in section 4.2.13.

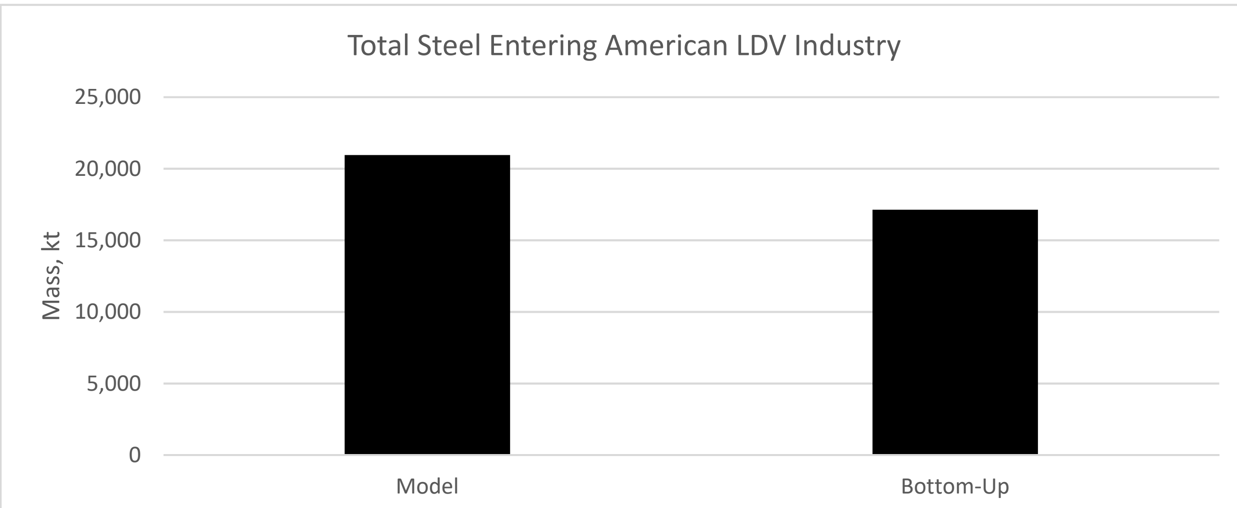

Figure 67: Model and bottom-up results for total amounts of steel entering the American LDV industry.

4.2.12 TOTAL PROCESS ENERGY DEMAND REGIONALITY

Regionalizing the total energy demand required for steel entering the American automotive industry results in the distribution shown in Figure 68. We found the total process energy demand associated with automotive steel to be 658,885 TJ. A 1% regional cutoff reveals eight countries (USA, Canada, Brazil, Russia, Colombia, Japan, Australia, and China) represent 88% of the total energy demand. The USA accounts for 70% of the total energy, with RFC contributing 54%, SERC 10%, and MRO 5%. Figure 68 further shows the regions that constitute the total process energy demand for each fuel type. Disaggregating the total energy demand by material product along steel's production processes (Figure 69), we observe that coke represents 54% of the total energy demand, followed by crude steel (14%) and steel mill products (11%) as the only steel material to account for over 10% of the total energy demand. Disaggregating total energy demand by crude steel production, we find that steel entering the American automotive industry produced via BOF represents 88% of the total energy demand.

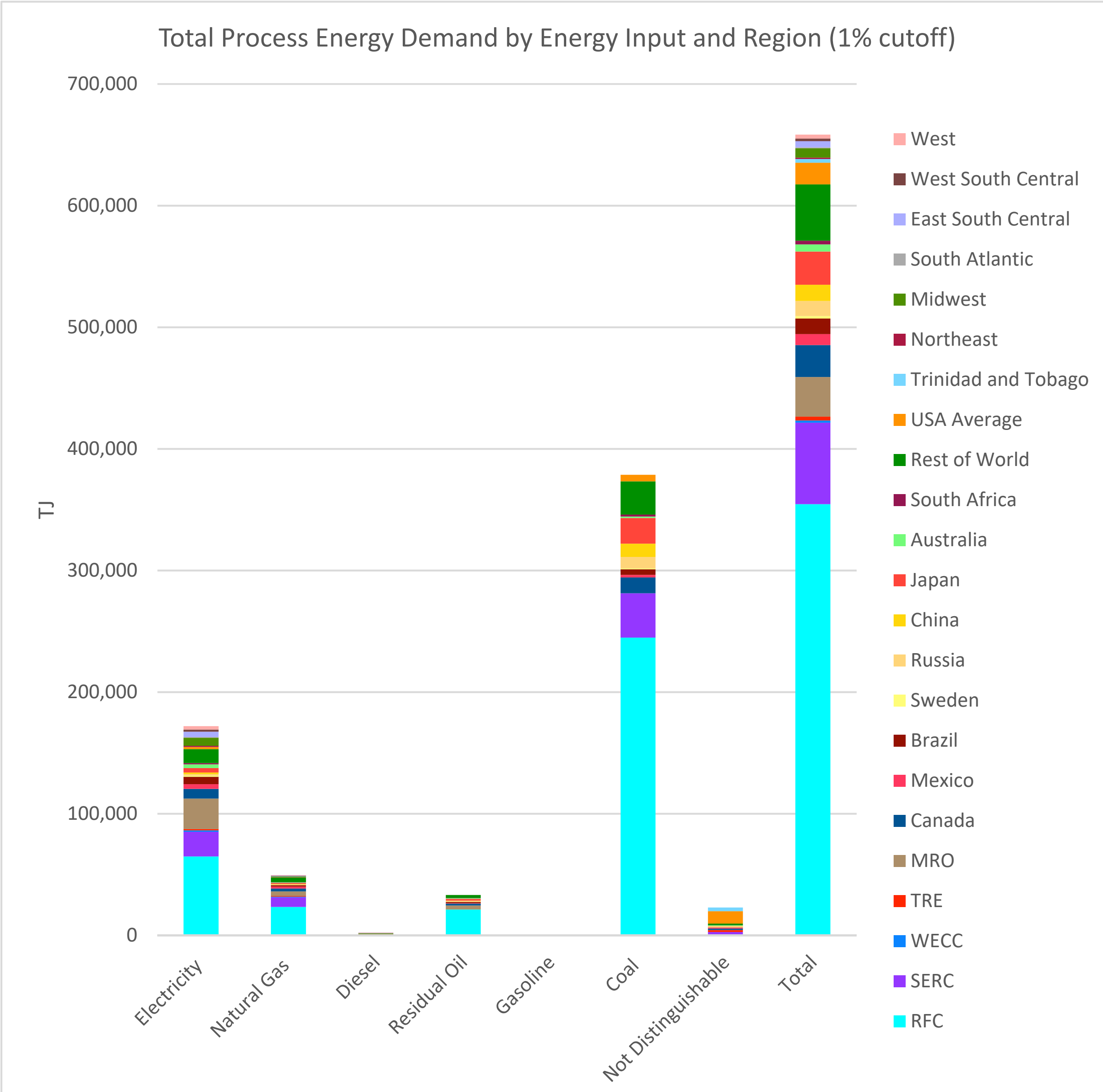

Figure 68: Regional distribution of total process energy demand for automotive steel entering the American automotive industry by energy input. Only regions contributing over 1% of the total energy for each energy input are shown. Regions under the 1% threshold are aggregated into the Rest of World region.

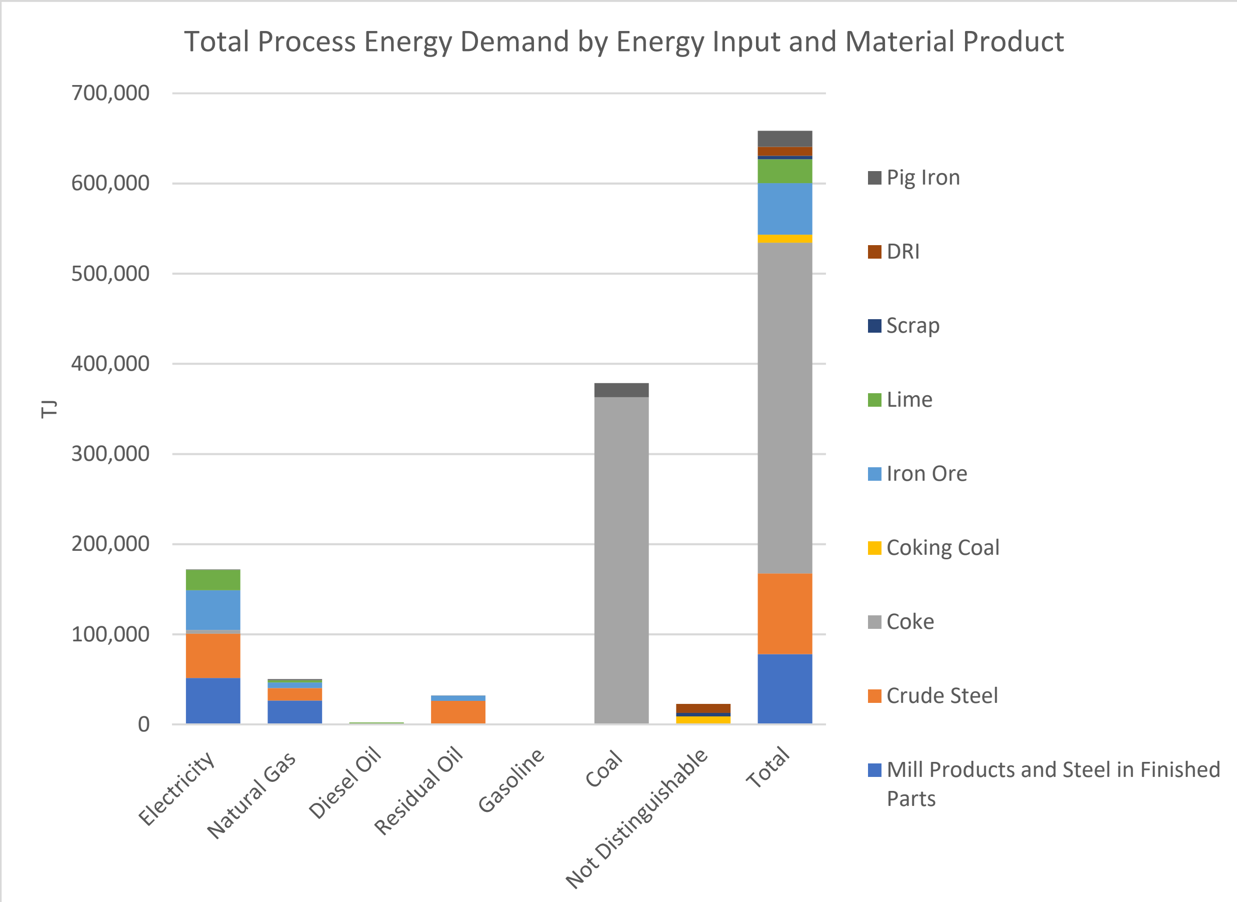

Figure 69: Distribution of the total process energy demand for automotive steel by energy input and further separated by material product.

4.2.13 RESULTS OF SCENARIO AND SENSITIVITY ANALYSES

The scenario and sensitivity analyses conducted on the automotive steel model are described in Table 16 and visualized in Figure 70 through Figure 86. Increasing the ratio of American to international steel mill products to 95:5 results in an 11% decrease in the total amount of steel entering the American LDV industry relative to the base case and a 11% decrease in total energy demand associated with automotive steel. Similarly, increasing the ratio of direct to indirect steel mill products to 85:15 results in a 12% decrease in steel mass to the American LDV industry and 12% decrease in total energy demand. Combining the two scenarios resulted in a 21% decrease in steel mass and 21% decrease in total energy demand of steel entering the American LDV industry. The decreased steel to American LDV values from each of these scenarios are closer to our bottom-up estimate than the base case scenario. The two scenarios combined improved the agreement between our model projection and our bottom-up estimate.

The increased ratio of American to international steel mill products changes the regional distribution of automotive steel mill products by decreasing the mass flows from international producers while maintaining the same RFC and SERC mass flows within America. The mass flows from RFC and SERC do not change since the amount of directly shipped American mill products remains static, forcing the international directly shipped mill product mass flows to decrease. This decrease in international mass flows of automotive steel mill products is reflected in its reduced supply share. The increased ratio of direct to indirect automotive steel mill products decreases the mass flow of indirect automotive steel mill products while maintaining the same mass flow from the direct route. One particular mill in the RFC region only supplies mill products via the indirect route and so decreasing the relative supply of indirect mill products would necessarily decrease the overall automotive steel mill product supply share from the RFC region.

Altering the ratios of American to international automotive steel mill products and direct to indirect automotive steel mill products also has consequences on upstream materials. Increasing the relative supply of American automotive steel mill products necessarily increases the relative supply of American raw materials since the American automotive chain is highly domestic. Changing the relative supply of direct automotive steel mill products only has a minor effect on regional distributions of raw materials. Relative supply of raw materials associated with RFC automotive steel mill products increases slightly at the expense of raw materials associated with SERC automotive steel mill products.

As the ratios of American to international automotive steel mill products and direct to indirect automotive steel mill products increase, the total mass flow and energy demand of steel in finished automotive parts decreases. Because the model ratio of automotive steel mill products to steel in finished automotive parts does not change, if the total mass of automotive steel mill products decreases, so too will the total mass of steel in finished automotive parts. Regional distributions of steel in finished automotive parts remain unaffected by the increased ratios as the decrease in total mass flow is not region-specific.

Table 16: Scenario labels and descriptions for Figure 70-Figure 86.

Scenario	Description
Base	Model case
Alt 1	95/5 American/International automotive steel mill products
Alt 2	85/15 automotive steel sheet produced via BOF/EAF
Alt 3	10/90 automotive steel bar and other steel produced via BOF/EAF
Alt 4	65/35 direct/indirect automotive steel mill products
Alt 5	85/15 direct/indirect automotive steel mill products
Alt 6	Alt 1 & Alt 5
Alt 7	Alt 2 & Alt 3
Alt 8	Alt 1, 2, 3, & 5

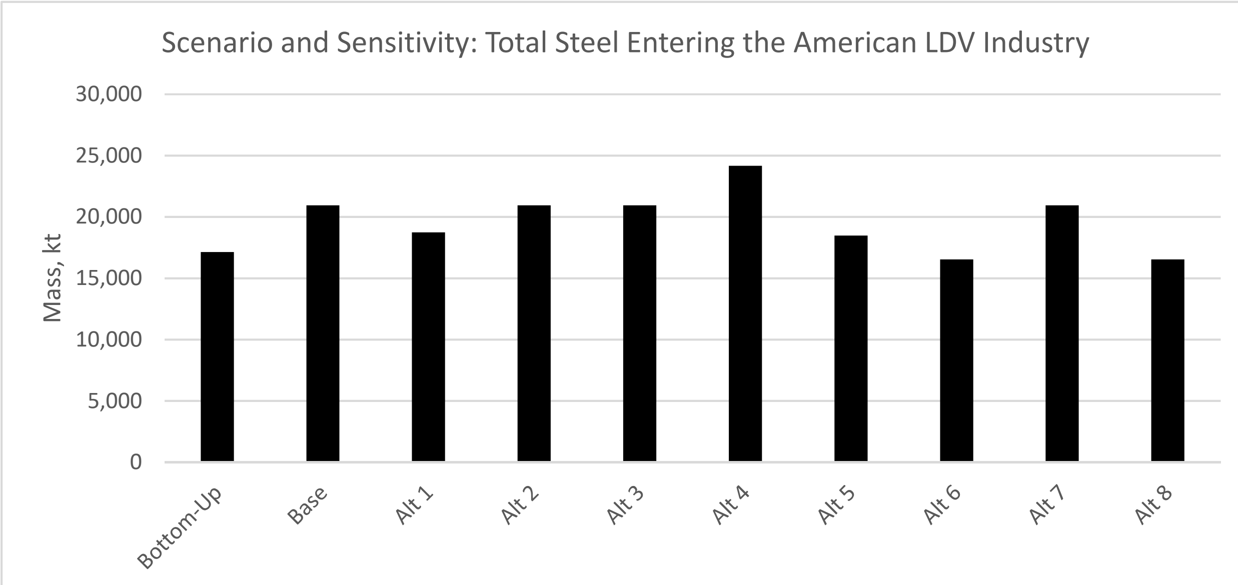

Figure 70: Total mass of steel entering the American LDV industry calculated by our bottom-up estimation and by each scenario described in Table 16.

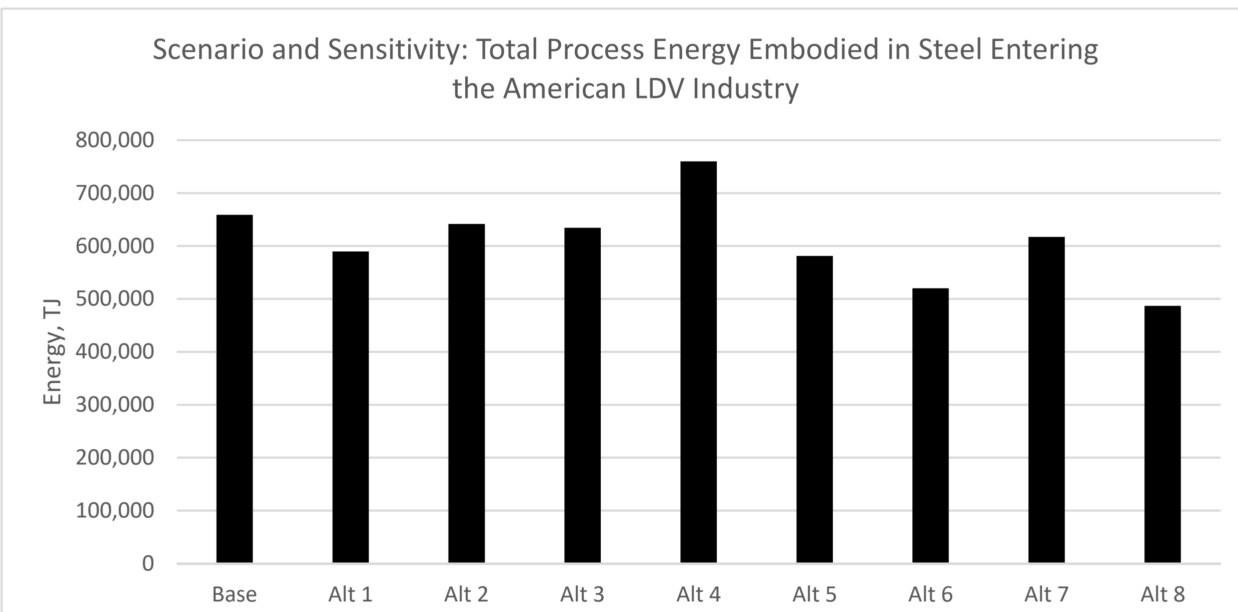

Figure 71: Total process energy demand embodied in automotive steel according to each scenario in Table 16. Process energy is not separated by type of energy input here but rather aggregated.

Decreasing the ratio of automotive steel sheet produced via BOF from 94% to 85% resulted in regional distributions of automotive steel mill products and crude steel from RFC decreasing and SERC increasing. Mass flows and energy demand from raw materials associated with BOF crude steel production decreased as those for EAF crude steel production increased. We also found that although the total energy demand decreased by 2.6%, energy demand associated with crude steel production increased by 7.8% relative to the base case. Similar results were observed when the ratio of automotive hot rolled steel bar and other steel produced via

BOF was decreased from 50% to 10%. In either case, the total amount of steel entering the American automotive industry is unaffected.

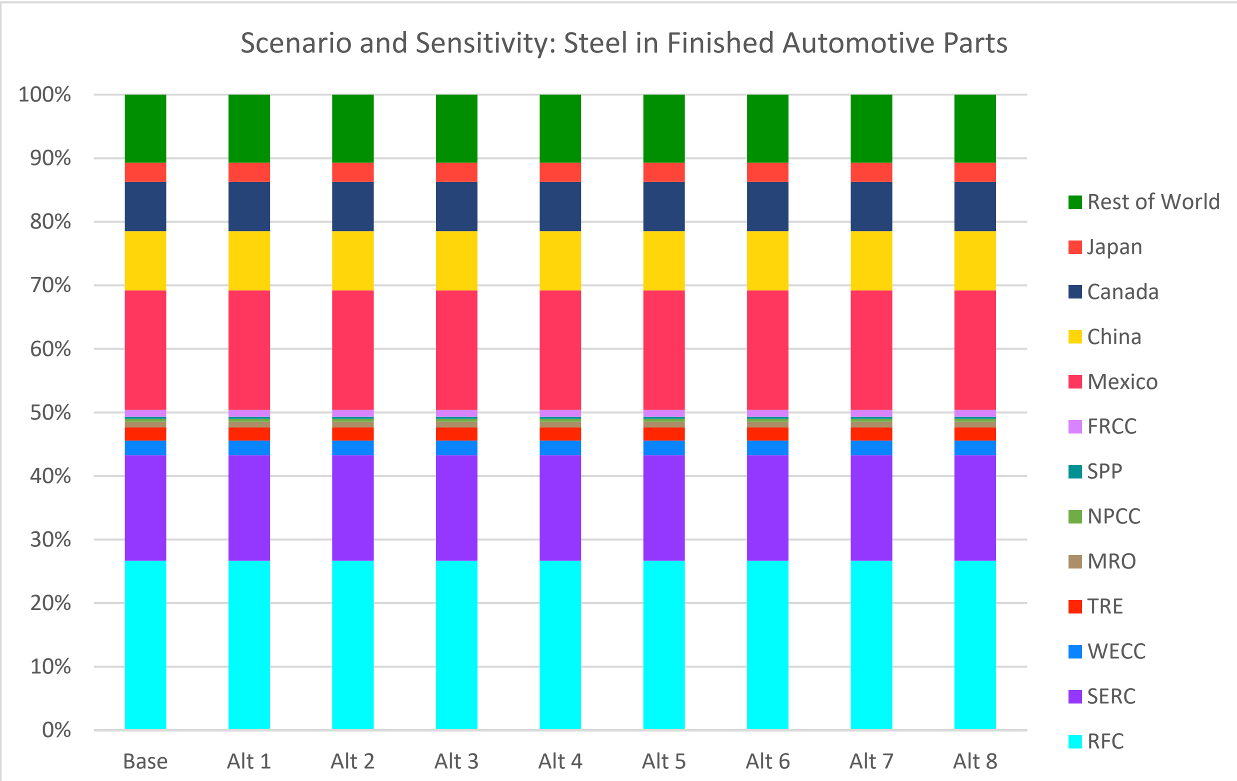

Figure 72: Regional distributions of both mass flows and total process energy demand for steel in finished automotive parts resulting from the scenarios detailed in Table 16. The regional distribution of mass flows and energy demand for steel in finished automotive parts are the same due to the assumption that energy input does not vary by region. Process energy is not separated by type of energy input here but rather aggregated.

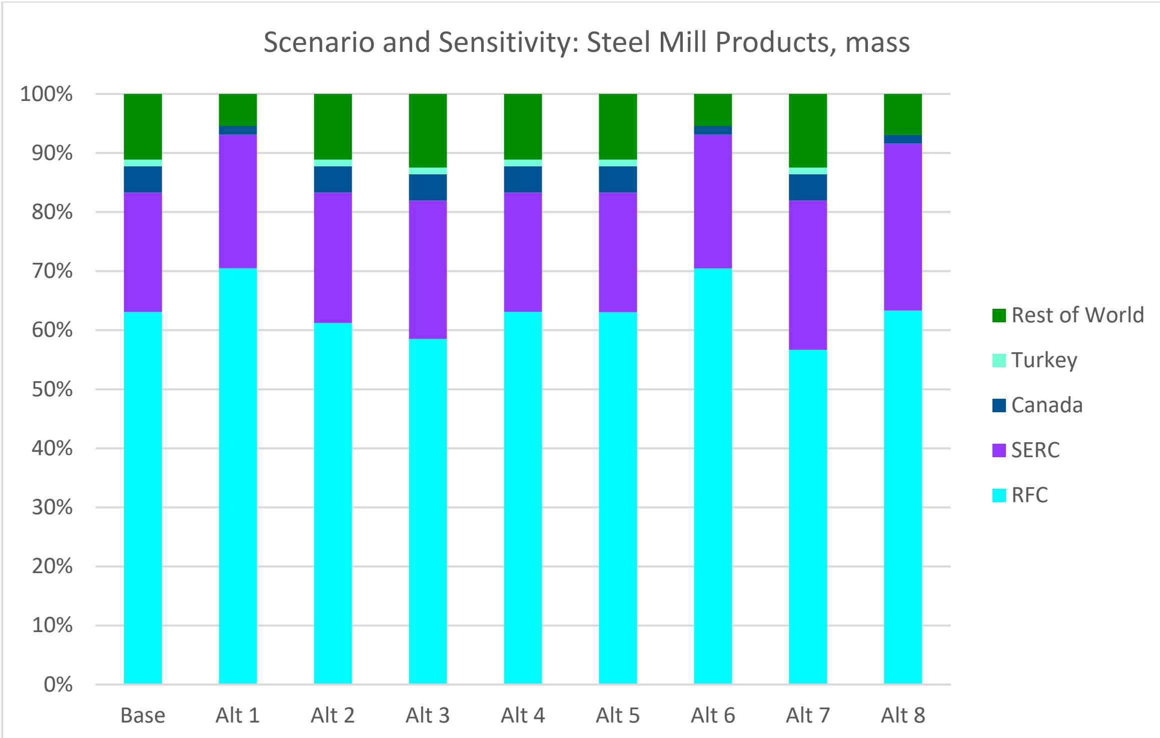

Figure 73: Regional distributions of mass flows for automotive steel mill products resulting from the scenarios detailed in Table 16.

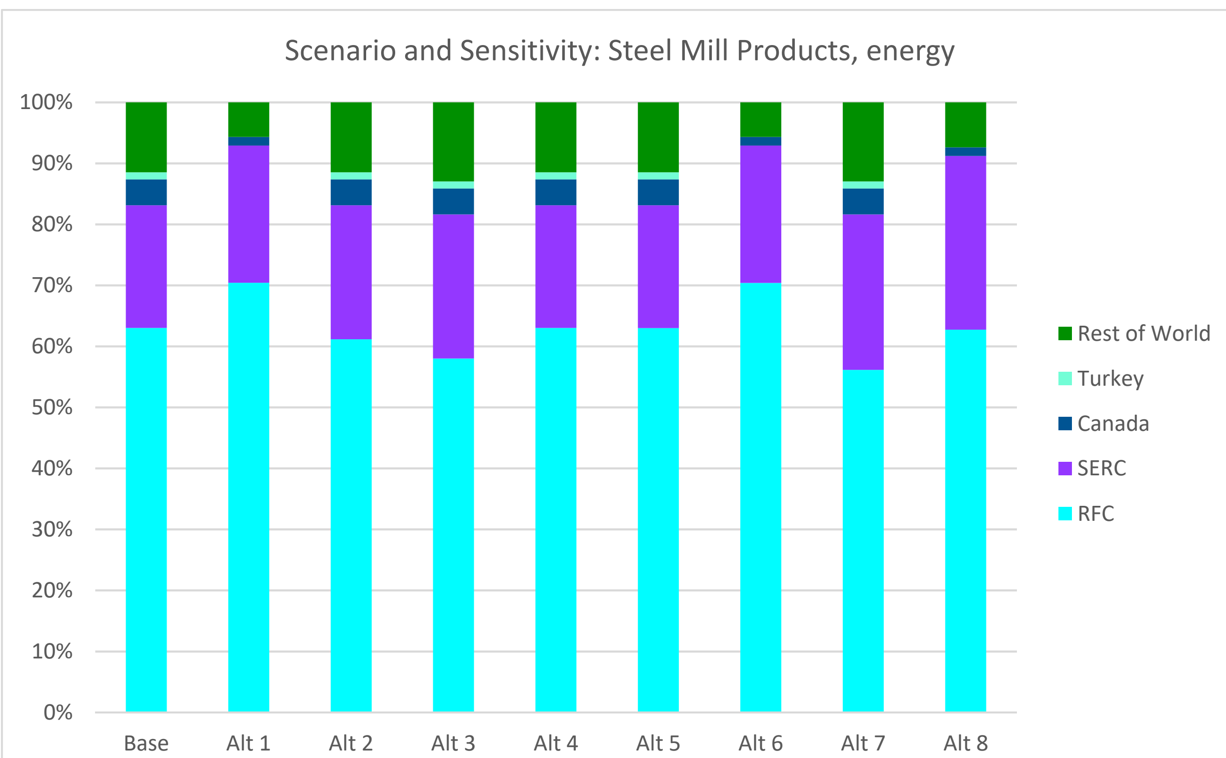

Figure 74: Regional distributions of process energy demand for automotive steel mill products resulting from the scenarios detailed in Table 16. Process energy is not separated by type of energy input here but rather aggregated.

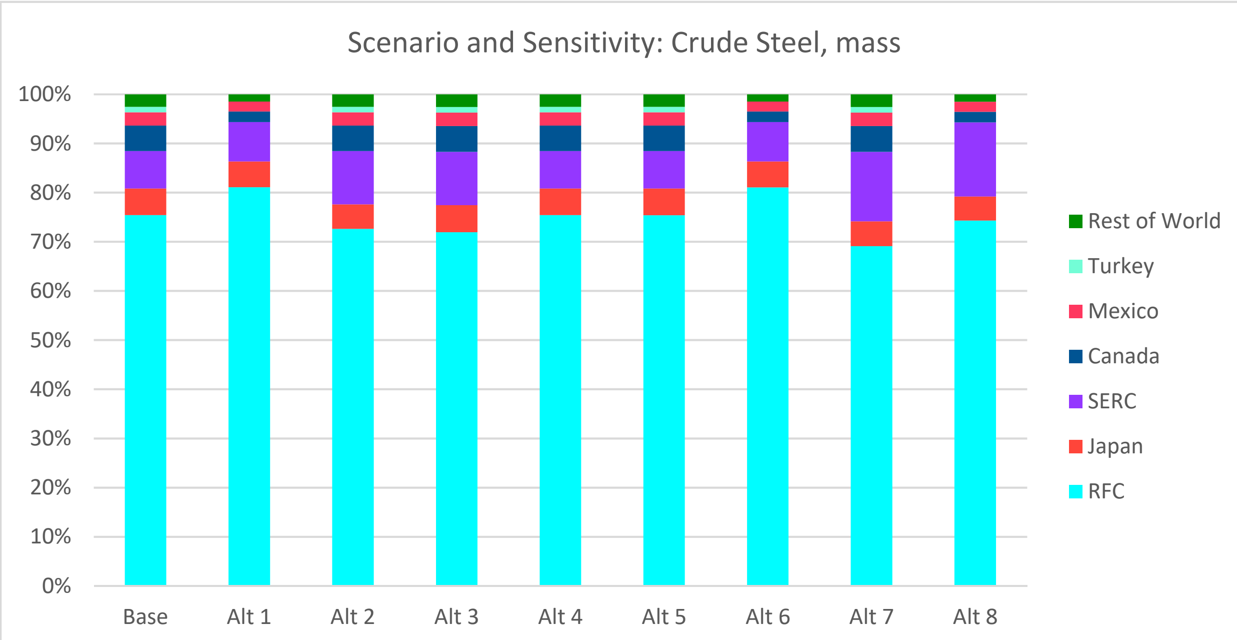

Figure 75: Regional distributions of mass flows for crude steel resulting from the scenarios detailed in Table 16.

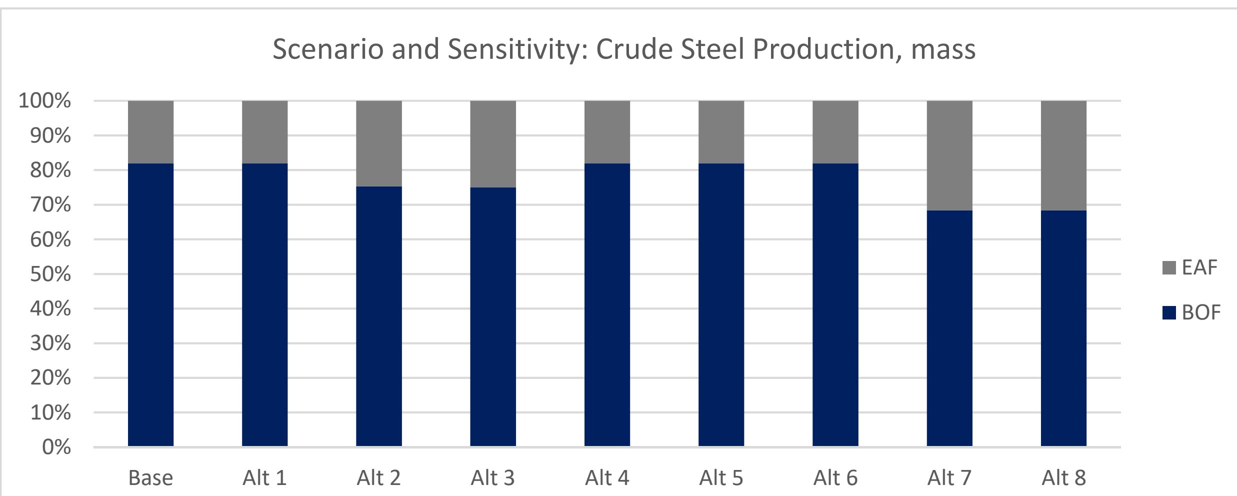

Figure 76: Distributions of crude steel production type by mass resulting from the scenarios detailed in Table 16.

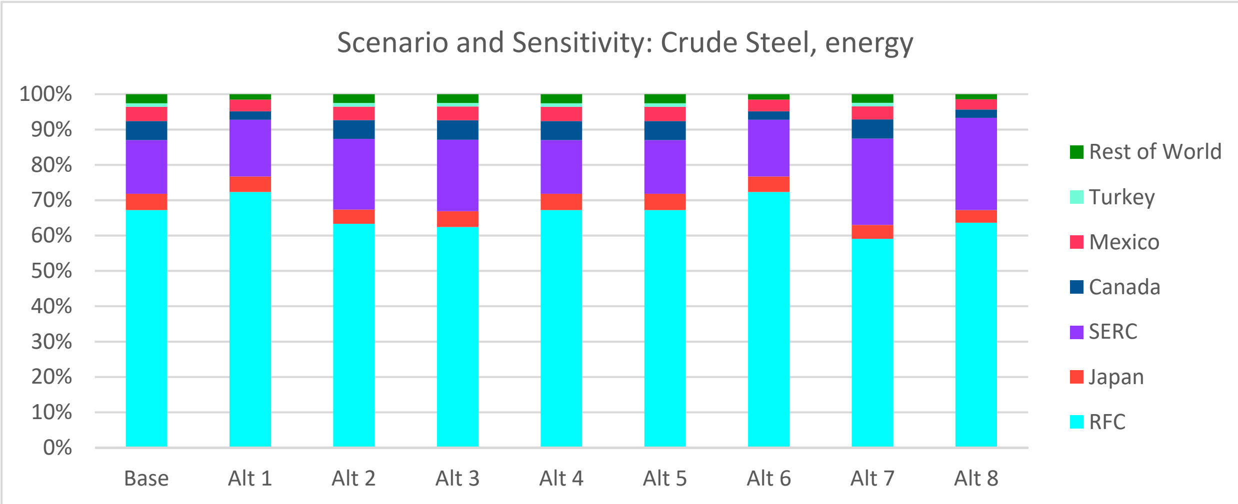

Figure 77: Regional distributions of process energy demand for crude steel resulting from the scenarios detailed in Table 16. Process energy is not separated by type of energy input here but rather aggregated.

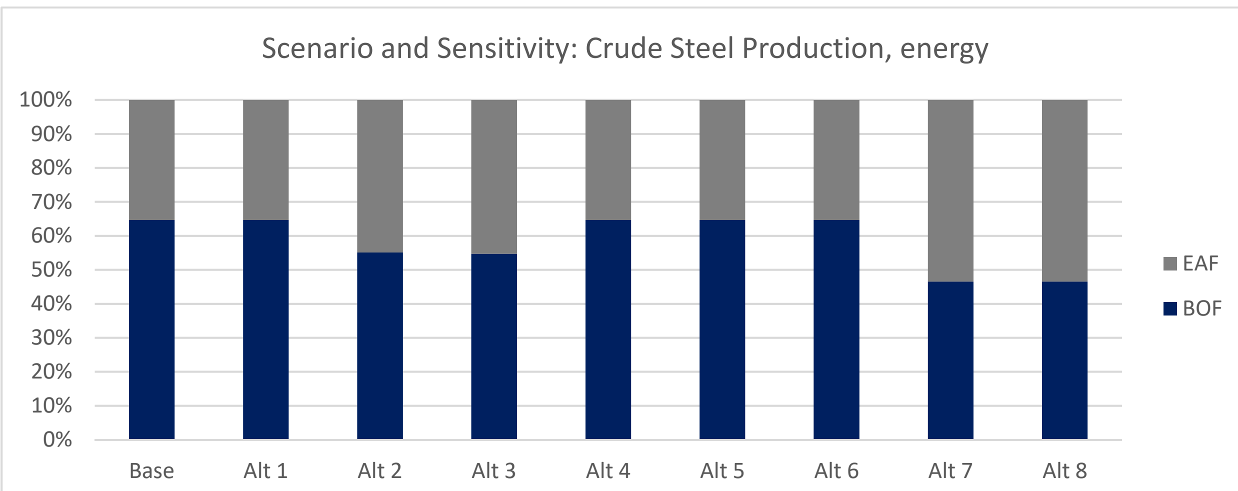

Figure 78: Distributions of crude steel production type by energy demand resulting from the scenarios detailed in Table 16. Process energy is not separated by type of energy input here but rather aggregated.

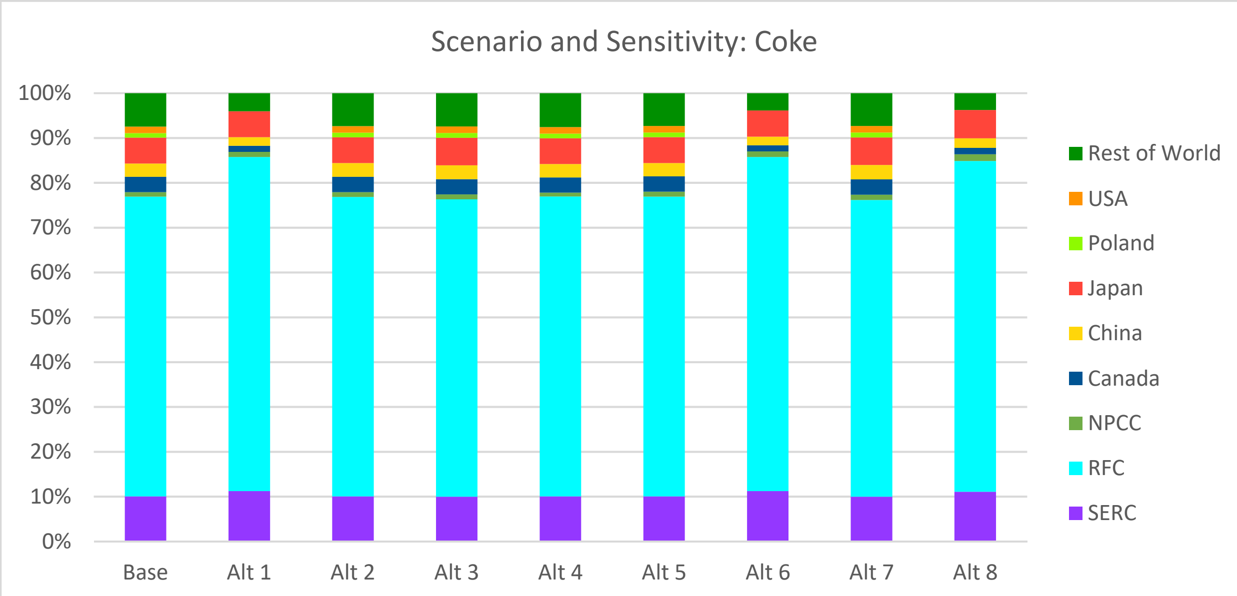

Figure 79: Regional distributions of both mass flows and process energy demand across each scenario described in Table 16 for coke. Regional distributions for mass flows and energy demand are the same since energy input does not vary by region. Process energy is not separated by type of energy input here but rather aggregated.

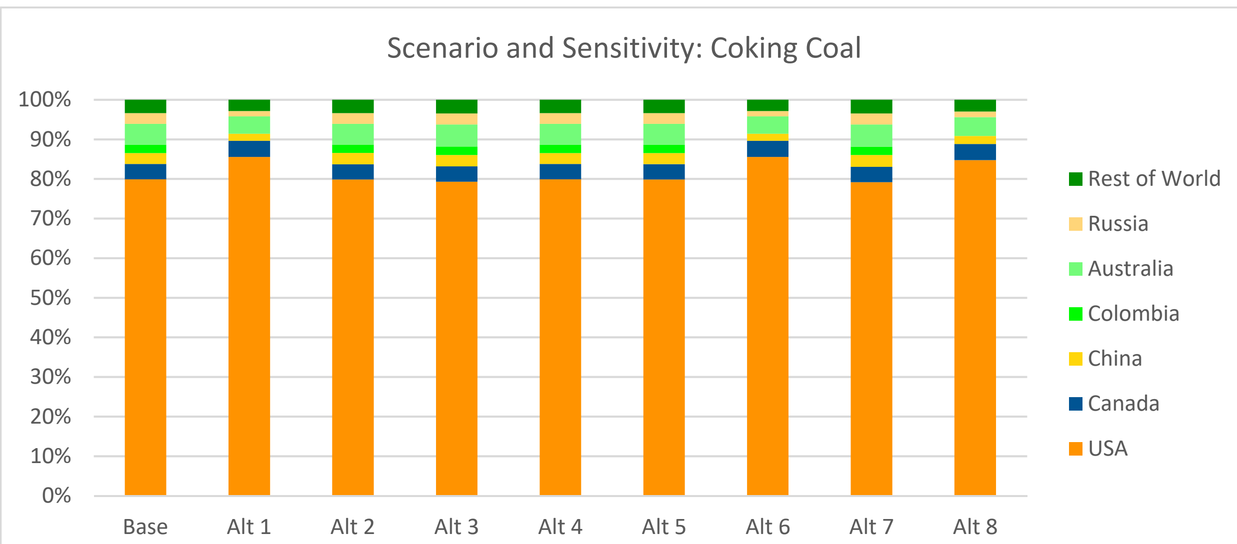

Figure 80: Regional distributions of both mass flows and process energy demand across each scenario described in Table 16 for coking coal. Regional distributions for mass flows and energy demand are the same since energy input does not vary by region. Process energy is not separated by type of energy input here but rather aggregated.

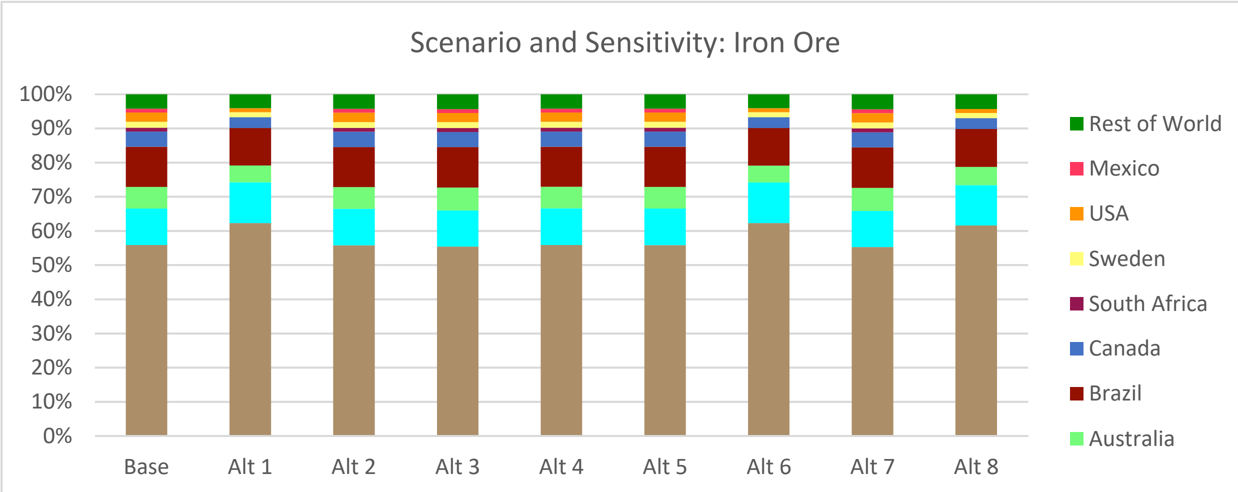

Figure 81: Regional distributions of both mass flows and process energy demand across each scenario described in Table 16 for iron ore. Regional distributions for mass flows and energy demand are the same since energy input does not vary by region. Process energy is not separated by type of energy input here but rather aggregated.

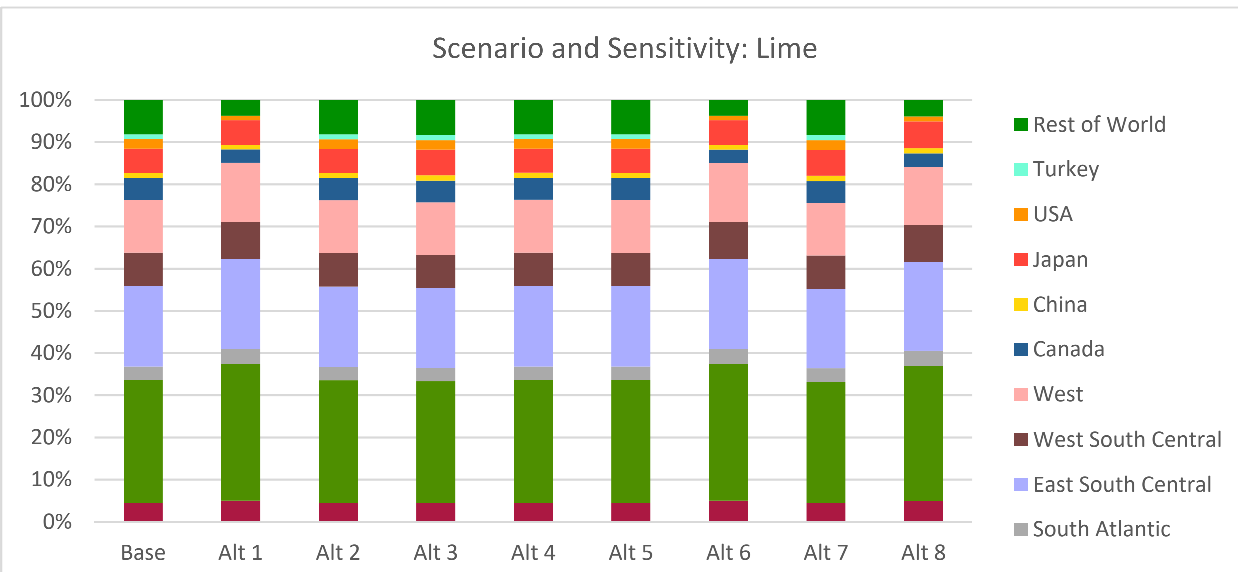

Figure 82: Regional distributions of both mass flows and process energy demand across each scenario described in Table 16 for lime. Regional distributions for mass flows and energy demand are the same since energy input does not vary by region. Process energy is not separated by type of energy input here but rather aggregated.

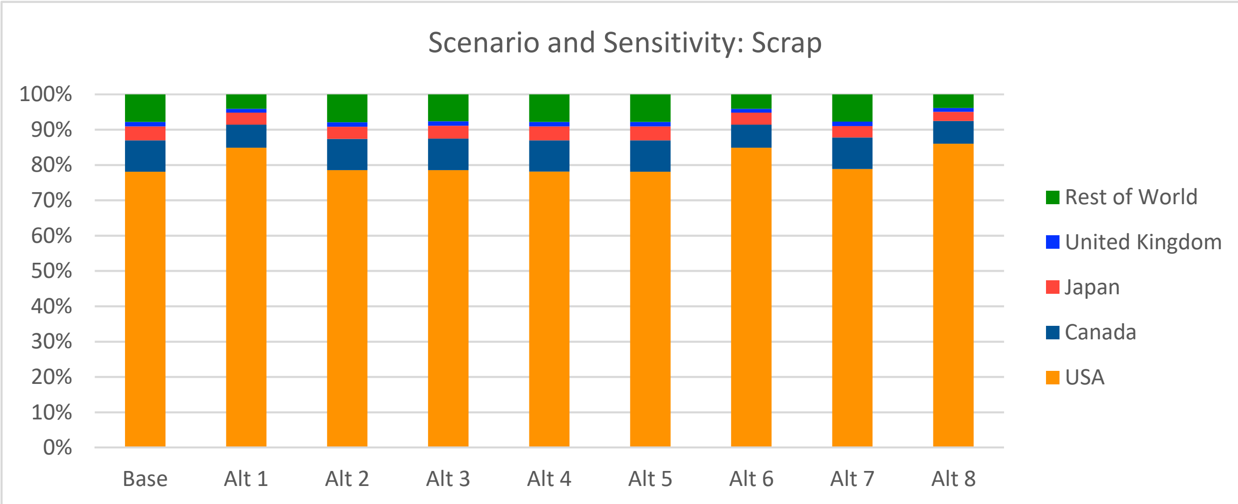

Figure 83: Regional distributions of both mass flows and process energy demand across each scenario described in Table 16 for scrap. Regional distributions for mass flows and energy demand are the same since energy input does not vary by region. Process energy is not separated by type of energy input here but rather aggregated.

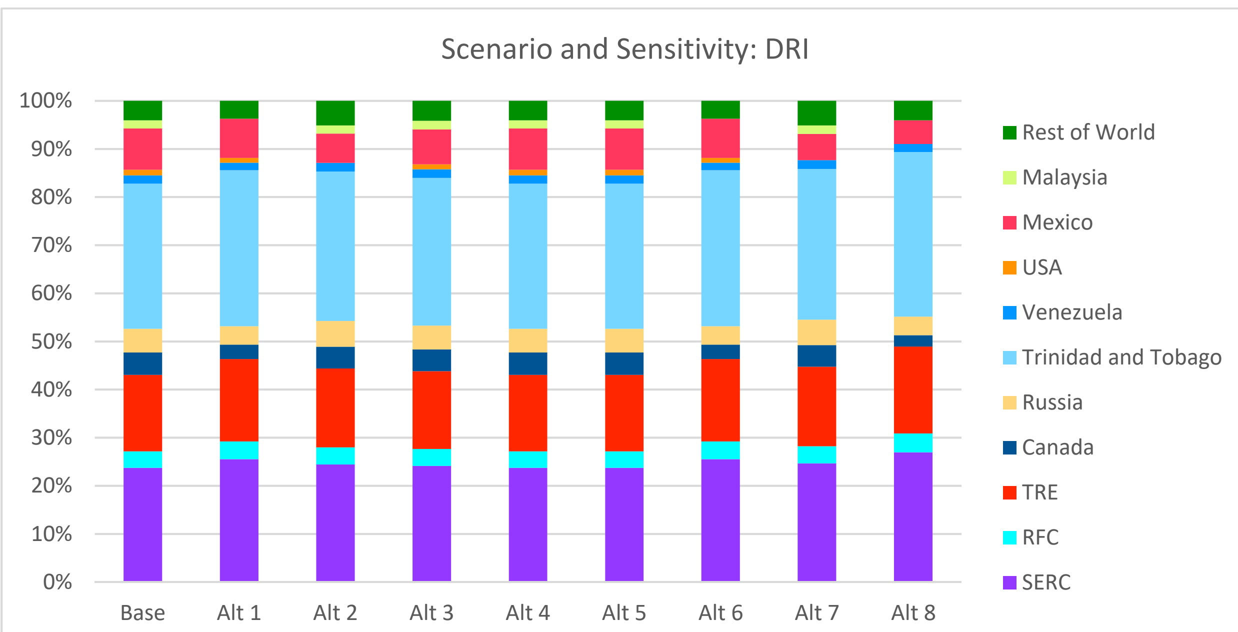

Figure 84: Regional distributions of both mass flows and process energy demand across each scenario described in Table 16 for DRI. Regional distributions for mass flows and energy demand are the same since energy input does not vary by region. Process energy is not separated by type of energy input here but rather aggregated.

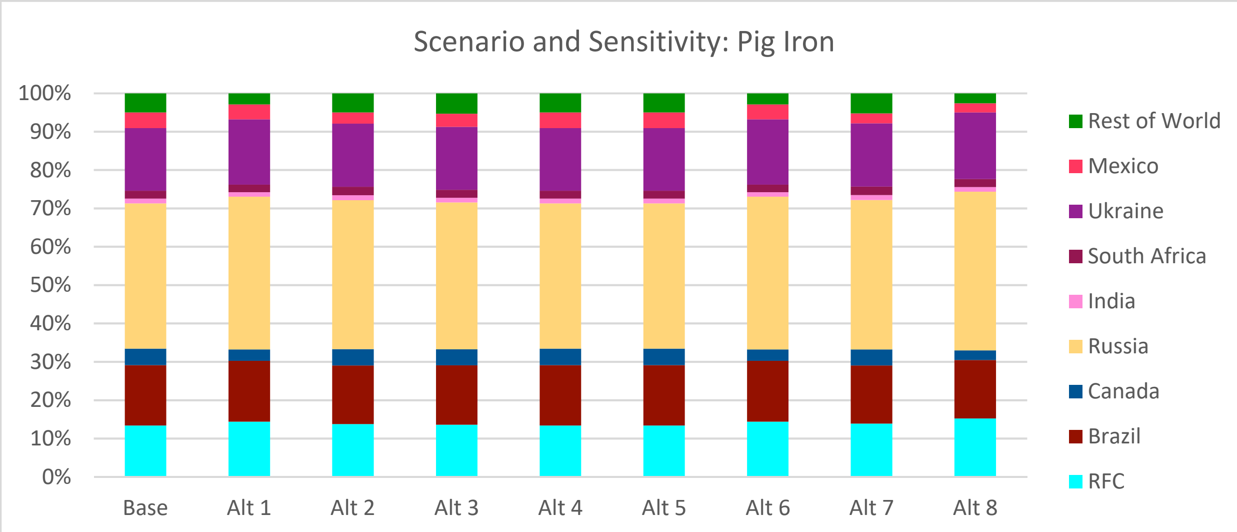

Figure 85: Regional distributions of both mass flows and process energy demand across each scenario described in Table 16 *for pig iron. Regional distributions for mass flows and energy demand are the same since energy input does not vary by region. Process energy is not separated by type of energy input here but rather aggregated.*

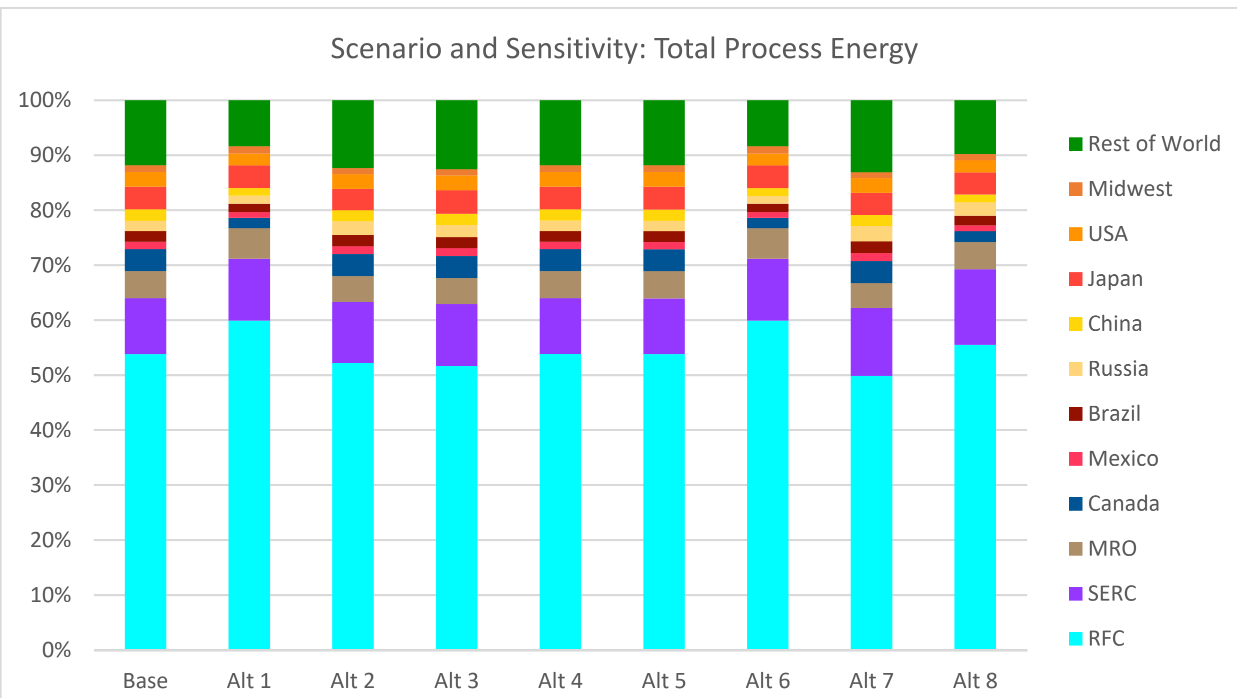

Figure 86: Regional distribution of the total process energy demand embodied in automotive steel across each scenario described in Table 16*. Process energy is not separated by type of energy input here but rather aggregated.*

Subjecting our model to the increased American to international steel mill product ratio, increased direct to indirect mill product ratio, decreased ratio of sheet products produced via BOF to EAF crude steel, and decreased ratio of hot-rolled bar and other steel produced via BOF to EAF crude steel all at the same time, we observe an overall total primary energy demand decrease of 26% relative to the base case. We combine these scenarios because each scenario reduces energy demand. Additionally, we observe a total steel to LDV value of 16,529 kt, which is 3.5% less than our bottom-up estimate. With respect to regional distributions of material products along the automotive steel production cycle, we observe greater overall relative shares of USA supplied materials compared with our base case. Within the USA supply shares, we find decreased contributions from the RFC region and increased contributions from the SERC region. The intracountry supply relationship between the RFC and SERC regions is dictated by the increase in automotive steel produced via EAF crude steel.

Exploring the sensitivity of our bottom-up calculation (Figure 87), we find that by reducing the steel sheet fabrication efficiency from 55% to 50%, the estimated total steel to American LDVs increases by 7.9% from the bottom-up base case of 17,136 kt as more steel sheet is required, resulting in only a 12% difference between our model and bottom-up values. Alternatively, by increasing the steel sheet fabrication efficiency from 55% to 60%, the estimated total steel to American LDVs decreases by 6.5% from the bottom-up base case and results in a 24% difference between our model and bottom-up values.

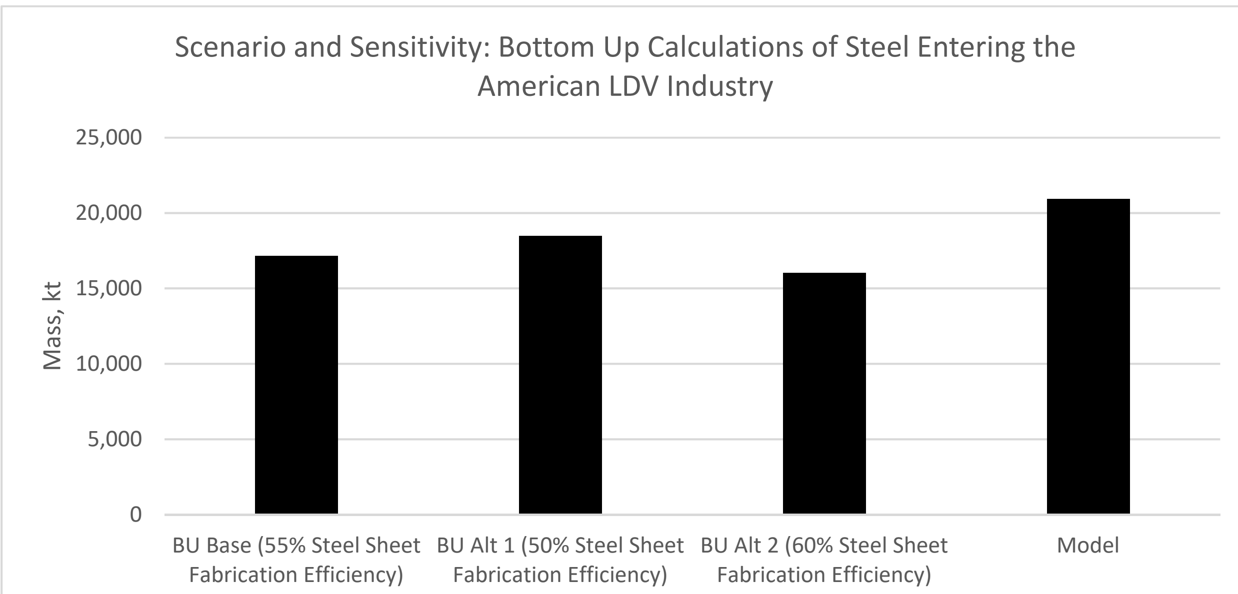

Figure 87: Effects of changing the steel sheet fabrication efficiency on our bottom-up estimation of total steel to the American LDV industry in reference to the model's calculation of the same value.

4.3 DISCUSSION

The RFC and SERC NERC regions dominate the supply of steel mill products and crude steel to the American automotive industry. This regionality aligns with the locations of American OEMs and tier 1 and 2 suppliers, indicating that the American automotive industry has strong localized supply chains. The future supply of DRI from the USA can be reasonably assumed to increase as USA DRI infrastructure increases (Tolomeo, Fitzgerald, & Eckelman 2019). Since 95% of the pig iron produced in the United States goes directly into BOFs for steel production, EAF steelmakers have turned towards international sources of pig iron for EAF crude steel feedstock.

Growth in EAF automotive steel would necessitate the increased utilization of DRI and pig iron and increase the energy demand associated with EAF crude steel since DRI and pig iron are fossil energy intensive. Although EAF crude steel does not embody as much energy as BOF crude steel, EAF crude steel's embodied energy is largely dependent on the amount of DRI and pig iron used as material inputs. From sensitivity analysis, we found that as the share of automotive steel produced via EAF increased, the total energy embodied in automotive steel decreased. That said, increasing EAF automotive steel would cause increased electricity demand, which further increases the impact of the regional characteristics of steel entering the automotive industry since electrical grids have varying fuel mixes. Further research to identify primary energy embodied by automotive steel, regional energy intensities of automotive steel, and regional GHG intensities of automotive steel is recommended to better granularize the environmental burdens of regional aluminum sourcing by the American automotive industry.

Steel in finished automotive parts is more likely to be of international origin since nearly half of the finished automotive parts used in American vehicles are imported.

Comparing our model projections and bottom-up estimates of the total steel to the American LDV industry, we observe reasonable agreement and see that as the American share of steel mill products increases towards industry expectations, the gap between our model projections and bottom-up estimates decreases. The direct-to-indirect steel mill product shipment ratio is one key parameter in our model that can produce a significant range of difference versus the bottom-up results. We observed that increasing direct shipments decreased the difference between our model and the bottom-up results. We need better data to estimate the amount of steel from service centers and converters (indirect shipments), which would facilitate a more accurate ratio characterization.

5. CONCLUSIONS

Using the framework we developed for regionally linked, sector-specific MFAs, we've identified the regional mass flows and energy demands associated with aluminum and steel entering the American automotive industry. We find that for aluminum, mill products are largely sourced from the NPCC, SERC, MRO, and RFC NERC regions. Automotive aluminum extrusions are largely sourced locally, and we recognize the need for further disaggregation of a "Local" region. We postulate that these local sources will be geographically proximate to automaker production facilities, so further investigation could target those potential relationships. Primary aluminum largely comes from American producers while alumina and bauxite are largely sourced internationally from countries with large bauxite reserves. Finished steel and crude steel entering the American automotive industry primarily come from the RFC and SERC NERC regions. The majority of the upstream raw materials required for steel production come from the USA, with DRI and pig iron being exceptions.

The total process energy demand embodied in automotive aluminum is heavily dominated by primary aluminum (i.e., the smelting process). We find that aside from increasing the amount of aluminum scrap used in automotive aluminum mill products, changing automotive aluminum mill product producers' sourcing patterns for primary aluminum holds the most significant potential in altering the greenhouse gas emissions associated with automotive aluminum due to the electricity intensive process for primary aluminum production and different electrical grids having different fuel mixes. We find that varying the regional source of automotive aluminum mill products has little effect on the total process energy demand embodied by automotive aluminum relative to varying the regional production of primary aluminum since the mill processes are comparatively small.

The embodied energy of automotive steel is largely driven by coke since the majority (82%) of steel entering the American automotive industry is produced via BOF crude steel. For EAF crude steel, while we find an inverse correlation between EAF utilization and total energy embodied in automotive steel, uncertainty in the material inputs of automotive steel produced via EAF limits our analysis. The use of DRI and pig iron to improve the quality of EAF crude steel increases the energy demand associated with the material product since DRI and pig iron are produced through energy-intensive processes. We observe that automotive steel produced via EAF uses more electricity and therefore requires more regional specificity to properly characterize its greenhouse gas emissions.

We present the framework we have developed as a tool for future MFAs across all industrial sectors and recommend future research on automotive aluminum and steel to regionalize cast aluminum products, aluminum scrap flows, and advanced high strength steel (AHSS) and ultrahigh-strength steel (UHSS).

Finally, as aluminum and steel continue to dominate the material composition of LDVs, we hope our analysis informs the sustainability of the American automotive, aluminum, and steel industries and acts as a platform for future automotive life cycle assessments seeking more spatially specific material input data.

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Regional-level analysis for the material flows and process energy demands of aluminum and steel in the American automotive industry

Hua, Keoleian, and Lewis

APPENDIX A

A.1 LITERATURE REVIEW TERMINOLOGY

Alumina – the common name given to aluminum oxide (Al_2O_3)

Aluminum – unalloyed aluminum or aluminum alloy

Bauxite – ore containing hydrous aluminum oxides and aluminum hydroxides, which are extracted and converted into alumina via the Bayer process

Basic Oxygen Furnace – steelmaking furnace that converts molten pig iron into steel through the oxidization of oxygen blown into the melt under a basic slag

Electric Arc Furnace – heats charged raw inputs via an electric arc to form steel, and allows the process to incorporate up to 100% recycled steel

Final products – (aluminum / steel) products that go into the use phase

Industry scrap – scrap metal from cuttings and defective parts during the fabrication processes

Ingot – cast (aluminum) product intended and suitable for remelting or forming by hot or cold working

Internal scrap – new scrap that is kept within the same company that it was generated and typically not reported in trade statistics, also known as turn-around scrap, in-house scrap, run-around scrap, and home scrap

New scrap – scrap generated during manufacturing and fabrication processes

Old scrap – scrap generated through processing of end-of-life products (also known as obsolete scrap)

Pig Iron – crude iron obtained directly out of a smelting furnace (typically in the form of small blocks)

Primary aluminum – aluminum produced from alumina, typically by electrolysis, and with an aluminum content of 99,7%.

Secondary aluminum – aluminum produced by recycling of aluminum scrap

Semi-fabricated products (semis) –mill product that has undergone some processing and is supplied for further processing before it is ready for use, often in the forms of rollings (for sheet & plate), castings, and extrusions

Slag – stony waste material separated from the iron products during the iron smelting process

Unwrought aluminum – aluminum obtained by casting without further hot or cold working, e.g. ingots for rolling, ingots for extruding, ingots for forging, ingots for remelting, cast plate or castings

Wrought aluminum – aluminum that has been subjected to hot working and/or cold working

A.2 LITERATURE REVIEW ACRONYMS

AA – Aluminum Association

ACP – Aluminum Containing Product

AISI – American Iron and Steel Institute

BOF – Basic Oxygen Furnace

BU – bottom-up

EAF – Electric Arc Furnace

ELV-dSS – End-of-life vehicle derived steel scrap

EOL – end-of-life

FBMD – flow-based using monetary data, a MFA model

FBPD – flow-based using physical data, a MFA model

GARC – Global Aluminum Recycling Committee, a constituent of IAI

GDP – Gross Domestic Product

GHG – greenhouse gas

IAI – International Aluminum Institute

IISI – International Iron and Steel Institute

IPCC – Intergovernmental Panel on Climate Change

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LME – London Metal Exchange

USA – United States

Metallgesellschaft – World Bureau of Metal Statistics

Mt – Million metric tons

NAFTA – North American Free Trade Agreement

OEM – original equipment manufacturer

SBPD – stock-based using physical data

SITC – standard industrial classification system, used to track internationally traded commodities

UACJ – United Aluminum Committee of Japan

UN Comtrade – United Nations commodity trade statistics database

UPIOM – unit physical input-output by materials, a MFA tool developed by Nakamura and colleagues

USGS – United States Geological Survey

A.3 ALUMINUM AND STEEL MFA LITERATURE REVIEW OBJECTIVE

The automotive industry in the United States is dominated by four key materials: steel, iron, aluminum and plastics (Wards Intelligence 2018). Extensive material flow analyses (MFAs) have been conducted across the steel, iron, and aluminum industries and include information about regional production, trade paths, industrial stock and recycling (Muller 2006; Michaelis and Jackson 2000; Pauliuk 2012; Daigo 2007; Wang 2007; Bertram et al. 2009; Chen and Graedel 2012; Liu and Müller 2013; Liu and Müller 2013; Modaresi and Müller 2012). Yet, little is known about the specific material flows into the transportation sector: vital information regarding the source locations, trade paths and final destinations of steel, iron and aluminum is not readily available. Within the transportation sector, the automotive industry elicits particular interest as the practice of light-weighting vehicles with aluminum and light weight steel continues to increase. It is hypothesized that that the steel and aluminum used in the domestic automotive sector is largely domestically produced, thus it impacts the energy consumption of the USA in a meaningful way. Further, knowledge of international trade flows into the domestic automotive market would help researchers understand the global energy impacts of these automotive materials. A clear understanding of the material flows of these metals into the automotive industry will allow researchers and industry experts to accurately analyze their supply chains, identify economic and environmental pain points, improve the overall efficiency of their procurement, and continue to reinforce the sustainability of both the metals and automotive industries.

The primary task of this memo is to gather, synthesize, and communicate the available methods and results of published aluminum, steel, and iron material flow analyses literature with the intention of informing a method for an automotive industry specific material flow analysis study of all three metals. The proposed study will utilize a developed method to compile, derive, and analyze spatial and temporal data for aluminum, steel, and iron stocks and flows—both domestic and international—into the USA automotive industry (including passenger vehicles, light-duty trucks, and heavy-duty trucks). The final product of the study will be a material flow analysis that documents the production volumes and regional sources for each metal (covering final products and intermediate / raw materials and including metal quality and scrap recycling analysis). The developed material flow analysis will be integrated into energy use models such as GREET by Argonne National Lab, inform future metals and automotive industry research, and support the sustainability of these industries.

A.4 STATE OF KNOWLEDGE: ALUMINUM

This section of the report reviews results of the aluminum life cycle literature, starting by describing the aluminum market, then summarizing the global and USA flow of aluminum, discussing global and USA primary and secondary aluminum production, and finally examining the flow of aluminum into the USA transportation sector—specifically focusing on the flow of aluminum semi-fabricated products, scrap, and final products into the USA automotive (the passenger car and light duty trucks) industry.

A.4.1 MATERIAL MARKET

The aluminum market has grown exponentially in the past century as the metal has become highly integrated into modern society. The aluminum market is built upon the aluminum cycle, which contains seven major components: bauxite mining, alumina production, aluminum ingot production, semis production, final product production, aluminum stock in use, and EOL aluminum recycling. Along this supply chain, both monetary and material value are generated at each step but not without consequence—producing aluminum is highly energy intensive (Colett et al. 2015, p. 30-1) and therefore GHG intensive (Figure A 1). As aluminum continues to become more widely used, understanding the impacts and sustainability of its production processes and material flow is paramount.

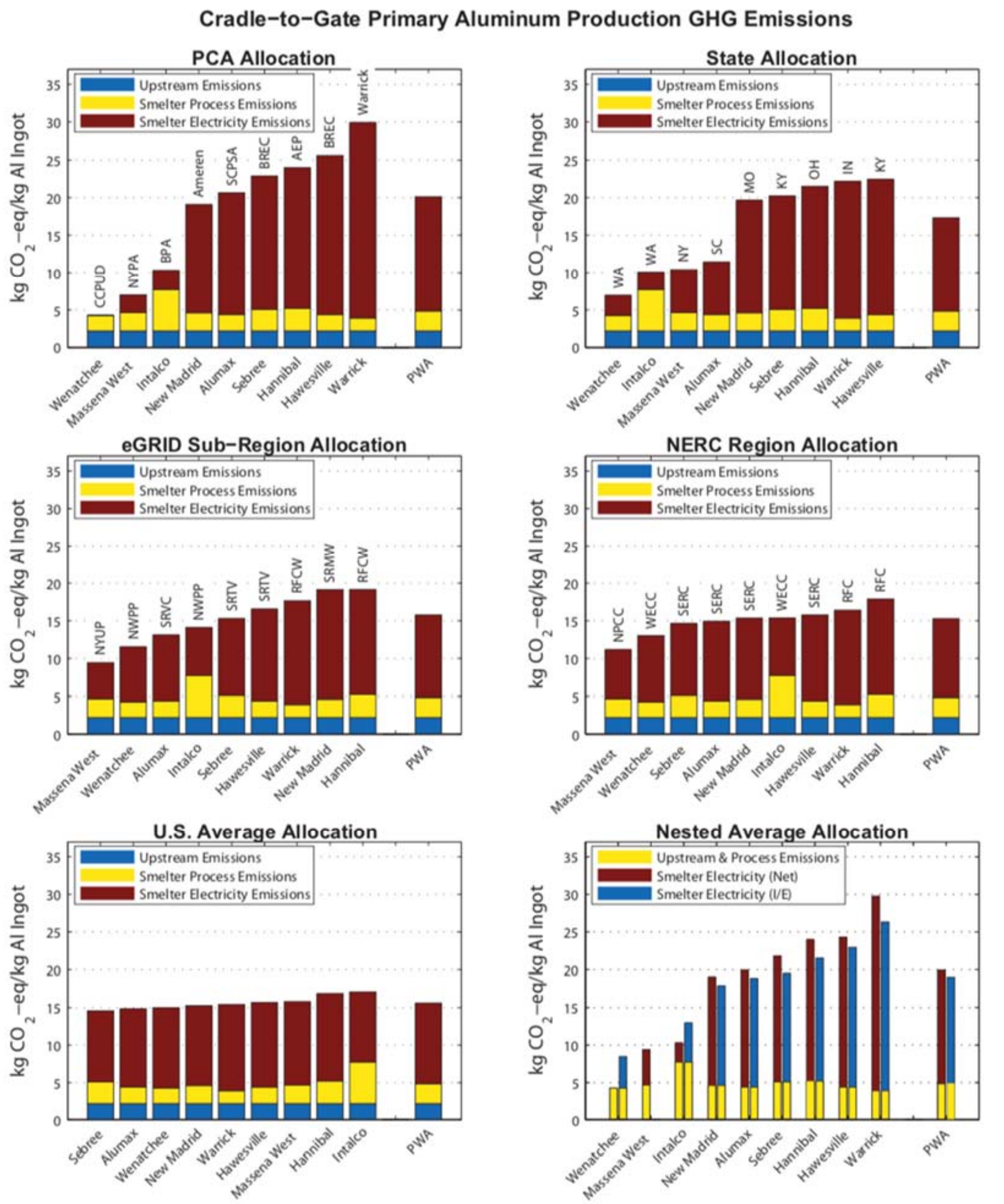


Figure 3 Cradle-to-gate primary aluminum production GHG emissions for the nine aluminum smelters operational in the United States in 2010 and national production-weighted average (PWA). GHG emissions protocol regions are displayed above each smelter's EF. No import/export nested average EF was calculated for Massena West because no import/export information was publically available for NYPA. GHG = greenhouse gas; EF = emission factor; PCA = power control area; eGRID = Emissions & Generation Resource Integrated Database; NERC = North American Electricity Reliability Corporation; kg CO_2-eq/kg Al = kilograms carbon dioxide equivalent per kilogram aluminum.

Figure A 1: The cradle-to-gate primary aluminum production GHG emissions for the nine different, operational aluminum smelters in 2010 (Colett et al. 2015, p. 36)

The value of aluminum—why its production and use has grown exponentially—stems from its low-density, high strength, and corrosion resistive nature. These qualities of the metal have propelled its use in the transportation, building and construction, machinery and equipment, consumer durables, electrical engineering, and containers and packaging industries. Since 1900 the global aluminum stocks in principal repositories have expanded sevenfold, with in-use aluminum stock increasing dramatically around 1950 due, in large part, to the building and construction (40%) and transportation (27%) industries (Liu and Müller March 2013, p. 4885-3).

Quantifying aluminum’s economic value, Figure A 2 shows the average USA spot market (otherwise known as all-in) price and annual average LME cash price of aluminum in both 2016 and 2015. Noticeably, the average USA spot market price of primary aluminum ($0.804 per pound) is greater than the average LME cash price of primary aluminum ($0.727). This difference in price is due to the fact that the USA spot market price of primary aluminum is an all-inclusive (cash price of aluminum plus premium), delivered price that reflects current market conditions whereas the LME cash price of primary aluminum is a global reference price of the metal that does not include any relevant premiums, leaving negotiations to be made between the producer and consumer for those premiums (LME 2018). Although many regions around the world operate on the LME cash price and subsequent premium negotiations, the USA has always operated on a spot market price (McBeth 2018). The pricing scheme of aluminum is of major, current interest as the recent 10% aluminum tariff the USA has placed on imported aluminum is set to have an effect on aluminum prices. (Dhue 2018). Although the LME cash price of primary aluminum may not be affected by the tariffs, the aluminum premium price will be, effectively increasing the price of imported aluminum. Further, domestic aluminum prices will also likely increase because of the aluminum tariff as domestic aluminum producers will see an increased demand and subsequently look to increase their profit margins (McBeth 2018).

TABLE 8
ALUMINUM PRICES[1]

(Dollars per pound)

Material	2015	2016
Primary aluminum, average:[2]		
U.S. market	0.882	0.804
London Metal Exchange cash price	0.754	0.727
NASAAC[3] cash price, average	0.801	0.772
Secondary alloy, average:[4]		
A319 (3% Cu)	1.010	0.889
A356 (0.2% Cu)	1.035	0.912
A360 (0.6% Cu)	1.032	0.905
A380 (3% Zn)	0.938	0.845
A413 (0.6% Cu)	1.035	0.907
Scrap, average:[4]		
Clean, dry turnings	0.559	0.544
Mixed low-copper-content clips	0.610	0.570
Old cast	0.601	0.565
Old sheet	0.572	0.537
Used beverage cans	0.651	0.620

[1]Table includes data available through June 7, 2017.
[2]Source: Platts Metals Week.
[3]North American Special Aluminum Alloy Contract.
[4]Source: American Metal Market.

Figure A 2: The USA market spot and LME prices for aluminum in 2015 and 2016 (Bray 2018, p. 5.14)

A.4.2 GLOBAL ALUMINUM FLOW

Aluminum is a highly globalized commodity and Figure A 3 illustrates the trade-linked global journey of aluminum along its life cycle. Over the course of its life cycle, aluminum traverses a vast number of countries and some general observations can be made. The Southern Hemisphere—where much of the aluminum reserves exist—is the main resource supplier for primary aluminum while aluminum production, consumption, and recycling potential concentrates in the Northern Hemisphere (Liu and Müller Sept. 2013, p. 11878-3), where more developed countries are located. Exploring this observation further reveals that country level magnitudes of aluminum stocks and flows strongly correlate to a country’s availability of aluminum resources, state of economic development, industrial structure, and lifestyle (Liu and Müller Sept. 2013, p. 11877-1).

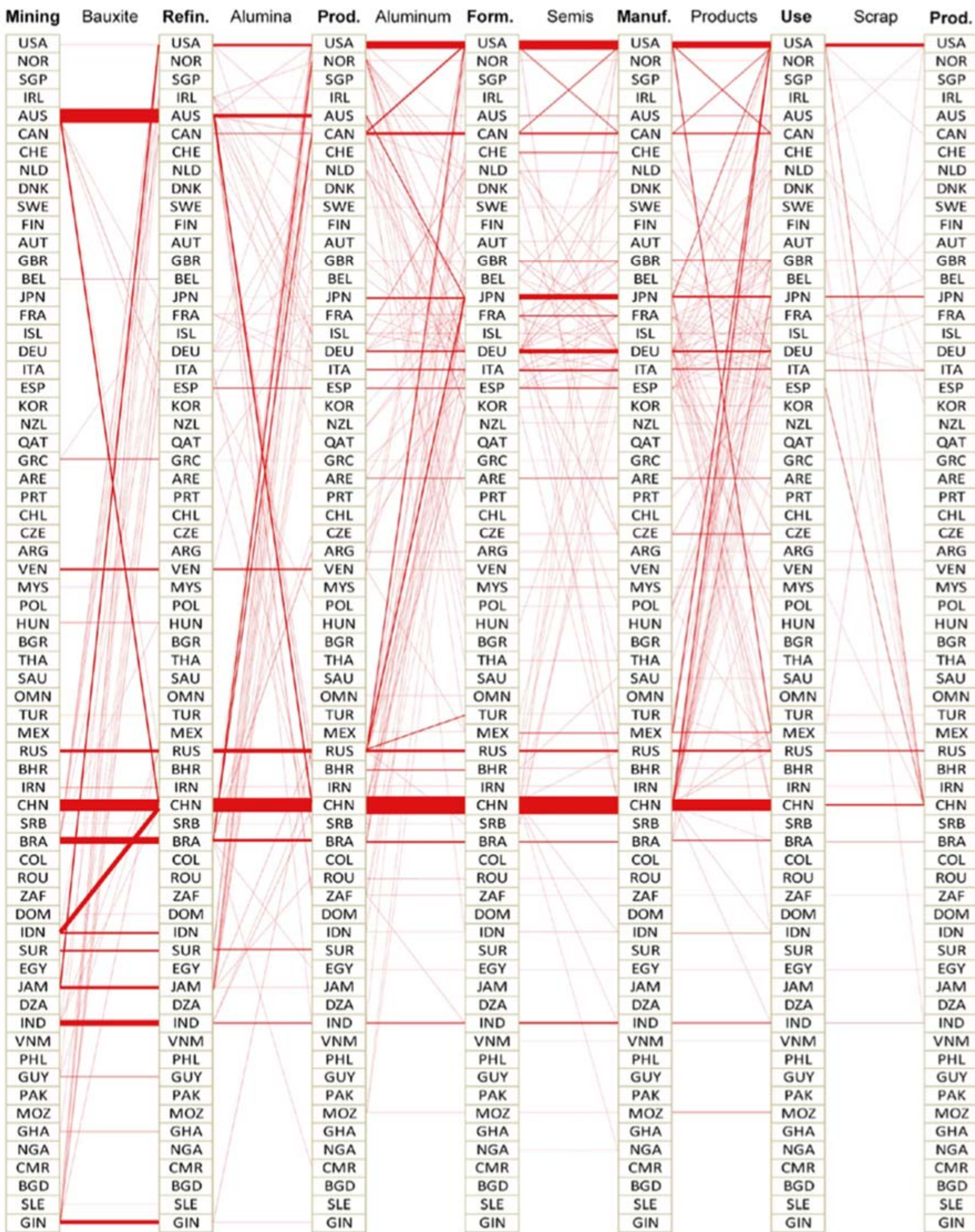


Figure 8. The trade-linked global journey of anthropogenic metallurgical aluminum for the year 2008. The horizontal links are for domestic shipment and the slash links are for trade. The widths of both links are proportional to the magnitude of flows. Shipment and trade flows smaller than 50 kt and all loss flows are omitted here for the convenience of visualization. The columns of countries are ordered by per capita GDP in 2008 (measured based on purchasing power parity in 1990 international dollars[36]).

Figure A 3:The trade-linked journey of aluminum along its life cycle, from bauxite mining to EOL secondary production, for the year 2008 (Liu and Müller Sept. 2013, p. 11879)

Analyzing country level aluminum in-use stocks, a country's per capita rate of total aluminum use has been shown to correlate with its level of development as indicated by GDP; aluminum in-use stocks start to increase from a threshold of 50 kg/capita at a per-capita GDP of 8,000-10,000 dollars (1990 international dollars) to reach between 100-600 kg/capita when GDP increases to a level of 20,000-35,000 dollars/capita (Liu and Müller March 2013, p. 4885-5) as indicated by Figure A 4. Further, developing and emerging countries tend to have a higher share of aluminum stocks in electrical engineering products like transmission and distribution infrastructure, while more economically developed, industrialized countries have higher shares of aluminum stocks in transportation and building and construction (Liu and Müller March 2013, p. 4885-3).

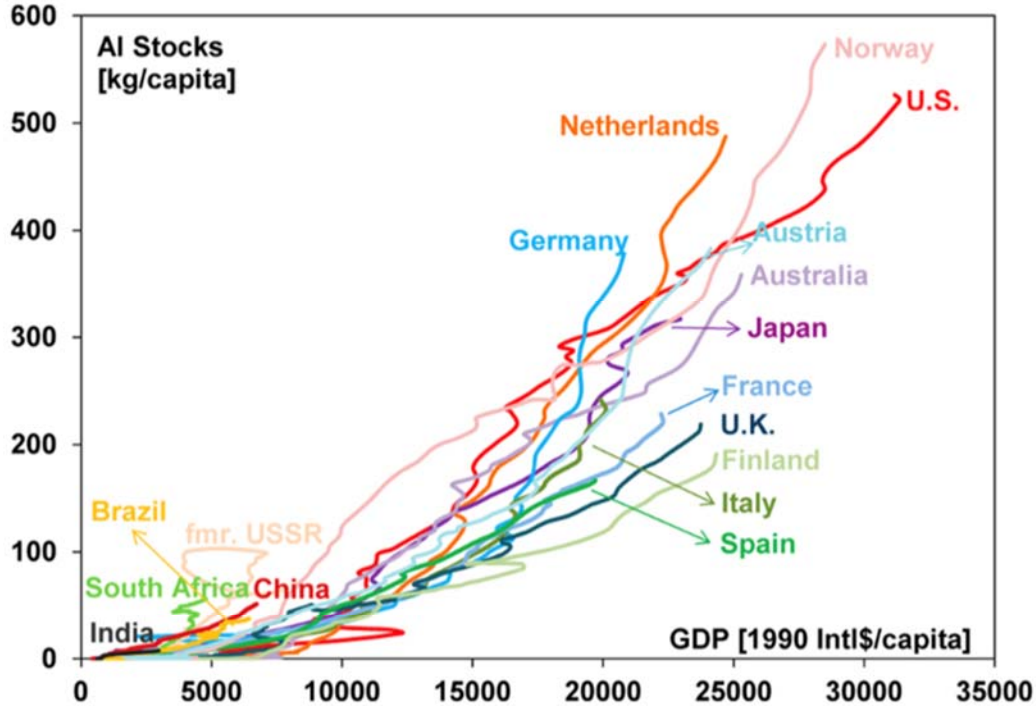


Figure 5. Per-capita aluminum stocks in use relative to per-capita GDP PPP for selected countries. The GDP data are measured based on purchasing power parity (PPP) in 1990 international Geary–Khamis dollars.[34] The stock data are shown only until 2008 because of GDP data availability.

Figure A 4: The relationship between a country's in-use aluminum stock and GDP (Liu and Müller March 2013, p. 4886)

Examining global aluminum flow, most industrialized countries and major economies have a heavy foreign dependence on aluminum in all forms (Liu and Müller Sept. 2013, p. 11877-3) while developing countries tend to be net exporters of aluminum raw materials. China is the biggest aluminum production and consumption country, relying mainly on its domestic extraction to supply aluminum flows, but the country also imports considerable amounts of bauxite, alumina, and scrap to satisfy its own domestic market and to export aluminum in the forms of ingots, semis, and final products to other countries (Liu and Müller Sept. 2013, p. 11877-1)—illustrating the countries capitalization on the aluminum value chain. Economic value of aluminum increases from mining to production, peaking at the manufacturing and fabrication processes in the aluminum life cycle—semis and final products are the highest valued forms of aluminum (Liu and Müller Sept. 2013, p. 11880-2). Along with China, the USA and Japan are the leading net importers of aluminum (illustrated in Figure A 5). Australia, Brazil, Indonesia, Jamaica, and Guinea—all located in the Southern Hemisphere and all containing large bauxite reserves—are important countries in the upstream aluminum processes of bauxite mining, alumina production, and aluminum production and heavily export these products. Russia, Venezuela, and Norway represent major primary aluminum production countries, with Norway being of particular interest as they utilize hydropower (a renewable energy source that emits no GHGs during the production of electricity, therefore representing a very environmentally advantageous source of power to drive primary aluminum production since the process is very energy intensive) to produce unwrought aluminum and semis that are then primarily exported to other regions—92% of Norway's domestically produced unwrought aluminum and 67% of its domestically produced semis are exported (Liu and Müller Sept. 2013, p. 11877-3). Figure A 6 illustrates the global aggregated trade flows of aluminum in bauxite, alumina, unwrought aluminum, semis, finished products, and scrap for the year 2008, further highlighting and decomposing the trade flows that were greater than 1 Mt/yr (Liu and Müller Sept. 2013, p. 11878).

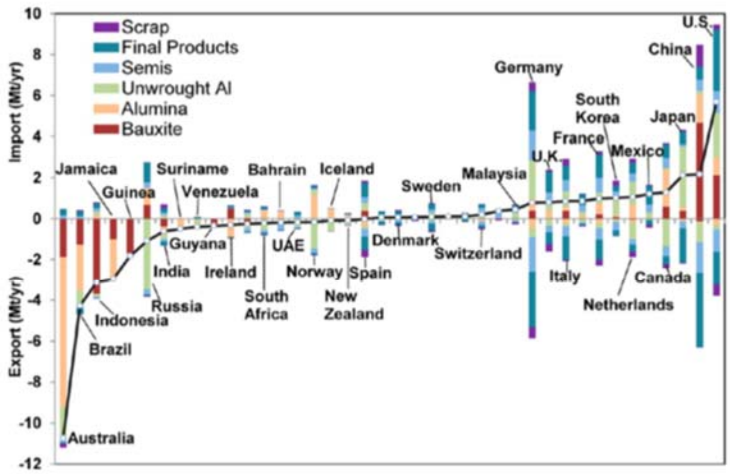


Figure 6. International trade of aluminum in bauxite, alumina, unwrought aluminum, semis, final products, and scrap in 2008. The countries are sorted by total net import from left to right (the dark curve represents total net trade). All values are aluminum metallic equivalent in Mt/yr. The ranking of trade on a regional level is shown in Figure S6 in the Supporting Information.

Figure A 5: Major countries and their imports and exports of different aluminum products, ordered by their net import of aluminum with the largest net importing countries being on the right (Liu and Müller Sept. 2013, p. 11877)

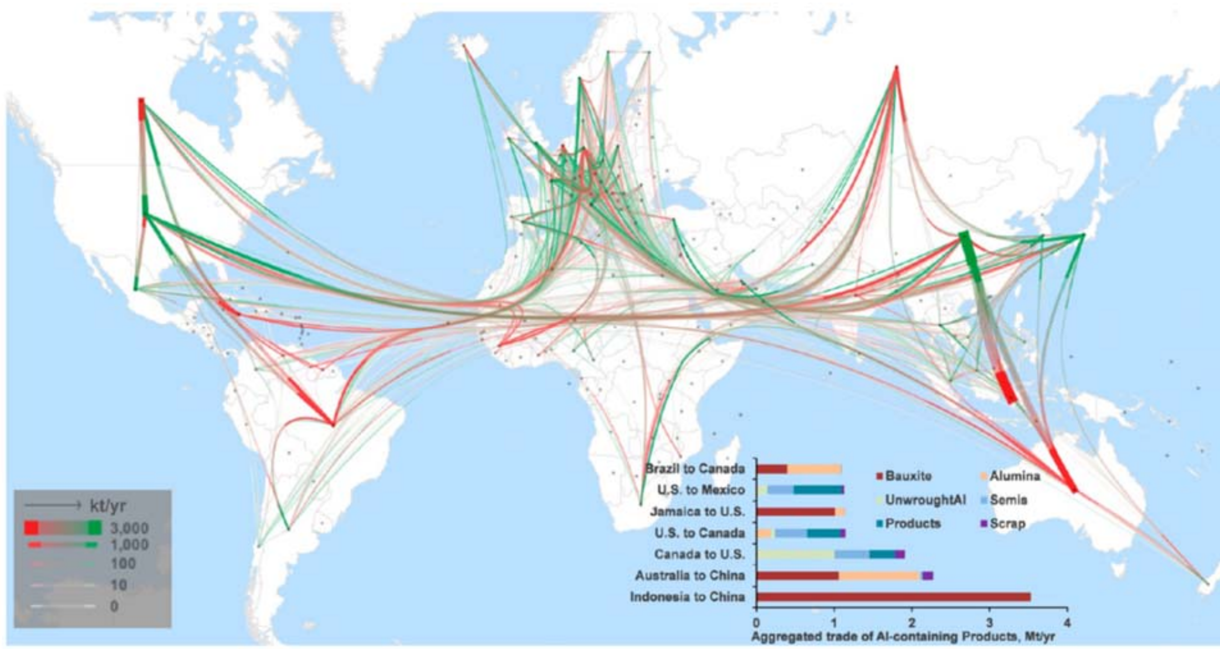


Figure A 6: The global aggregated trade flows of aluminum in bauxite, alumina, unwrought aluminum, semis, finished products, and scrap for the year 2008. Origins are in red and destinations are in green. The widths of flows are proportional to physical trade values. The bar graph shows the decomposition of trade flows that are larger than 1 Mt/yr (Liu and Müller Sept. 2013, p. 11878)

As a highly globalized commodity, aluminum (on top of its energy and GHG intense production burden) incurs environmental burden in its transport at different stages of its life cycle. Although potentially dwarfed by the production burden, the transportation burden associated with transnational trade of aluminum needs to be considered when conducting a comprehensive LCA of the metal.

Global environmental justice is another key issue that needs to be addressed when discussing the globalization of aluminum's life cycle. Because industrialized and developed countries import large amounts of both raw aluminum materials and primary aluminum, they shift upstream aluminum GHG burdens to the countries that are mining bauxite and producing primary aluminum for export, projecting the negative environmental and health effects associated with increased GHG emissions onto nations that might not have the means to address those effects adequately.

A.4.3 USA ALUMINUM FLOW

Historically, the USA was a net exporter of aluminum final products until 1983, after which the USA has been a net importer of aluminum final products. Additionally, the USA has been a net importer of unwrought aluminum and net exporter of aluminum scrap since 1960, with net export of aluminum scrap increasing significantly after 2000 because domestic secondary aluminum production capacity could not utilize all of the aluminum scrap generated (Chen and Graedel 2012, p. 101-1).

Currently, the USA aluminum industry depends heavily on imports of almost all aluminum containing products, excluding scrap and semis (Liu and Müller Sept. 2013, p. 11877-1). In 2016, the USA exported 2.82 Mt of aluminum and imported 6.02 Mt of aluminum according to the 2018 USGS minerals yearbook for aluminum. Within these import and export statistics, the USA was a net importer of crude aluminum metals and alloys and a net exporter of semis and scrap. These import and export statistics from USGS can be visualized in Table A 1 and Table A 2, respectively.

Table A 1: USA aluminum imports for consumption by country or locality in 2016 (Bray 2018, p. 5.17)

TABLE 12

U.S. IMPORTS FOR CONSUMPTION OF ALUMINUM, BY COUNTRY OR LOCALITY[1]

	Metals and alloys, crude		Plates, sheets, bars, etc.[2]		Scrap		Total	
Country or locality	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)	Quantity (metric tons)	Value (thousands)
2015:								
Argentina	85,900	$187,000	5	$47	--	--	85,900	$187,000
Australia	19,400	44,800	220	2,500	251	$393	19,800	47,700
Bahrain	74,400	168,000	35,000 [r]	102,000	--	--	109,000	269,000
Belgium	1,640	7,880	7,160	35,800 [r]	15	28	8,810	43,800
Brazil	3,700	8,420	10,000	27,100	13,300	21,400	27,000	56,900
Canada	2,230,000	4,670,000	253,000	945,000	340,000	514,000 [r]	2,820,000	6,130,000
China	3,220	8,470 [r]	391,000	1,110,000	369	813	394,000 [r]	1,120,000
France	10,900 [r]	87,600	10,100 [r]	66,200 [r]	159	133	21,100 [r]	154,000 [r]
Germany	7,010 [r]	18,600 [r]	70,000 [r]	299,000 [r]	1,160	7,320	78,100 [r]	325,000 [r]
Italy	7,620	14,000	10,900	56,100 [r]	760	333	19,300	70,500 [r]
Japan	15	70	27,000 [r]	120,000	760 [r]	1,410 [r]	27,800	121,000 [r]
Korea, Republic of	15,900	34,200	22,000	73,100	545	1,290	38,400	109,000
Mexico	21,700	42,300 [r]	43,000 [r]	200,000 [r]	97,200 [r]	144,000	162,000	386,000 [r]
Netherlands	1,780	5,860	2,730	15,300	467	730	4,980	21,900
Panama	142	224	43	188	4,830	6,660	5,010	7,070
Russia	279,000	617,000	16,900	65,200	739	1,430	297,000	683,000
South Africa	9,870	24,300	47,100 [r]	154,000 [r]	--	--	57,000 [r]	178,000 [r]
Spain	7,250	14,000	982	5,980 [r]	1,120	1,420	9,360	21,400
United Arab Emirates	293,000	662,000	17	102	1,410	2,090	294,000	664,000 [r]
United Kingdom	566	2,500	12,500	50,200 [r]	3,990	6,550	17,000 [r]	59,200 [r]
Venezuela	63,700	120,000	141	260	5,090 [r]	8,100 [r]	68,900	128,000
Other	245,000 [r]	566,000 [r]	218,000 [r]	787,000 [r]	48,900	76,300 [r]	512,000 [r]	1,430,000 [r]
Total	3,380,000	7,300,000 [r]	1,180,000	4,110,000	521,000	795,000	5,080,000	12,200,000
2016:								
Argentina	174,000	304,000	--	--	15	22,700	174,000	326,000
Australia	6,370	10,900	232	3,110	1,320	1,730	7,920	15,800
Bahrain	107,000	195,000	51,200	134,000	--	--	158,000	329,000
Belgium	1,320	5,580	7,310	34,300	--	--	8,630	39,900
Brazil	28,300	48,100	15,000	33,000	15,800	20,700	59,200	102,000
Canada	2,300,000	4,230,000	254,000	888,000	364,000	488,000	2,920,000	5,600,000
China	2,080	6,070	368,000	934,000	801	1,250	371,000	941,000
France	9,990	86,200	16,800	93,900	1,620	387	28,400	181,000
Germany	1,720	5,290	65,400	250,000	801	980	67,900	256,000
Italy	574	1,080	10,200	47,700	289	110	11,100	48,900
Japan	6	34	29,100	124,000	496	1,270	29,600	125,000
Korea, Republic of	7,440	14,600	14,400	48,500	8,520	17,000	30,400	80,100
Mexico	11,700	18,200	43,600	189,000	133,000	168,000	188,000	375,000
Netherlands	1,450	5,030	4,230	21,500	934	1,210	6,610	27,700
Panama	35	50	71	183	5,700	7,080	5,810	7,320
Russia	721,000	1,260,000	15,600	50,700	--	--	737,000	1,310,000
South Africa	12,000	25,300	61,200	161,000	77	107	73,300	186,000
Spain	1,780	3,780	1,650	7,880	3,930	4,370	7,360	16,000
United Arab Emirates	547,000	1,010,000	1	13	1,870	1,720	549,000	1,020,000
United Kingdom	785	3,090	10,400	41,100	3,670	4,710	14,800	48,900
Venezuela	59	98,100	507	912	12,300	19,700	12,900	119,000
Other	301,000	531,000	209,000	713,000	54,400	45,000	565,000	1,290,000
Total	4,230,000	7,860,000	1,180,000	3,770,000	609,000	806,000	6,020,000	12,400,000

[r]Revised. -- Zero.

[1]Table includes data available through June 7, 2017. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Includes circles, disks, pipes, rods, tubes, etc.

Source: U.S. Census Bureau.

Table A 2: USA aluminum exports for consumption by country or locality in 2016 (Bray 2018, p. 5.15)

TABLE 10
U.S. EXPORTS OF ALUMINUM, BY COUNTRY OR LOCALITY[1]

Country or locality	Metals and alloys, crude: Quantity (metric tons)	Metals and alloys, crude: Value (thousands)	Plates, sheets, bars, etc.[2]: Quantity (metric tons)	Plates, sheets, bars, etc.[2]: Value (thousands)	Scrap: Quantity (metric tons)	Scrap: Value (thousands)	Total: Quantity (metric tons)	Total: Value (thousands)
2015:								
Brazil	1,770	$4,120 [r]	5,900	$49,200	1,360	$2,040	9,030	$55,400
Canada	105,000	240,000	436,000 [r]	1,590,000 [r]	119,000	229,000	660,000 [r]	2,060,000 [r]
China	487	1,800	38,100	261,000 [r]	845,000 [r]	1,310,000	884,000 [r]	1,570,000
France	4,440	14,000	15,500	136,000	2,290	10,700	22,200	161,000
Germany	3,150	11,100	12,000	116,000	5,550	7,170	20,700	134,000
Hong Kong	38	135	1,940 [r]	17,300 [r]	29,400 [r]	33,900 [r]	31,400 [r]	51,400 [r]
Italy	61	301	2,860	38,200	160	1,300	3,080	39,800
Japan	1,830	7,300	22,400	235,000	13,900	32,700	38,200	275,000
Kazakhstan	--	--	65	463	--	--	65	463
Korea, Republic of	1,350	3,290	32,700	261,000	169,000 [r]	266,000 [r]	203,000 [r]	530,000 [r]
Mexico	180,000	410,000	460,000	1,810,000	179,000 [r]	305,000 [r]	818,000 [r]	2,530,000
Netherlands	1,300	3,710	788	8,160	209	360	2,290	12,200
Philippines	65	169	401	4,600	147	889	613	5,660
Russia	3	15	57	1,020	299	445	359	1,480
Saudi Arabia	8	59	5,960	27,600	94	116	6,070	27,800
Singapore	1,460	3,940	3,400	37,100	143	159	5,010	41,200
South Africa	14	87	188	1,920	--	--	202	2,010
Taiwan	4,550 [r]	12,400 [r]	4,440 [r]	36,400	37,500 [r]	56,800 [r]	46,400 [r]	106,000
Thailand	94	306	5,430	29,100	2,420 [r]	3,360 [r]	7,950 [r]	32,800 [r]
United Kingdom	734	3,430	17,200	159,000	1,340	1,230	19,200	163,000 [r]
Venezuela	11	48	1,230	11,100	--	--	1,240	11,200
Other	3,890 [r]	13,700 [r]	83,700	438,000	143,000	189,000	231,000	640,000 [r]
Total	310,000	730,000	1,150,000	5,270,000 [r]	1,550,000	2,450,000 [r]	3,010,000	8,450,000
2016:								
Brazil	126	298	5,260	44,200	75	104	5,460	44,600
Canada	91,500	184,000	437,000	1,500,000	109,000	202,000	637,000	1,890,000
China	489	2,030	35,200	245,000	690,000	916,000	726,000	1,160,000
France	5,870	19,600	11,700	112,000	2,800	10,200	20,300	142,000
Germany	1,470	6,080	9,540	96,500	5,090	5,140	16,100	108,000
Hong Kong	47	197	1,870	18,400	46,500	59,700	48,400	78,400
Italy	128	316	2,290	31,300	23	102	2,440	31,700
Japan	1,680	6,040	27,200	278,000	18,100	36,300	46,900	321,000
Kazakhstan	--	--	1	175	--	--	1	175
Korea, Republic of	587	3,460	33,200	260,000	145,000	191,000	179,000	454,000
Mexico	151,000	314,000	436,000	1,670,000	128,000	193,000	715,000	2,180,000
Netherlands	1,450	3,750	2,680	22,900	271	390	4,400	27,100
Philippines	1	8	428	4,810	1,740	1,540	2,170	6,360
Russia	3	40	53	1,140	2,170	5,380	2,230	6,560
Saudi Arabia	21	151	7,220	32,700	--	--	7,240	32,800
Singapore	141	1,610	2,840	32,300	--	--	2,980	33,900
South Africa	12	28	101	926	--	--	113	954
Taiwan	3,110	7,740	4,990	40,100	33,300	43,600	41,400	91,500
Thailand	159	306	5,570	29,300	3,570	4,540	9,310	34,200
United Kingdom	879	3,280	14,900	145,000	1,130	2,350	16,900	151,000
Venezuela	7	62	381	2,640	3	180	391	2,890
Other	3,390	12,000	162,000	642,000	164,000	212,000	330,000	866,000
Total	262,000	565,000	1,200,000	5,210,000	1,350,000	1,880,000	2,820,000	7,660,000

[r]Revised. -- Zero.
[1]Table includes data available through June 7, 2017. Data are rounded to no more than three significant digits; may not add to totals shown.
[2]Includes castings, forgings, and unclassified semifabricated forms.

Source: U.S. Census Bureau.

Interestingly, although the USA is a net exporter of aluminum semis, it is just barely. In 2016, the USA imported 1.18 Mt of aluminum semis while the country exported 1.2 Mt of aluminum semis. This near equivalence may be explained in part by the fact that the USA is one of few countries that has a near complete domestic aluminum industrial chain—that is the majority of aluminum, once it enters the USA at various stages along its life cycle, will remain in the USA for the rest of its life cycle until it becomes scrap (Liu and Müller Sept. 2013, p. 11878-3).

Looking more specifically at international flows of aluminum into and out of the USA, much of the country's bauxite comes from Jamaica while a large amount of bilateral trade of unwrought aluminum and semis occurs with Canada—which contributes to the common market integration of the USA and Canada within North America (Liu and Müller Sept. 2013, p. 11878-1). In 2016, Canada remained the leading aluminum source country for the USA, accounting for 54% of crude metal and alloys, 22% of semis, 60% of scrap, and 48% of total unmanufactured aluminum imports. Further, China accounted for 31% of USA semis imports, Mexico accounted for 22% of USA scrap imports, and Russia and the United Arab Emirates accounted for 17% and 13%, respectively, of USA crude aluminum metal and alloy imports. (Bray 2018, p 5.3-7)

Within the USA, the end-use domestic distribution of aluminum is of great accounting value. Industry statistics and LCI profiles compiled by AA may be able to provide detailed information about the end-use domestic distribution of aluminum semis in the USA, but without those datasets the USGS minerals yearbook for aluminum can again be consulted although it only provides end-use distribution of aluminum semis at the North American level. In 2016, the distribution of aluminum to these end-use sectors in the USA and Canada (Table A 3) are as follows: Transportation (35.2%), Containers and Packaging (18.0%), Building and Construction (12.3%), Electrical (7.0%), Consumer Durables (6.6%), Machinery and equipment (6.5%), Other Markets (2.6%) and Exports (11.8%). Notably, the transportation sector is, by a significant margin, the largest market for aluminum in the USA and Canada. Additionally, the distribution of North American aluminum supply in 2016 (Table A 4) are as follows: Primary Production

(33.6%), Secondary Recovery (37.2%), Imports of Ingot & Mill Products (27.5%), and Inventory Change and Other Adjustments to Supply (1.7%). Secondary recovery (secondary production), perhaps surprisingly, is the largest share of North American aluminum supply. It would be interesting to see the USA distribution of aluminum supply and how it varies from the North American aluminum supply knowing that the USA is a net importer of most aluminum products and net exporter of scrap. Subsequently, tracking the growth of secondary production in North American (and specifically in USA) aluminum supply will be of major interest as the aluminum industry hopes to operate more sustainably. Analyzing North American aluminum demand, the product distribution of aluminum producer shipments plus imports in 2016 (Table A 5) are as follows: Sheet, Plate & Foil (44.4%), Extrusions (20.8%), Electrical Wire & Cable (2.9%), Other (2.3%), and Ingot for Castings & Other (29.6%).

Table A 3: The distribution of end-use shipments of aluminum products in the USA and Canada by industry as reported in the 2018 USGS Minerals yearbook for aluminum (Bray 2018, p. 5.13)

TABLE 6
DISTRIBUTION OF END-USE SHIPMENTS OF ALUMINUM PRODUCTS
IN THE UNITED STATES AND CANADA, BY INDUSTRY[1]

	2015		2016[p]	
Industry	Quantity (thousand metric tons)	Percent of grand total[r]	Quantity (thousand metric tons)	Percent of grand total
Containers and packaging	2,140 r	17.8	2,160	18.0
Building and construction	1,420	11.8	1,470	12.3
Transportation	4,180	34.9	4,220	35.2
Electrical	800 r	6.7	836	7.0
Consumer durables	741	6.2	794	6.6
Machinery and equipment	768 r	6.4	784	6.5
Other markets	327	2.7	312	2.6
Total	10,400	86.5	10,600	88.2
Exports	1,620 r	13.5	1,410	11.8
Grand total	12,000 r	100	12,000	100

[p]Preliminary. [r]Revised.
[1]Table includes data available through August 3, 2017. Data are rounded to no more than three significant digits; may not add to totals shown.

Source: The Aluminum Association Inc.

Table A 4: The distribution of North American aluminum supply sources for the year 2016, as obtained from the Aluminum Association's free to the public industry statistics (Aluminum Association Facts at a Glance 2016, 2018)

North America Aluminum Supply (millions of pounds)		
Components of Supply	**2016**	**% of total**
Primary Production	8,879	33.6
Secondary Recovery	9,837	37.2
Imports of Ingot & Mill Products	7,266	27.5
Inventory Change and Other Adjustments to Supply	447	1.7
Total Supply	**26,428**	**100.0**

Source: The Aluminum Association, Aluminium Association of Canada, U.S. Geological Survey, U.S. Bureau of the Census

Table A 5: The distribution of North American aluminum demand, indicated by aluminum product shipments plus imports for the year 2016, as obtained from the Aluminum Association's free to the public industry statistics (Aluminum Association Facts at a Glance 2016, 2018)

Producer Shipments plus Imports (millions of pounds)		
Product Form	**2016**	**% of total**
Sheet, Plate & Foil	11,739	44.4
Extrusions	5,488	20.8
Electrical Wire & Cable	761	2.9
Other	618	2.3
Total Mill Products	18,606	70.4
Ingot for Castings & Other	7,822	29.6
Total Aluminum Demand	**26,428**	**100.0**

Source: The Aluminum Association

Another key takeaway about USA aluminum flow is that it is vulnerable to crisis. After three historical energy crises and the 2008 financial crisis, the aluminum industry tended to produce less alumina, less primary aluminum, fewer semis, fewer final products, and therefore import less bauxite and alumina but more unwrought aluminum and final products (Chen and Graedel 2012, p. 101-1).

Lastly, the aluminum tariff imposed by the USA on imported aluminum may feasibly decrease the amount of aluminum that the USA imports, although many USA firms and individuals that use aluminum have filed exemption requests. As of November 1st 2018, 4,105 aluminum tariff exemption requests have been filed and 23.9% of those requests have been responded to, with 840 exemption approvals and 141 exemption denials (QuantGov 2018). Even so, imported aluminum is here predicted to decrease and could potentially be reflected in 2017 and 2018 aluminum import data.

A.4.4 USA PRIMARY PRODUCTION

According to IAI, in 2017 the total amount of global, primary aluminum produced was 63.404 Mt (Table A 6) with China as the clear leader, producing 35.905 Mt and holding a 56.6% global production share, followed by Europe (7.775 Mt, 12.3%) and North America (3.950 Mt, 6.23%).

Table A 6: IAI Annual primary aluminum production estimates by world region (World Aluminum 2018)

PERIOD	AFRICA	ASIA (EX CHINA)	GCC	CHINA (ESTIMATED)	NORTH AMERICA	SOUTH AMERICA	WEST EUROPE	EAST & CENTRAL EUROPE	OCEANIA	ROW EST. UN-REPORTED	TOTAL	DAILY AVERAGE
2017	1,679	3,951	5,149	35,905	3,950	1,378	3,776	3,999	1,817	1,800	63,404	173.7
2016	1,691	3,442	5,197	32,641	4,027	1,361	3,779	3,981	1,971	1,800	59,890	163.6
2015	1,687	3,001	5,104	31,518	4,469	1,325	3,745	3,829	1,978	1,080	57,736	158.2
2014	1,746	2,429	4,832	28,317	4,585	1,543	3,596	3,764	2,035	1,080	53,927	147.7
2013	1,812	2,439	3,887	26,534	4,918	1,906	3,616	3,995	2,104	1,080	52,291	143.3
2012	1,639	2,535	3,662	23,534	4,851	2,052	3,605	4,323	2,186	780	49,167	134.3
2011	1,805	2,533	3,483	20,072	4,969	2,185	4,027	4,319	2,306	576	46,275	126.8
2010	1,742	2,500	2,724	17,331	4,689	2,305	3,800	4,253	2,277	732	42,353	116
2009	1,681	4,400	ND	13,684	4,759	2,508	3,722	4,117	2,211	624	37,706	103.3
2008	1,715	3,923	ND	13,585	5,783	2,660	4,618	4,658	2,297	732	39,971	109.2
2007	1,815	3,717	ND	12,588	5,642	2,558	4,305	4,460	2,315	732	38,132	104.5

Examining global trends in primary aluminum production over the past ten years, China has nearly tripled their aluminum production while North American aluminum production has dipped by 30%. Every other world region other than the Gulf Cooperation Council (GCC) has experienced similar dips in aluminum production. China's dominance in aluminum production has created tensions in the aluminum industry and as evident by the recent aluminum tariff imposed by the USA on international aluminum, holds the potential to alter global flow of aluminum.

Within North America, primary aluminum production totaled 0.741 Mt (1.17% global production share) for the USA (Table A 7) and 3.212 Mt (5.07% global production share) for Canada (Table A 8) in 2017 (Aluminum Association USA Primary Aluminum Production Report 2018, p. 3; Aluminum Association Canadian Primary Aluminum Production Report 2018). Interestingly, compared to 2017, primary aluminum production in the USA has increased in

2018. This can likely be attributed to the re-opening of the aluminum smelting plant in New Madrid county, MO (now owned and operated by Magnitude 7 Metals) in May of 2018 (Heller and Anderson 2018) and the partial re-opening of Alcoa's Warrick plant during the summer of 2018 (Martin 2018). Previous analysis of the domestic aluminum industry in 2010 identified nine operational smelters and characterized their energy intensities using various methods (Figure A 1), including a novel nested average electricity allocation protocol (Colett, et al. 2015, p. 30-1). An update to of the results from that study could be of interest. Between 2015 and 2017, the domestic aluminum industry was at its low, with only five smelters operational (Bray 2018, p. 5.10). Currently, there are seven operational aluminum smelters in the USA—Alcoa's Massena West, Intalco, and Warrick plants (Alcoa 2017), Century Aluminum's Hawesville, Sebree, and Mt. Holly plants (Home 2018; Bray 2018, p. 5.10), and the Magnitude 7 Metals plant. With the increase in primary aluminum capacity in the last year and the recently imposed aluminum tariffs on international aluminum, the domestic aluminum industry and domestic aluminum production can feasibly be projected to grow in coming years.

In this section, it is important to note that while Alcoa Corp. operates primary aluminum production in the USA, it is Arconic (the second independent, publicly traded company that Alcoa Inc. split into in 2016) that primarily operates aluminum semis production in the USA (Alcoa 2016).

Table A 7: USA primary aluminum production in 2017 and 2018 (Aluminum Association USA Primary Aluminum Production Report 2018, p. 3)

U.S. PRIMARY ALUMINUM PRODUCTION

(Metric Tons)

	Production		Average Daily Production		Annual Rate of Production	
	2018	2017	2018	2017	2018	2017
January	66,039	62,495	2,130	2,016	777,556	735,828
February	61,077	56,457	2,181	2,016	796,182	735,957
March	70,852	62,811	2,286	2,026	834,225	739,549
QTR Total	197,968	181,763	2,200	2,020	802,870	737,150
April	70,717	60,022	2,357	2,001	860,390	730,268
May	73,393	63,825	2,368	2,059	864,143	751,488
June	62,593	61,323	2,086	2,044	761,548	746,097
QTR Total	206,703	185,170	2,271	2,035	829,083	742,715
July	68,162	63,375	2,199	2,044	802,553	746,190
August	75,780	62,972	2,445	2,031	892,248	741,445
September	76,578	60,447	2,553	2,015	931,699	735,439
QTR Total	220,520	186,794	2,397	2,030	874,889	741,085
October	85,250	62,582	2,750	2,019	1,003,750	736,853
November		60,812		2,027		739,879
December		63,763		2,057		750,758
QTR Total		187,157		2,034		742,525
Current YTD	710,441	616,309	2,337	2,027	852,997	739,976
Total Year		740,884		2,030		740,884

Table A 8: Canadian primary aluminum production in 2017 and 2018 (Aluminum Association Canadian Primary Aluminum Production Report 2018)

Canadian Primary Aluminium Production

November 8, 2018 — The Aluminium Association of Canada reports that primary aluminium production in Canada in October 2018 totalled 246,790 metric tons. The monthly production was up 3.54% in comparison with the month of September 2018. The year-to-date average daily production is 8,024 tons. Compared to last year, the annual projection of production would be lower by -8.83%.

Production report for October 2018

(figures in metric tons)	Production		Average daily rate of production		Annual projection of production	
	2018	2017	2018	2017	2018	2017
January	255,664	274,590	8,247	8,858	3,010,237	3,233,076
February	224,713	247,616	8,025	8,843	2,969,766	3,230,464
March	248,831	275,002	8,027	8,871	2,956,439	3,232,951
Quarter	**729,208**	**797,208**	**8,100**	**8,857**	**2,978,814**	**3,232,164**
April	240,357	265,915	8,012	8,864	2,948,415	3,233,538
May	248,295	271,700	8,010	8,765	2,943,427	3,226,640
June	240,172	261,529	8,006	8,718	2,939,871	3,219,190
Quarter	**728,824**	**799,144**	**8,009**	**8,782**	**2,943,904**	**3,226,456**
July	247,417	271,606	7,981	8,761	2,936,052	3,216,154
August	248,681	273,389	8,022	8,819	2,935,047	3,216,502
September	238,343	263,602	7,945	8,787	2,931,135	3,215,464
Quarter	**734,441**	**808,597**	**7,983**	**8,789**	**2,934,078**	**3,216,040**
October	**246,790**	272,717	**7,961**	8,797	**2,928,597**	3,215,019
November	-	261,553	-	8,718	-	3,212,038
December	-	**272,905**	-	**8,803**	-	**3,212,138**
Quarter	**246,790**	**807,175**	**7,961**	**8,773**	**2,928,597**	**3,213,065**
Total year	**2,439,263**	**3,212,124**	**8,024**	**8,800**	**2,928,597**	**3,212,138**

Source: Aluminium Association of Canada (Participating companies include Alcoa Canada, Aluminerie Alouette Inc., and Rio Tinto)

A.4.5 USA RECYCLYING AND SECONDARY PRODUCTION

A considerable amount of aluminum has been moved from the lithosphere to the anthroposphere—an estimated 15% of known overall resources of aluminum existed as anthropogenic aluminum stock in 2010 (Liu and Müller March 2013, p. 4885-6). As a result of this, there exists an ever-accumulating potential for recycled aluminum and secondary production of aluminum.

The aluminum industry, understanding the energy intensity of primary aluminum production and in efforts to market its focus on sustainability, advocates for other industries to mine “the infrastructure of society” (e.g. cars, cans, buildings) (Bertram 2009, p. 650-1) and participate in secondary production rather than primary. Secondary production of aluminum converts aluminum scrap into new aluminum products and requires only 5-10% of the energy needed for primary aluminum production (Chen and Graedel 2012, p. 92-2).

As previously mentioned, secondary aluminum in North America represented 37.2% of the total aluminum supply in 2016. With North American primary aluminum production having declined 30% in the past ten years, the proliferation of secondary aluminum has helped satisfy domestic aluminum consumption together with aluminum imports.

In the USA, secondary aluminum recovery totaled 3.58 Mt in 2016, 1.58 Mt from old scrap and 2.10 Mt from new scrap (Bray 2018, p 5.9). Much of the aluminum recycling centers around the beverage and automotive industries. New scrap (fabrication scrap) recovery is covered in the next subsection and primarily refers to the aluminum that is recovered during manufacturing and fabrication processes. Old scrap (EOL scrap) recovery, which accounts for slightly less than half of USA total secondary aluminum recovery heavily depends on aluminum stock lifetimes, which vary with the product that the aluminum is contained in. Automotive aluminum has been shown to have an EOL recycling rate of 91% (Kelly and Apelian DATE UNKNOWN, p. 6-1).

According to Modaresi and Müller (Modaresi and Müller 2012, p. 8587-2): “The current practice for recycling of castings and mixed contaminated scrap deals with quality challenges by deploying two strategies that are often used in combination: (1) scrap is diluted with primary aluminum or low-alloyed scrap to reduce the alloy concentration below critical levels; and (2) recycled scrap is used in products with a higher alloy content, typically secondary castings, which are employed mainly in automotive applications.” Furthermore, they assert that because passenger cars are the primary employers of secondary castings—the major recipient of recycled aluminum from all sectors—they act as a bottleneck for secondary casting (Modaresi and Müller 2012, p. 8587-3). Modaresi and Müller ran a dynamic material flow model for the global vehicle system to assess the likelihood, timing, and extent of potential scrap surplus based on the passenger car bottleneck and concluded that the sum of scrap supply from passenger cars and additional aluminum resources for dilution exceeds secondary castings demand by 2018 for a baseline scenario (Modaresi and Müller 2012, p. 8592-3). Additionally, they provided several strategies to delay a scrap surplus including enhanced scrap sorting in the automotive industry, scrap recovery and sorting in nonautomotive sectors, and alternative applications for mixed or casting scrap (Modaresi and Müller 2012, p. 8593). Identifying the detailed end-use and product distribution of secondary aluminum could identify and further clarify bottlenecks that restrict the usage of secondary aluminum and sustainability of the aluminum industry.

Relatedly, the aluminum industry has long held the contention that the majority of recycled EOL automotive aluminum returns again to the automotive industry through secondary production, but the actual end-use distribution of secondary aluminum from EOL automotive aluminum is uncertain (Kelly and Apelian DATE UNKNOWN, p. 6-1). This uncertainty creates an interesting dock for future automotive aluminum research; analyzing the actual end-use distribution of secondary aluminum from EOL automotive aluminum could help characterize more accurately the recycled aluminum content of automotive aluminum.

Looking towards the future, secondary aluminum can feasibly be predicted to increase. Aside from the aluminum industry's promotion of secondary aluminum for sustainability purposes, the recent international aluminum tariff poses a threat to aluminum imports and although primary aluminum production capacity is projected to increase, secondary aluminum will likely also need to play a role in filling any aluminum deficit caused by the tariff.

A.4.6 USA FABRICATION (NEW) SCRAP

Fabrication scrap—otherwise known as new scrap—can provide key insights into the aluminum supply chain at the recycling and secondary production level. An important distinction in terminology should be made here between new scrap and internal scrap. While internal scrap and new scrap refer to the same material, that is aluminum scrap generated during manufacturing and fabrication processes, internal scrap is new scrap that is kept within the same company that it was generated and typically not reported in trade statistics.

New scrap generation rates in the fabrication and manufacturing process for different aluminum semis are reported by Chen and Graedel (Chen and Graedel 2012, p. S18) and shown in Table A 9. It is important to note that new scrap generation rate equals one minus the fabrication yield rate (material efficiency).

Table A 9: New scrap generation rates for aluminum semis (Chen and Graedel 2012, p. S18)

Table S. 5

New scrap generation rates in the fabrication and manufacturing processes

Sub-process	Internal	External	Total	Assumed based on
Foundry casting	94%	5%	99%	(The Aluminum Association, 1998) (European Aluminum Association, 2008; PE Americas, 2010)
Sheet & plate	32%	12%	44%	
Foil	25%	15%	40%	
Extruded products	29%	15%	44%	
Electrical conductor	34%	10%	44%	
Wire	39%	5%	44%	
Powder & paste	0%	0%	0%	
Forgings & impacts	20%	10%	30%	
C&P	-	20.5%	-	(PE Americas, 2010)
Sectors other than C&P	-	8.0%	-	-

Fabrication yield rates of aluminum by end-use sector from GARC are reported by Liu and Müller (Liu and Müller March 2013, p. S8) and shown in Table A 10. Notably, the transportation sector exhibits a fabrication yield of 80%. Further exploring the transportation sector, the auto and light truck fabrication yield rate is reported to be 84% (Liu et al. 2012, p. S13). The specific fabrication yield rates for automotive aluminum sheet cold stamping and extrusion are reported by Bushi—who used GREET 2017 to estimate the 54% fabrication yield rate of aluminum cold stamping (Bushi 2018, p. 51)—and shown in Table A 11. Combining the fabrication yield rate of aluminum cold stamping with the process scrap recycling yield rate and assuming a 100% scrap collection rate, it is calculated that 44% of the scrap incurred from aluminum stamping is recovered (0.957*0.46) and the overall fabrication yield of aluminum during cold stamping is 98% (0.54 + 0.957*0.46).

Table A 10: Fabrication yield rates of aluminum by end-use sector from GARC (Liu and Müller March 2013, p. S8)

Table S4. Fabrication scrap generation rate by product category (GARC 2011).

Product category	Building & Construction	Transportation	Containers & Packaging	Machinery & Equipment	Electrical Engineering	Consumer Durables	Others
Code	BC	Trans	C&A	M&E	EE	CD	Others
Fabrication Yield	90%	80%	75%	75%	85%	80%	80%

Table A 11: Fabrication yield rates for aluminum sheet cold stamping and aluminum extrusion (Bushi 2018, p. 51)

Table 11. Fabrication scrap and yield values per main material and fabrication technologies

Main auto parts fabrication technology	Auto part fabrication			Process scrap recycling	
	Yield[1] (%)	Amount of scrap (in kg/kg part)	Reference(s)	Yield (Y_f) (in %)	Reference
Aluminum sheet cold stamping[4]	54%	0.852	(44) (45)	95.7%	(26)
Aluminum extrusion	77.5%	0.290	(26)	95.7%	(26)
Steel sheet cold stamping[4]	54%	0.852	(44) (45)	91.6%	1/1.092kg (30)[3]
Steel sheet hot stamping[4]	54%	0.852	(44) (45)		
Steel sheet roll forming	95%	0.053	(46)		
Plastics injection molding[5]	95.7%	0.045	(33)	100%	(2)

[1] Fabrication yield is also known as "material efficiency", "material utilization";
[2] The Aluminum Association has developed two LCI profiles of secondary aluminum ingot (26): *Al recycling ingot (100% scrap)*, used to calculate the "Value of Al fabrication scrap" and *secondary aluminum ingot (primary metal and alloy added)*, used to calculate the "Value of Al EOL scrap". The definition of primary and secondary Al products is provided in Annex G;
[3] "Value of steel scrap" LCI profile [$=Y_f \times (E_{prim} - E_{sec})$] is calculated and provided in a rolled-up form by worldsteel (30). To avoid any data misuse, steel primary and secondary LCI profiles are not made available to LCA practitioners. The definition of primary and secondary steel products is provided in Annex G;
[4] The material efficiency for stamping is estimated to be 54% (90% for blanking and 60% for forming) for both steel and aluminum auto parts in GREET 2017 (44), (45)—see Section 8.2. The Baseline and AA LWT body systems use 91% and 90% cold stamped auto parts, respectively. The Baseline and AA LWT body systems use 2.7% and 3.4% hot stamped auto parts, respectively.
[5] Refers to NA data for injection molding of polypropylene, the most common thermoplasts used for auto parts.

A.4.7 USA TRANSPORTATION SECTOR

The transportation sector accounts for 35% of the total in-use aluminum stock in the USA (Chen and Graedel 2012, p. 99-Table 2), and as mentioned previously, in 2016 the transportation sector accounted for 35.2% of the end-use distribution of aluminum products in North America. Historically, a significant increase in the aluminum flow into the transportation sector occurred after 1990, when vehicle light-weighting started to gain major footing. After 1995, more than 35% of aluminum extruded semis were used by the transportation sector, and beginning around 2000, 60-75% of foundry castings were utilized by the transportation sector (Chen and Graedel 2012, p. 96-3).

The transportation sector can largely be broken down into the air, marine, rail, and automobile industries. Often when studies refer to the transportation sector, they do not distinguish these industries, but instead aggregate and analyze them as “transportation.”

AA divides the transportation sector into the “trailers and semitrailers,” “trucks and buses,” “passenger cars & light trucks,” “travel trailers & rec vehicles,” and “other” industries (Aluminum Association Sheet & Plate End Use Report 2010, p. 3). A sample of AA’s sheet & plate shipments by end use report, obtained from their website, is shown in Table A 12. Based on the sample provided, the passenger car & light trucks industry accounted for 35.6% of the sheet & plate shipments to the transportation sector in 2009.

Table A 12: USA and Canadian producers’ direct shipments of aluminum sheet & plate by end-use sample (Aluminum Association Sheet & Plate End Use Report 2010, p. 3)

Producers' Shipments of Aluminum Sheet & Plate by End Use
(Figures in thousands of pounds)

U.S. and Canadian producer mill direct shipments as reported by participating companies. Excludes distributor shipments to shared markets.

Select Market [1]	4th Qtr		% Chg	3rd Qtr	% Chg	Full Year		
(thousands of pounds)	2009	2008	4Q/4Q	2009	4Q/3Q	2009	2008	% Chg
Windows, doors & screens	12,456	11,830	5.3	15,236	-18.2	49,102	65,296	-24.8
Awnings & canopies	2,553	2,721	-6.2	5,244	-51.3	13,403	15,248	-12.1
Residential siding, roofing, sofits & fascia [2]	73,512	79,999	-8.1	100,519	-26.9	317,322	391,227	-18.9
Commercial, industrial, rural roofing & siding	16,059	13,031	23.2	13,661	17.6	52,944	51,769	2.3
Curtain wall, store fronts & entrances	3,376	4,849	-30.4	4,472	-24.5	16,005	18,948	-15.5
Bridge, street & highway	4,918	3,435	43.2	5,731	-14.2	18,868	28,770	-34.4
Gutters & downspouts	51,275	44,475	15.3	65,220	-21.4	205,863	219,258	-6.1
Other	30,668	26,021	17.9	33,640	-8.8	116,514	134,655	-13.5
Total Building & Construction	194,817	186,361	4.5	243,723	-20.1	790,021	925,171	-14.6
Trailers and semitrailers	22,105	19,760	11.9	19,399	13.9	77,564	138,456	-44.0
Trucks and buses	10,570	10,118	4.5	9,998	5.7	36,458	62,092	-41.3
Passenger cars & light trucks	68,867	70,714	-2.6	58,852	17.0	220,649	337,216	-34.6
Travel Trailers & Rec Vehicles	8,302	3,798	118.6	6,860	21.0	25,229	42,029	-40.0
Other	60,289	76,720	-21.4	61,751	-2.4	259,853	302,620	-14.1
Total Transportation	170,133	181,110	-6.1	156,860	8.5	619,753	882,413	-29.8

A.4.8 USA AUTOMOTIVE INDUSTRY

The North American light vehicle industry is valued at $416 billion (American Chemistry Council 2018, p. 2-1). The industry is a heavy end user of aluminum as vehicle light-weighting practices to increase fuel economy continue progressing.

The average aluminum content of North American vehicles as a percent of total vehicle weight has been reported as 10.5% in 2017 by the American Chemistry Council (American Chemistry Council 2018, p. 6) and 11% (in 2016) by Ducker Worldwide (Ducker Worldwide 2017, slide 14). Moreover, Ducker Worldwide summarized the nearly 100 key components that they tracked into approximately 30 key components and systems and created a graph (Figure A 7) to indicate the net pounds of aluminum per vehicle of each key component or system (Ducker Worldwide 2017, slide 20). Additionally, they circled the components that they predicted will increase in net pounds of aluminum per vehicle in 2020. In 2006 the USGS reported that aluminum stocks contained within automobiles in use, as a percentage of all aluminum stocks in use within the USA, was 13.8%—a number estimated by utilizing a bottom-up accounting approach (Buckingham, 2006, p. 2-Table 2). Further, 57% of all automotive aluminum was sourced from recycled metal in 2006 and more than half of all engine blocks manufactured in North America were made from recycled aluminum in 2009 (USITC 2010, p. 26-1)

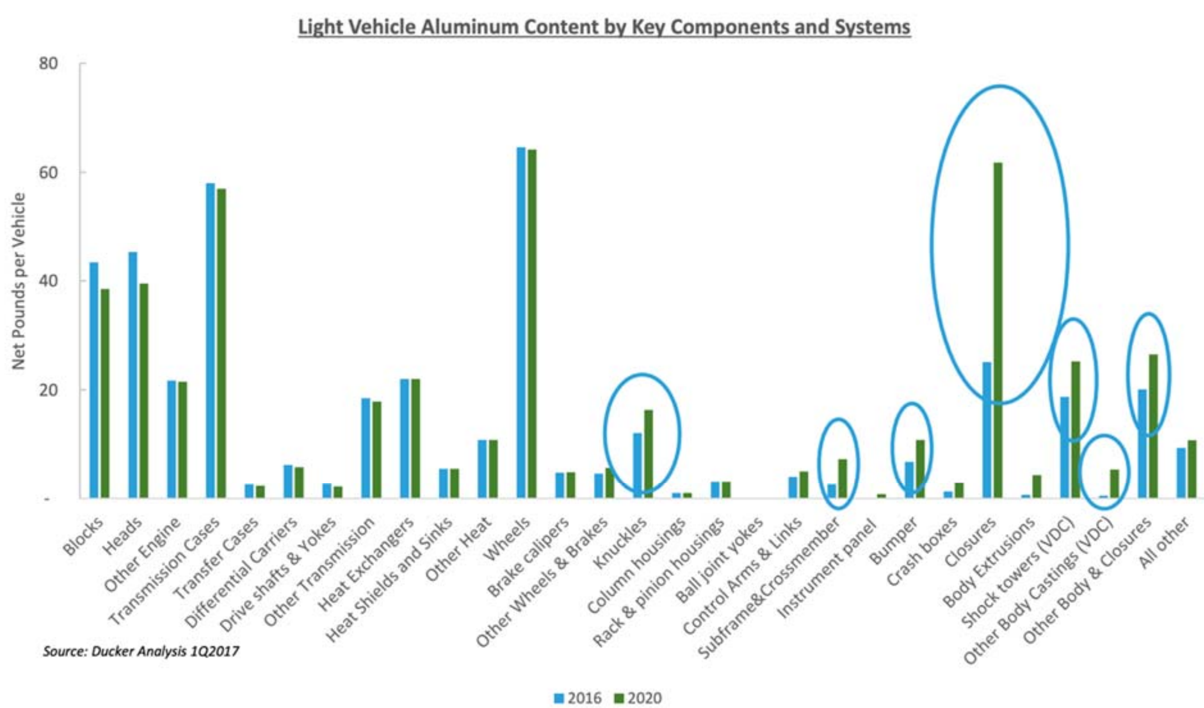


Figure A 7: Ducker Worldwide's graph depicting net pounds of aluminum per vehicle by key component or system (Ducker Worldwide 2017, slide 20)

To identify aluminum flow into the USA automotive industry, AA's industry statistics and LCI profiles may be of valuable use. *We are in the process of obtaining such data.*

Aside from direct insight from AA, automotive material in-use stocks can be determined by two methods—bottom-up analysis and flow-based monetary data analysis—as described in a 2017 article by Chen (Chen 2017, p. S1-7). The study analyzed the transportation sector as a whole but also detailed automotive industry specifics by analyzing aluminum in-use stocks of light vehicles (passenger cars, light-duty trucks). The bottom-up method used Bureau of Transportation Statistics data on passenger car and truck stock and Ducker Worldwide's calculated aluminum contents for passenger cars and trucks to calculate aluminum stock in passenger cars, two-axle four-tire trucks, and heavy single-unit trucks. It should be noted that the study was sponsored by AA.

Reviewing published news articles, some insights on the relationship between the aluminum industry and the USA automotive industry can be identified. A March 12, 2018 article for Automotive News by Michael Marinez stated: "The aluminum Ford uses to build the F-150 comes mainly from two USA suppliers: Novelis and Arconic. Ford said 98 percent of its aluminum comes from the USA, as does 95 percent of its steel. Arconic supplies virtually all of its aluminum from plants in Iowa, Tennessee, Pennsylvania and Texas. It's unclear where Novelis gets aluminum for the F-150, but the company gets roughly one-third of its aluminum from Canada, while the rest comes from the USA, Steve Fisher, the company's CEO, said last week on CNBC." Charles Uthus of the American Automotive Policy Council (AAPC), on a 12/05/18 call, noted that the major USA automotive OEMs (Ford, FCA US, and GM) source 90%+ of their aluminum and steel domestically (although here the term "domestically" was unclear if it was in reference to the USA exclusively or North America as a whole). Further, the recent USMCA trade agreement, which retained the 10% tariff on imported aluminum (including aluminum from Canada and Mexico) also requires that 70 percent of automotive aluminum be sourced from North America (Fergusson and Villarreal 2018). In contrast, a May 7, 2017 article for Automotive News by David Sedgwick stated that "…other competitors -- such as Aleris International Inc. of Ohio, Constellium of the Netherlands and UACJ Corp. of Japan -- are piling into North America's automotive market," suggesting that the presence of imported aluminum in the USA automotive industry will increase in subsequent years. The uncertainty of automotive aluminum sourcing in the near future supports the need for automotive aluminum material flow analyses to be conducted and updated repeatedly in order to capture an accurate snapshot of the industry's supply chain.

Exploring internal scrap within the automotive industry, in April 2017 Ford Motor Company announced that in three of its factories (two of which produce F-Series trucks), a closed-loop scrap recycling system recycles 20 million pounds of aluminum a month from fabrication processes (internal scrap), which the company asserts could be used to produce 37,000 F-Series truck bodies a month, implying that each F-Series truck contains approximately 540lbs of aluminum. This internal recycling of fabrication scrap holds the potential to reduce Ford's semis requirements from aluminum manufactures and could be reflected in the 2017 and 2018 end-use distribution statistics of aluminum into the passenger cars and light duty trucks industry.

While strategies exist to calculate the aluminum stock in passenger cars & light duty trucks (whether that be through direct data from AA or bottom-up accounting estimations), identifying where the aluminum stock in passenger cars & light duty trucks comes from, across a temporal axis, remains a major challenge.

A.4.9 ALUMINUM QUALITY

The 6XXX series heat-treatable alloys (HTAs) and 5XXX series non-heat-treatable alloys (NHTAs) are commonly used aluminum grades for auto body parts (Bushi 2018, p. 24-1). Additionally, in in one of the original aluminum material flow analysis papers, by Hatayama et al. in 2007, 1000 series, 3003, 4000 series, 5052, other 5000 series, 6063, and 7000 series aluminum alloys were all identified in automobiles (Hatayama et al. 2007, p. 2520). The table depicting the allocation of these alloys to various vehicle parts is shown in Table A 13 but is limited to only three automobile categories: heat exchanger, engine, “other.” Exploring automotive aluminum quality more, most engines are identified to be from aluminum casting alloys 319, A356, or A357 (Carly 2017). A more comprehensive table correlating alloy designation in automobile parts is provided by UACJ and a link to the table is included here (https://uacj-automobile.com/types_and_applications.html).

Table A 13: Aluminum alloys used in automobiles (Hatayama et al. 2007)

2520 H. Hatayama, H. Yamada, I. Daigo, Y. Matsuno and Y. Adachi

Table 4 Identifiable and inferable elements defined by end use and alloy.

		Foil	Fabricated metal	Beverage can		General machinery	Electric communication machinery		Automobile			Construction	Other products	Exports
				Body	End/Tab		Fin	Other	Heat exchanger	Engine	Other			
Mill products	1000 series	++	+			+	+	+	+		+			
	2000 series													
	3003						+	+	+					
	3004			++										
	Other 3000 series			++								+		
	4000 series								++					
	5052		+		++	+		+			+	+		
	5182				++								*	
	Other 5000 series					+					+	+		
	6061		+					+				+		
	6063		+			+		+			+	+		
	Other 6000 series							+				+		
	7000 series		+								+			
	8000 series													
Castings			++			++		++		++				
Die-castings			++			++		++		++				

++; Identifiable element
+; Inferable element
*; Calculated element
Blank; Null

A.5 STATE OF KNOWLEDGE: STEEL

A.5.1 STEEL PRODUCTION PROCESS

The production of steel consists of two major processes and stages: production, and fabrication and manufacturing. While, nomenclature may alter between studies, all major studies in the industry break down the production of steel into these categories, which are the first two processes in a material flow analysis.

The first process is production or the mining and processing of raw materials, including mill operations. Steel production consists of three steps. First, a blast furnace burns coke and reduces iron ore (~60% iron) to molten pig iron (~94% iron), forming the byproduct slag (Wang 2007, 5120-9). Next, the process of steel-making eliminates remaining impurities and produces steel from raw iron (>98% iron) either using a Basic Oxygen Furnace (BOF) or an Electric Arc

Furnace (EAF) (Wang 2007, 5121-1). A key difference is input material for each furnace, with BOFs utilizing pig iron, while EAFs may use up to 100% iron scrap. Molten steel output from both furnace types is rolled and fabricated into desired shapes, known as semi-finished products or "semis". Iron production consists of foundries which produce iron castings by remelting pig iron and other scrap (Wang 2007, 5121-1). All semis then leave the production mills and are transported for further processing, including international and domestic trade (Wang 2007, 5121-1). Defective products and edge trimmings accumulate in steel mills and foundries and are known as "home scrap", which are typically recycled directly into the furnaces. Other byproducts (e.g., slag, sludge) are either recycled within the mills or recycled as construction aggregate.

Through the Fabrication and Manufacturing process, semis are processed into finished products which flow into in-use stocks, which are typically broken down into five categories: (1) buildings, (2) industrial machinery, (3) transportation, (4) Appliances, and (5) other. Cuttings and defective products, known as "industry scrap", are processed with other scrap and recycling through the end-of-life processes. Typically, 10-15% of fabricated products end up as scrap (Wang 2007, 5121-8).

While, not a process in steel production, recycling is an important input into iron and steel production. Recycling is the process for handling iron discards from in-use stock and scrap from fabrication. The recovered portion of in-use discards is known as "obsolete scrap" or "old scrap". Obsolete scrap is mixed with industrial scrap and the mixture is known as "purchased scrap". These scrap flows serve as major input resources for steel production.

A.5.2 GLOBAL STEEL INDUSTRY

Despite a reduction in world steel demand following the global recession in 2008, steel production and consumption continues to grow each year. Demand in 2018 will reach 1,616.1 Mt (a 1.8% increase over 2017) and is expected to grow another 0.7% in 2019 to 1,626.7 Mt (Worldsteel Outlook 2018, p. 1-1). Steelmaking capacity has more than doubled from 1,060 Mt in 2000 to 2,320 Mt in 2014. Following the global financial crisis, the demand for steel has underperformed this growth in capacity. In 2009, global overcapacity exceeded 500 Mt for the first time, and has subsequently grown to 700 Mt with utilization rates hovering around 70%. This increase in overcapacity was driven by an increase of capacity in China from 771 Mt in 2000 to 1,200 Mt just 15 years later, forcing production utilization rates across the world below the 80% mark necessary for long-term industry profitability (Fenton 2015, p. 37.1-1).

By 2017, Chinese steel production accounted for nearly half of the world's raw steel production with their exports exceeding 800 Mt, and Chinese pig iron production accounted for over half of the world's production (Fenton 2018, p. 83-5). China is only recently a leader in steel consumption and production, leading to shortages in steel scrap, as all steel stock is still in the use phase. Large amounts of steel scrap are expected in the near future, dramatically increasing the opportunity for scrap to be a major material input for further steel production (see later section on Chinese steel flow).

Other leading steel producers include Japan, Russia, Korea and the United States (Table A 14).

Table A 14: Global Raw Steel and Pig Iron Production in Mt, 2016-2017 (Fenton 2018, p. 83)

World Production:

	Pig iron		Raw steel	
	2016	2017[e]	2016	2017[e]
United States	22	23	78	82
Brazil	25	28	31	34
China	704	730	808	843
France	10	11	14	16
Germany	28	28	42	44
India	62	65	96	99
Japan	81	78	105	104
Korea, Republic of	46	47	69	70
Russia	52	60	71	70
Taiwan	15	15	22	23
Turkey	10	11	33	37
Ukraine	24	20	24	21
United Kingdom	6	6	8	8
Other countries	70	79	209	224
World total (rounded)	1,160	1,200	1,610	1,700

World production of pig iron in 2017 totaled 1,200 Mt and production of raw steel in 2017 totaled 1,700 Mt (Fenton 2018, p. 83-5). Total world production of finished steel exceeded 1,626 Mt (Worldsteel Outlook 2018, p. 1-1). Global demand is similarly dominated by China, Japan, the USA, Russia and Korea, with the inclusion of India and Germany as key consumers (Table A 15). The world's leading steelmakers are ArcelorMittal (97.0 Mt) and China Baowu Group (65.4 Mt) (Worldsteel Top Steel Makers 2017, p. 1-1).

Table A 15: Top 10 Steel Consuming Countries in 2017 in Mt (Worldsteel Outtloke 2018, p. 1)

SRO April 2018, finished steel products

Countries	million tonnes 2017	2018 (f)	2019 (f)	y-o-y growth rates, % 2017	2018 (f)	2019 (f)
China	736.8	736.8	722.1	8.3	0.0	-2.0
United States	97.7	100.3	102.3	6.4	2.7	2.0
India	87.2	92.0	97.5	4.3	5.5	6.0
Japan	64.4	64.5	64.9	3.7	0.1	0.6
South Korea	56.4	57.0	57.5	-1.2	1.0	1.0
Germany	41.8	42.0	41.9	3.1	0.5	-0.2
Russia	40.6	41.5	42.1	5.1	2.1	1.4
Turkey	36.1	37.9	39.8	5.8	5.0	5.0
Mexico	26.4	27.3	27.7	4.0	3.5	1.5
Italy	24.5	24.9	25.2	1.8	1.7	1.1

f - forecast

A.5.3 USA STEEL INDUSTRY

In the United States, the value of iron and steel industry production was approximately $147 billion in 2017 compared to $130 billion in 2016. Production capacity was 111 Mt (~3.8% of world production). Pig iron was produced by three companies with integrated steel mills in nine locations, while raw steel was produced by 54 companies at 110 minimills (Fenton 2018, p. 82-1). Table A 16 outlines steel production from 2013 to 2017 in the United States.

Table A 16: United States Steel Industry Production and Consumption Statistics, 2013-2017 (Fenton 2018, p.82)

Salient Statistics—United States:	2013	2014	2015	2016	2017[e]
Pig iron production[2]	30.3	29.4	25.4	22.3	23
Raw steel production	86.9	88.2	78.8	78.5	82
Basic oxygen furnaces, percent	39.4	37.4	37.3	33.0	32
Electric arc furnaces, percent	60.6	62.6	62.7	67.0	68
Continuously cast steel, percent	98.8	98.5	99.0	99.4	99
Shipments:					
Steel mill products	86.6	89.1	78.5	78.5	83
Steel castings[e, 3]	0.4	0.4	0.4	0.4	0.4
Iron castings[e, 3]	4.0	4.0	4.0	4.0	4.0
Imports:					
Steel mill products	29.2	40.2	35.2	30.0	36
Semifinished products	6.6	9.6	6.6	6.1	8.4
Exports, steel mill products	11.5	10.9	9.0	8.4	11
Consumption, apparent (steel)[4]	98	107	99	95	100
Producer price index for steel mill products (1982=100)[5]	195.0	200.2	177.1	167.8	188
Stocks, service centers, yearend[6]	7.6	9.0	7.5	6.6	7
Total employment, average, number:					
Blast furnaces and steel mills[5]	90,900	91,000	87,000	83,600	83,000
Iron and steel foundries[5]	69,400	67,600	64,900	65,000	64,000
Net import reliance[7] as a percentage of apparent consumption	12	30	22	17	18

By state, Indiana leads the nation accounting for 27% of domestic production followed by Ohio (12%), Michigan (6%) and Pennsylvania (6%) (Fenton 2018, p. 82-1). The large discard rate of in-use stock, due to the decades of steel product accumulation, allows the USA to recycling significant levels of steel scrap – secondary resources contribute approximately 60% of the raw materials for domestic crude steel production (Wang 2007, 5122-13).

In order to fulfill the large consumer demand for steel in the United States, the nation imports large amounts of iron ore, steel mill products and manufactured goods (Wang 2007, 5122-13). NAFTA imported 17.0 Mt of steel in 2017 from Asia, including Japan and China, although 10.7 Mt was imported from other Asian countries (Worldsteel Stats Yearbook 2017).

Internal NAFTA trading totaled 19 Mt as goods moved significantly between the three free trade countries.

A.5.4 STEEL RECYCLING

Due to its versatility, steel has become the most utilized metal, and as a result produces 9% of global energy-related carbon emissions (Pauliuk 2011, 148-2). As global awareness around climate change increases and pressure to reduce greenhouse gas emissions mounts, the steel industry is dedicating more and more resources to the exploration of increased recycling and reuse. Secondary use of steel scrap can dramatically reduce the carbon emissions of the steel industry, while limiting raw material extraction and consumption. There are three main forms of steel scrap: home scrap is waste steel generated during steel production; prompt scrap is the steel waste from the steel good manufacturing processes; and post-use scrap is the steel waste recovered from obsolete steel goods (e.g., end-of-life vehicles or buildings) (Michaelis 2000, 138-1).

In 2014 (the most recent year of data), 55 Mt of steel was recycled, derived mostly from appliances, automobiles, cans, and construction materials. The recycling rate was about 81% of steel scrap. The reduced energy needs equate to the electrical demand in one year for one-fifth of all American households (Fenton-Scrap 2015, 38.1-2).

Just as raw steel, steel semis and steel finished products are globally traded, steel scrap is a traded commodity. The United States is the leading exporter of steel scrap, exporting 13.0 Mt in 2015 compared to Japan (7.8 Mt), Germany (7.5 Mt), and the U.K. (7.3 Mt). The USA steel scrap surplus totaled 9.2 Mt ($3.1 billion) in 2015, although it has decreased in recent years. It is important to note the increase need for a steel scrap market and industry in China as steel consumption grows rapidly in that country. Dramatic increases in steel consumption in China will lead to a sharp rise in steel scrap availability in China between 2025 and 2050 (Pauliuk 2011, 153-6). This new influx of scrap to the industry will require the development of a circular economy that will greatly alter the steel industry and potentially sharply decrease the requirement for virgin steel production.

Within the automotive industry, 18 Mt of steel is recycled from cars each year – a typical car is 60% iron and steel, with about 25% of the body made from recycled steel. The amount of steel recycled from the automotive industry compared to the amount of steel consumed in the industry annually is nearly a 100% rate of recycling (Fenton-Scrap 2015, 38.1-3). End-of-life vehicles (ELV) and the subsequently derived steel scrap (ELV-dSS) face quality issues as end-of-life processes include a mix of metals and alloys due to inefficient and inexact sorting / separating processes. These incomplete processes create an open rather than closed-loop recycling cycle, leading to degradation in metal quality, particularly around copper contamination, a process known as down-cycling (Nakamura 2012, 9266-3). Typical recycling processes remove copper-containing components, reusable components and non-reusable parts before mixing and shredding the rest together. Contamination is most commonly caused by copper accumulating, but it can also be caused by alloy elements such as chromium, which are consumed by the auto industry for alloy element enriched steel (Ohno 2015, 12-2). Ohno et al. discusses key methods for sorting scrap to maintain key material properties and composition without quality degradation (Ohno 2015, 16-1). Continued attention to scrap cycle are required in the steel automotive industry as recycling becomes more prominent and as specialized steels are used more for lightweight, high strength applications.

A.5.5 USA AUTOMOTIVE STEEL INDUSTRY

In the automotive industry, steel and iron make up a large portion of a typical vehicle's composition. By weight, iron and steel account for 60% of the average modern automobile, composing nearly all of the vehicle's frame, body, suspension, exhaust, radiator and drivetrain (Table A 17) (Ward 2018). Auto steel is unique in that it requires exceptionally high-quality standards, particularly regarding wear resistance and impact resistance for exposed steel sheets.

Table A 17: Average Materials Content of North America Light Vehicles, 2013-2016 (Ward 2018, p. 1)

	2016		2015		2014		2013	
Material	**Pounds**	**Percent**	**Pounds**	**Percent**	**Pounds**	**Percent**	**Pounds**	**Percent**
Regular Steel	1,335	33.2	1,330	33.3	1,342	34.2	1,354	34.7
High and Medium Strength Steel	742	18.4	701	17.6	649	16.5	627	16.1
Stainless Steel	74	1.8	75	1.9	73	1.9	74	1.9
Other Steels	32	0.8	32	0.8	32	0.8	32	0.8
Iron Castings	249	6.2	268	6.7	278	7.1	271	6.9
Aluminum	410	10.2	395	9.9	368	9.4	355	9.1
Magnesium	11	0.3	10	0.2	10	0.2	10	0.3
Copper and Brass	66	1.6	66	1.7	68	1.7	70	1.8
Lead	35	0.9	35	0.9	36	0.9	35	0.9
Zinc Castings	8	0.2	8	0.2	8	0.2	8	0.2
Powder Metal	44	1.1	45	1.1	46	1.2	45	1.2
Other Metals	5	0.1	5	0.1	4	0.1	5	0.1
Plastics and Plastic Composites	332	8.3	334	8.4	329	8.4	328	8.4
Rubber	199	4.9	198	5.0	196	5.0	198	5.1
Coatings	28	0.7	29	0.7	28	0.7	28	0.7
Textiles	44	1.1	45	1.1	49	1.2	50	1.3
Fluids and Lubricants	226	5.6	225	5.6	224	5.7	222	5.7
Glass	93	2.3	95	2.4	96	2.4	96	2.5
Other Materials	92	2.3	95	2.4	93	2.4	92	2.4
Total	**4,026**	**100.0**	**3,991**	**100.0**	**3,928**	**100.0**	**3,900**	**100.0**
Pounds per vehicle. Data reflects light vehicles built in North America. Source: American Chemistry Council.								

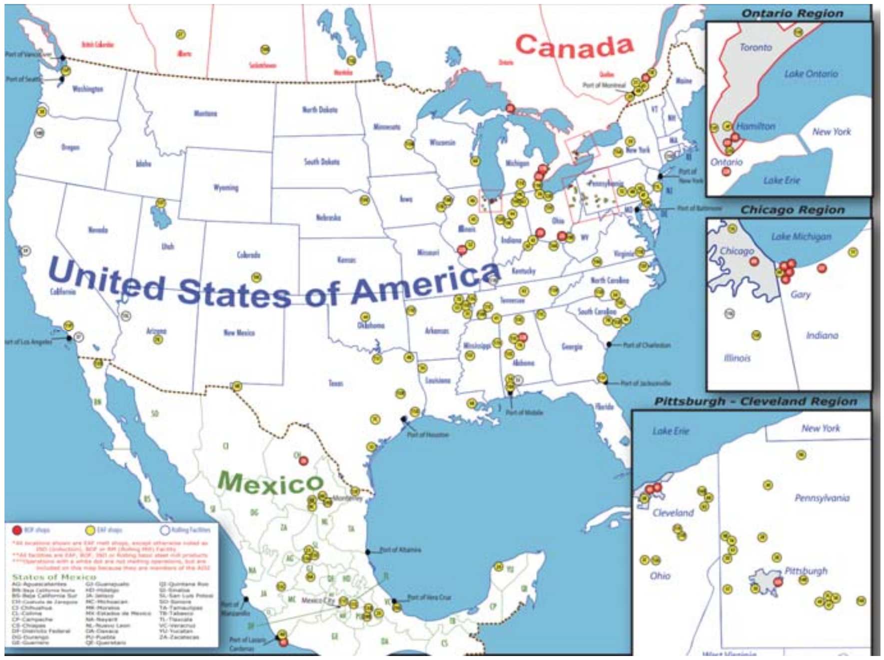


Figure A 8: Domestic Steel Plant Locations across North America (AISI Steel Plant NA, 2013)

The future of the auto steel industry depends on its ability to compete with aluminum and other lightweight materials as auto manufacturers are increasingly pressured to increase fuel efficiency. Thus, lighter, stronger steels have been developed for deployment in new vehicle models. High-strength steel consumption in North American vehicles is projected to increase 76% by 2025 over 2015 levels; while global auto demand for press-hardened steel sheet is projected to increase 26% by 2020 (Fenton 2018, p. 83-3).

A.5.6 USA AUTOMOTIVE STEEL STOCK

In 2005 the USGS reported that 5.3% of all USA steel stock in use was in the automotive industry. At the time, this included 217 million automobiles at 2,210 lbs of steel per car (Table A 18) (USGS 2005, 1-6). In 2006, Muller et al. studied the anthropogenic iron cycle and closely estimated the steel stock in the transportation sector. They considered both a bottom-up approach, using relevant products and their compositions, and a top-down approach, using historic trade data and estimated lifetime distributions. Ultimately the study used a top down approach to analyze historical patterns of the stock (Muller 2006). Transportation product lifetimes are considered to be 15, 20 or 25 years with a deviation of 7.5 years. The final transportation steel stock in the USA was estimated at 650 Tg (Muller 2006, 16112).

Table A 18: Automotive Stock Statistics including Average Steel Content (USGS 2005, p. 2)

Autos and steel stocks	Calendar year								
	Mid-1960s	1970	1975	1980	1985	1990	1995	2000	2001
Automobiles in use, in millions of units	90.6	98.1	120	140	157	179	193	213	217
Average steel content per vehicle in use, in pounds	3,000	3,050	3,160	2,950	2,680	2,410	2,260	2,220	2,210
Steel stocks contained within automobiles in use, in Mt	125	136	172	187	191	196	198	214	217
All steel stocks in use, in Mt	1,702	2,210	2,570	2,920	3,180	3,410	3,660	4,010	4,070
Steel stocks contained within automobiles in use, as a percentage of all steel stocks in use	7.3	6.2	6.7	6.4	6.0	5.7	5.4	5.3	5.3

In 2009, a study used both a top-down and a bottom-up approach to evaluate the USA automotive steel stock (Hirato 2009, 1967-1). Steel stock in the automotive industry was estimated based on Muller et al. 2006, assuming 90% of transportation stock is used in the automotive industry (transportation includes automobiles, railroads, aircraft and more). They estimated the steel automotive stock in the USA to be 480 Mt to 870 Mt based on the vehicle lifetime assumption. From a bottom up perspective, the steel stock in the USA was estimated to be 754 Mt to 767 Mt (Hirato 2009, 1967-1).

Both the top-down and bottom-up approaches used to estimate the steel stock in the automotive industry present pros and cons, particularly around ease of data collection and uncertainty. For the bottom-up approach, data collection can become cumbersome due to its sheer quantity. Also, variations in the production year of automobiles in the current stock create uncertainty around the steel composition of an average vehicle. For the top down approach, uncertainty is introduced by the unknown length of life of a vehicle. It is further important to recognize that assumptions are likely to vary greatly from country to country (Hirato 2009, 1971-2).

A.6 MATERIAL FLOW ANALYSIS OVERVIEW

The industrial application of metals has significantly removed stocks of metals from the lithosphere and into the anthroposphere. In order to analyze the material cycles of these metals and the environmental impacts associated with those material cycles, the method of material flow analysis (MFA) in industrial ecology has been pioneered in the last two decades. The main goals of MFA models are: 1. To gain a better understanding of past and current metal stocks and flows, 2. To show change over time, 3. To predict global future scrap flows and the extent to which future worldwide metal market demand will be met by recycling versus new smelter capacity, 4. To develop scenarios for inventories of future industrial greenhouse gas emissions, and 5. To forecast the energy and ecological benefits of increased recycling rates, the use of metal products in energy saving applications, and potential improvements in industry efficiency (Bertram et al., 2009).

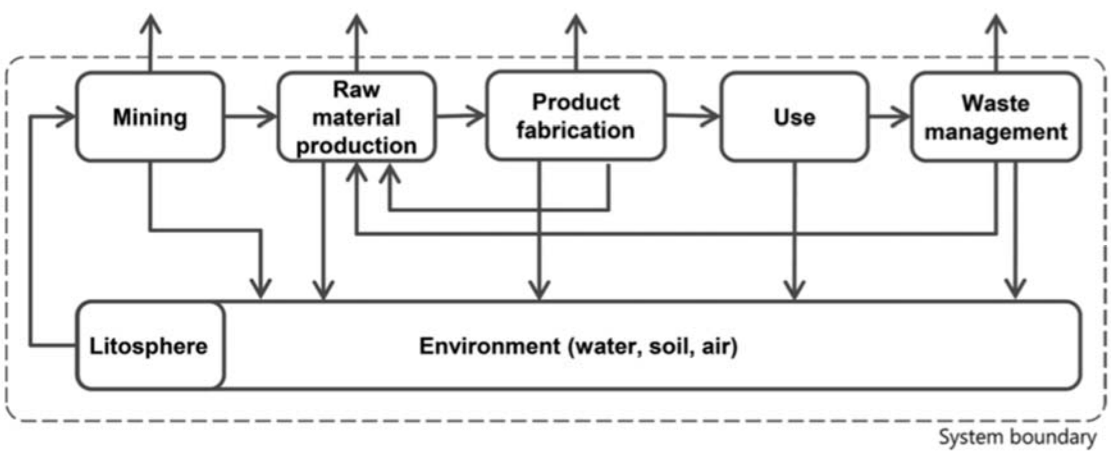


Figure 1. System overview of a generic dynamic material flow model of metals.

Figure A 9: System Overview of a Generic Dynamic Material Flow Model (Muller et al. 2014)

Material flow analyses generally follow the life cycle of a metal from lithosphere mineral extraction, along the metal's supply and production chain, into a final product that enters the anthropogenic use phase, and finally to end-of-life waste management practices that either recycle or dispose of the metal (Figure A 9). The two major MFA approaches are the top-down approach and bottom up approach. The top-down approach is the most commonly used, suited well for larger spatial scales, and analyzes all flows into or out of a clearly defined system and aggregates stocks over time while the bottom-up approach is beneficial for smaller spatial dimensions, where production and trade data may be lacking, and is based upon empirical statistics of different products in use or in waste flows within a specific geographic region at a given point in time and assumptions of the average metal content per product (Glöser et al., 2013).

In the following sections, specific MFA methods for steel and iron and aluminum in the literature will be investigated to identify key strategies that will inform an MFA of steel and iron and aluminum into the USA automotive industry.

A.7 MFA METHODS: ALUMINUM

The pioneering of material flow analysis in the aluminum industry is often accredited to Martchek (Martchek 2006) and Hatayama (Hatayama 2007), with Chen, Graedel, Liu, and Müller further expanding the state of knowledge of the aluminum industry in subsequent MFAs. The methods of key studies that have highlighted dynamic stocks and flows and product-level analysis of aluminum stocks in the USA, the global trade of anthropogenic aluminum, and the evolution of global aluminum stocks are reported here.

A.7.1 CHEN AND GRAEDEL 2012

In 2012, Chen and Graedel utilized a top-down material flow analysis to characterize the cumulative aluminum stocks and flows in the USA between 1900-2009. In order to do so, they reported all stocks and flow values as average annual mass of aluminum in its pure form while also categorizing aluminum stocks and flows into four groups. Their categories of aluminum stocks were: bauxite ore stocks, in-use stocks, hibernating stocks, and loss stocks (from tailing ponds, slag repositories and landfills, obsolete stocks and exports of EOL products, and non-metallic use). Their categories of aluminum flows were: trade flows, loss flows, transformation flows (that is the transformation of aluminum from chemical compounds to refined metal), and recycling flows of aluminum scrap (both old and new). The system boundaries that Chen and Graedel established for their study is shown in Figure A 10 and symbol definitions for the system are given in Figure A 11.

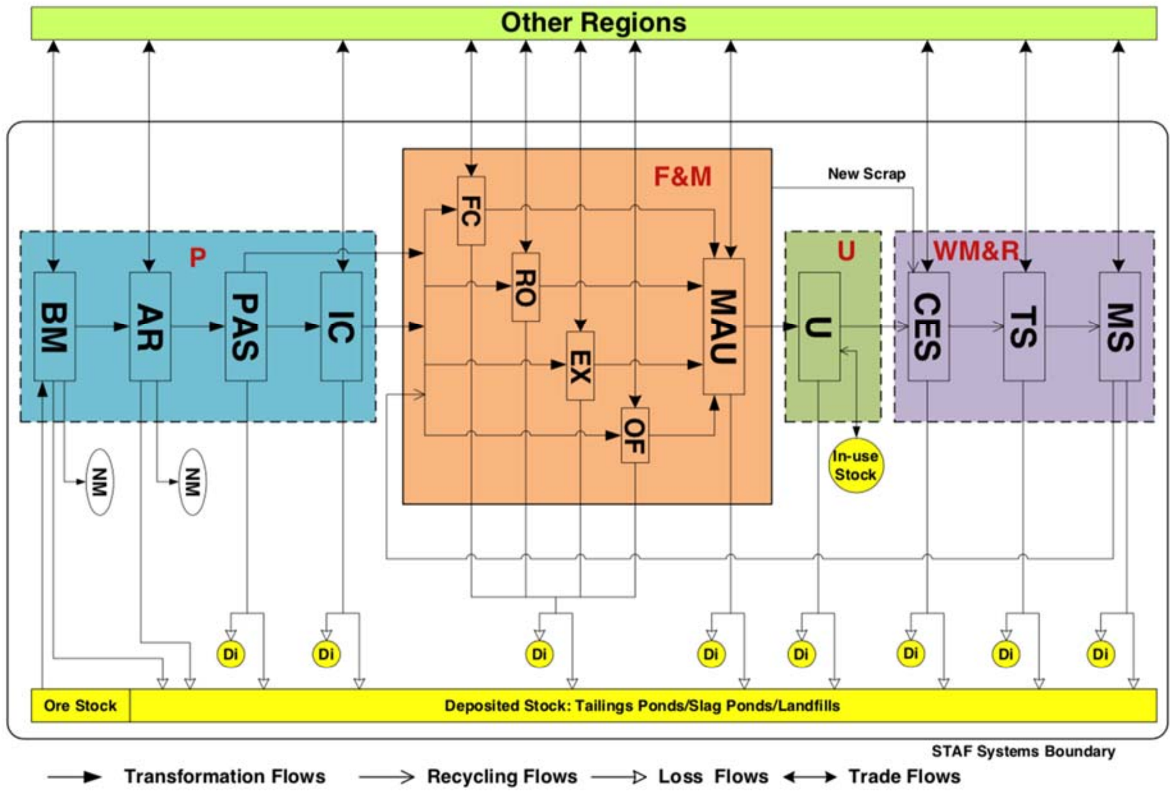


Fig. S. 1 Schematic diagram for the anthropogenic aluminum life cycle. NM = Non-metallic Use; Di = Dissipated Loss Stock. Refer to Table S. 1 for the symbols of the life processes. PAS and IC processes are basically located near each other in the same factory. We divide them into two separate stages by following conventions of life cycle assessment of aluminum in many reports (European Aluminum Association, 2008; International Aluminium Institute, 2003; 2007; The Aluminum Association, 1998).

Figure A 10: The aluminum MFA system boundary used by Chen and Gradel in 2012 (Chen and Graedel 2012, p. S4)

Table S. 1

Symbols and indices of life processes of anthropogenic aluminum cycle in this study

Life Processes	Symbols	Indices
Production	**P**	**-**
Bauxite Mining	BM	1
Alumina Refining	AR	2
Primary Aluminum Smelting	PAS	3
Ingot Casting	IC	4
Fabrication & Manufacturing	**F&M**	**-**
Foundry Casting	FC	5-a
Fabrication of Wrought Products	FW	-
Rolling	RO	5-b
Extrusions	EX	5-c
Other Fabrication Processes	OF	5-d
Manufacturing	MAU	6
Use	**U**	**-**
Use	U	7
Waste Management & Recycling	**WM&R**	**-**
Collection of EOL Products and Scrap	CES	8
Treatment of Scrap	TS	9
Melting of Scrap	MS	10

Figure A 11: The symbol definitions for the aluminum MFA system used by Chen and Gradel in 2012 (Chen and Graedel 2012, p. S5)

In order to calculate aluminum flows, Chen and Graedel took four approaches—they calculated trade flows directly based on obtained statistics, they calculated loss flows (new scrap generation) by combining statistics with loss coefficients, they modeled old scrap generation using a top-down method, and they further deduced flows using mass balance. After calculating flows, annual changes of various stocks were determined by accumulating the stock's annual change from 1900-2009.

Chen and Graedel collected and grouped data into six categories. Data on aluminum production and apparent consumption based on shipments of ACPs from bauxite to various mill products was obtained from USGS and AA. Data on import and export of ACPs was obtained primarily from the UN Comtrade database using SITC codes of various ACPs while data from USGS and AA were also consulted. The SITC codes used for transportation sector ACPs is shown in Figure A 12. Data on the aluminum contents of various ACPs was obtained from Ducker Worldwide. Data on loss rates of aluminum during different life cycle processes was deduced from life cycle assessment reports (including reports from the European Aluminum Association, AA, and PE Americas) or obtained from interviews with AA experts. When a loss rate of aluminum was given for only one year, it was assumed that loss rates throughout the whole 1900-2009 period were the same as in that one year and when loss rates of aluminum were given for several years, it was assumed that loss rates before the given earliest year were the same as the one in that earliest year and loss rates after the given last year were the same as the one in that last year, while loss rates between given years were calculated using an interpolation method. Data on the composition of aluminum flows from fabrication to manufacturing processes into in-use stock was obtained from end-use distribution statistics provided by AA. Finally, data on the lifespans of final products in the use stage were computed by averaging literature lifespan values of final products; literature including (Hatayama et al. 2007), (Melo 1999), (Schlesinger 2007), (Dahlström et al. 2004), and (Hatayama et al. 2009) were consulted.

MAU	Transportation, Air	-	7114, 7341, 7349, 89999	(SECSPC, 2004a; b), (Wang et al. , 2004), (U.S. Geological Survey, 2005), (Lou and Shi, 2008), (Amicarelli et al. , 2004), (Ducker Worldwide, 2008a; b), (Mathieux and Brissaud, 2010), (Recalde et al. , 2008), (Wang and Graedel, 2010)
	Transportation, Marine	-	7351, 7353, 7359	
	Transportation, Rail	-	71966, 7311, 7312, 7313, 7314, 7315, 7316, 7317	
	Transportation, Road	-	7321, 7322, 7323, 7324, 7325, 7326, 7327, 7328, 7329, 7331, 7333, 7334	
	Transportation, Multi-application Parts	-	7113, 7115	
	Building & Construction	-	6324, 6912, 69313, 69882, 69884, 69886	
	Machinery & Equipment	-	7111, 7112, 7121, 7122, 7123, 7125, 7129, 7151, 7152, 7171, 7172, 7173, 7181, 7182, 7183, 7184, 7185, 7191, 7192, 7193, 7195, 71961, 71963, 71964, 71965, 7197, 7198, 7199, 7295, 8613, 8617, 8618, 8619	
	Consumer Durables	-	69723, 69792, 6981, 6982, 7141, 7142, 7143, 7149, 71941, 71942, 71943, 71962, 7241, 7242, 7249, 72501, 72502, 72503, 72504, 72505, 7261, 7262, 7291, 7292, 7293, 7294, 7296, 7297, 7299, 8124, 8210, 8413, 8612, 8614, 8615, 8616, 8641, 8642, 8911, 8914, 8918, 8919, 8941, 8942, 8944, 8945, 8951	

Figure A 12: The SITC codes used for ACPs in the transportation sector, with automotive codes highlighted, used by Chen and Graedel in 2012 (Chen and Graedel 2012, p. S6)

Equations for calculating stocks and flows, stocks change, and accumulation of stocks are finely detailed in the article's supplementary information and captured in Table A 19.

Table A 19: The main equations to calculate stocks and flows used by Chen and Graedel in 2012 (Chen and Graedel 2012, p. S15&16)

Table S. 4

A summary of the main equations for accounting stocks and flows

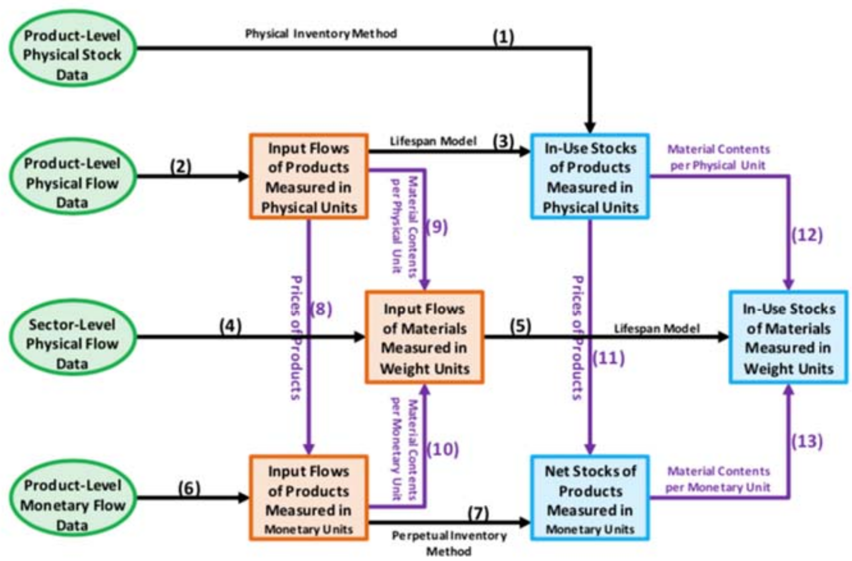
Stocks or Flows	Equation NO.	Equation	Notes
Trade flows			
Import	(4)	$F^{import}_{AL,i,j} = F^{import}_{p,i,j} \times C_{AL,i,j}$	F: flows. C: aluminum concentration. *i*: process *i*. *j*: year *j*.
Export	(5)	$F^{export}_{AL,i,j} = F^{export}_{p,i,j} \times C_{AL,i,j}$	
Net import	(6)	$F^{netimport}_{AL,i,j} = F^{import}_{AL,i,j} - F^{export}_{AL,i,j}$	
Loss flows			
Loss from use	(8)	$F^{loss}_{AL,7,j} = P_{steel,j} \times D^{forsteel}_{AL,j}$	*P*: production. D: demand of aluminum deoxidizer for producing one ton of steel.
Loss from all other processes	(7)	$F^{loss}_{AL,i,j} = F^{FromPre}_{AL,i,j} \times R^{loss}_{AL,i,j}$	*FromPre*: flows from the previous process. R: rate.
Scrap generation			
Scrap generation by sector	(13)	$P_{AL,7,j,k} = \sum_m F^{ToNext}_{AL,6,j-m,k} \times p_{m,k}$	$p_{m,k}$: the obsolete share of final products in sector k after they serve m years in the Use stage
Mass balance			
For use process	(2)	$F^{FromPre}_{AL,i,j} + S^{inuse}_{AL,j-1} = F^{ToNext}_{AL,i,j} + F^{loss}_{AL,i,j} + S^{inuse}_{AL,j}$	*ToNext*: flows to the next process.
For all other processes	(1)	$F^{FromPre}_{AL,i,j} + F^{import}_{AL,i,j} = F^{ToNext}_{AL,i,j} + F^{export}_{AL,i,j} + F^{loss}_{AL,i,j}$	

Stocks change		
Bauxite stock	(15)	$\Delta S^{ore}_{AL,j} = P_{AL,1,j} + F^{loss}_{AL,1,j}$
In-use stock	(16)	$\Delta S^{inuse}_{AL,j} = F^{input}_{AL,7,j} - P_{AL,7,j} - F^{loss}_{AL,7,j}$
Tailings	(17)	$\Delta S^{Tailings}_{AL,j} = F^{loss}_{AL,1,j} + F^{loss}_{AL,2,j}$
Slag and landfills	(18)	$\Delta S^{Slag\&Landfill}_{AL,j} = F^{loss}_{AL,3,j} + F^{loss}_{AL,4,j} + F^{loss}_{AL,5,j} + F^{loss}_{AL,7,j} + F^{loss}_{AL,9,j} + F^{loss}_{AL,10,j}$
Obsolete stock	(19)	$\Delta S^{Obsolete}_{AL,j} = F^{loss}_{AL,8,j}$
Non-metallic use	(20)	$\Delta S^{NonMetallic}_{AL,j} = F^{NMBauxite}_{AL,j} + F^{NMAlumina}_{AL,j}$
Accumulation of stocks		
Except bauxite stock	(21)	$S_{AL,n} = \sum_{j=1900}^{n} \Delta S_{AL,j}$

To exclusively isolate USA stocks and flows from fabrication and manufacturing to the use phase, efforts were made to exclude Canadian producers net shipments of mill products. Given data on the total North American supply of aluminum from AA, the USA share was calculated and then that percentage was applied to North American producers' net shipments of mill products to determine the USA producers net shipments of mill products.

A.7.2 CHEN 2017

In 2017, Chen utilized four MFA methods—the bottom-up (BU) method, flow-based using physical data (FBPD) method, stock-based using physical data (SBPD method), and flow-based using monetary data (FBMD) method—to estimate in-use aluminum stocks at the product level. These method schematics are shown in Figure A 13. Of these four methods, the BU and FBMD methods were used to estimate in-use aluminum stocks of products in the automotive industry (cars and trucks) and because of such, they will be focused on here. To calculate in-use automotive aluminum stock over time, the BU method effectively multiplied multiyear data on the aluminum contents of "passenger cars" and "two and four-axle trucks" from Ducker Worldwide by multiyear data on the physical stocks of "passenger cars" and "two and four-axle trucks" in the USA obtained from the Bureau of Transportation Statistics. The FBMD method calculated in-use automotive aluminum stock by estimating average aluminum contents of "autos" and "light trucks" (in units of kg of aluminum per monetary unit of product) from the unit physical input-output by materials (UPIOM) model developed by Nakamura and colleagues and the corresponding USA input-output tables from the USA Bureau of Economic Analysis and then multiplying the estimated average aluminum contents of "autos" and "light trucks" by the physical stocks of "autos" and "light trucks" in the USA obtained from the Bureau of Transportation Statistics. While the terminology for classifying automobiles changed between the BU method and the FBMD method, the accounted stocks were presumed to be the same. The data that Chen 2017 utilized to undergo both the BU and FBMD methods are available as a supplemental information excel file.



(a) Paths linking data with results

Method Names	Paths
Top-Down Method (T-D)	(4) + (5)
Bottom-Up Method (B-U)	(1) + (12)
Flow-Based Using Physical Data (FBPD)	(2) + (9) + (5)
Stock-Based Using Physical Data (SBPD)	(2) + (3) + (12)
Flow-Based Using Monetary Data (FBMD)	(6) + (10) + (5)
Stock-Based Using Monetary Data (SBMD)	(6) + (7) + (13)

(b) Description of methods

Figure S1-1 Methods for estimating in-use stocks of materials contained in products

Source: Adapted from Chen and Graedel (2014)[1]

Figure A 13: The various methods used by Chen in 2017 to estimate aluminum in-use stocks contained in products (Chen 2017, p. S1-5)

A.7.3 LIU AND MÜLLER SEPTEMBER 2013

Liu and Müller's 2013 study used the anthropogenic aluminum life cycle system definition (Figure A 14) from a previous 2012 (Liu et al. 2012) study to map the global trade of anthropogenic aluminum. The temporal scale of their system was the year 2008 and the spatial scale was a list of 66 countries or geographical territories that were grouped into 10 world regions.

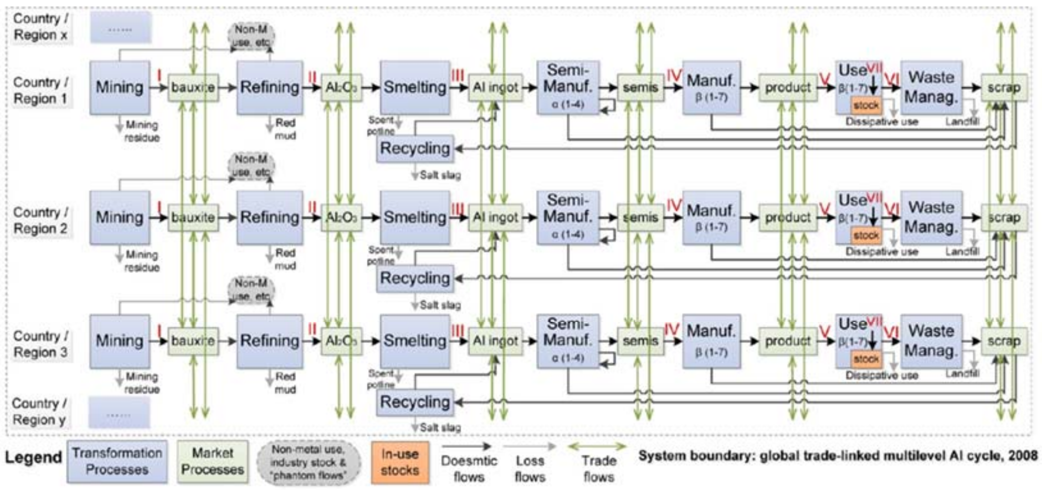


Figure 1. System definition of the trade-linked multilevel global anthropogenic aluminum cycle. Four categories of semimanufacturing processes and products: α (1−4): rolling, extrusion, shape casting, and others. Seven categories of manufacturing processes and final products β (1−7): building and construction (B&C), transportation (Trans), containers and packaging (C&P), machinery and equipment (M&E), electrical engineering (EE), consumer durables (CD), and other uses (Others). The dashed ovals indicate nonmetallurgical aluminum use, industry stock, and "phantom flows" required to close the mass balance of production. The roman letters (I−VII) indicate flows from which metal production and use rates are compared in Figure 3.

Figure A 14: Anthropogenic aluminum life cycle system definition used by Liu and Müller in 2013 (Liu and Müller Sept. 2013, p. 11874)

All aluminum flows were quantified in aluminum metallic equivalents. Production data for bauxite, alumina, and primary aluminum was taken from the USGS minerals yearbook while secondary aluminum production data was taken from Metallgesellschaft (1889-2007) and (Mitchell 2007). Data on the domestic shipment of aluminum semis into end-use sectors was taken from GARC. Life cycle loses were assumed to be 10% for mining, 9.8% for refining, 2.6% for primary aluminum production, 30% for scrap generation during semis production with 25% internal recycling assumed. End-use manufacturing processes were estimated to have the transfer coefficients shown in Table A 10. Additionally, stocks in use and flows leaving use were calculated using the lifetime model established in (Liu and Müller March 2013), notably the product lifetime assumption within the transportation sector was 20 years (Table A 20).

Most interestingly, Liu and Müller estimated the international trade for 126 ACPs based on UN Comtrade data. All of the UN Comtrade flows were reported in monetary values and only 90% of them cover physical values at the same time. The schematic for an algorithm that systematically reviewed and revised the UN Comtrade data, to account for the physical data gaps and import-export inconsistencies, is shown in Figure A 15 and the specific system of equations used in the algorithm can be found in the supplemental information of the paper. Additionally, the UN Comtrade SITC codes for transportation sector ACPs, associated ACP aluminum content percentages, and the associated uncertainty values are shown in Figure A 16.

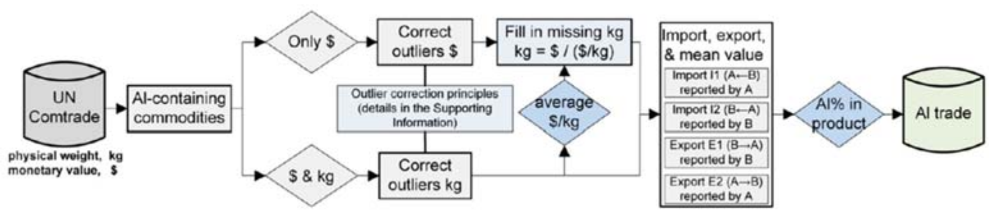


Figure 2. The algorithm to systematically review and revise the UN Comtrade data.

Figure A 15: The algorithm used by Liu and Müller in 2013 to systematically review and revise UN Comtrade data for physical gaps or import-export inconsistencies (Liu and Müller Sept. 2013, p. 11875)

Use categories	SITC1	Commodity name	Al%	Uncertainty
Building & Construction (B&C)	S1-6912	Fin, structural parts & structures of aluminum	90.0%	low
	S1-72505	Electric space heating equipment etc.	3.0%	high
	S1-8121	Central heating apparatus and parts	2.0%	high
	S1-81242	Lamps & lighting fittings & parts thereof	2.0%	high
Transportation (Trans)	S1-7115	Internal combustion engines, not for aircraft	25.0%	high
	S1-7294	Automotive electrical equipment	5.0%	high
	S1-7321	Passenger motor cars, other than buses	5.1% *	low
	S1-7326	Chassis with engs. Mntd. For vehicles of 732.1	1.0%	high
	S1-7328	Bodies & parts motor vehicles ex motorcycles	10.0%	high
	S1-7114	Aircraft incl. jet propulsion engines	3.0%	medium
	S1-7341	Aircraft, heavier than air	70.0%	medium
	S1-73491	Airships & balloons	50.0%	high
	S1-73492	Parts of aircraft,airships,etc.	70.0%	medium
	S1-7113	Steam engines and steam turbines	2.0%	high
	S1-7311	Railway locomotives steam and tenders	1.0%	medium
	S1-7312	Electric railway locomotives, not self generat.	1.0%	medium
	S1-7313	Railway locomotives, not steam or electric	1.0%	medium
	S1-7314	Mechanically propelled railway and tramway cars	1.0%	medium
	S1-7315	Rail & tram passenger cars not mech propelled	1.0%	medium
	S1-7316	Rail.&tram.freight cars,not mechanically propd.	1.0%	medium
	S1-7317	Parts of railway locomotives & rolling stock	1.0%	medium
	S1-7322	Buses, including trolleybuses	8.0%	high
	S1-7323	Lorries and trucks, including ambulances, etc.	6.0%	medium
	S1-7324	Special purpose lorries, trucks and vans	6.0%	medium
	S1-7325	Road tractors for tractor trailer combinations	3.5%	medium
	S1-7327	Other chassis with engines mounted	1.0%	high
	S1-73291	Motorcycles,auto cycles,etc.& side cars	10.0%	high
	S1-73292	Parts solely for use of heading 73291	10.0%	high
	S1-73311	Cycles,not motorized	20.0%	medium
	S1-73312	Parts of vehicles of heading 733 11 & 733 4	20.0%	high
	S1-7333	Trailers & oth vehicles not motorized, & parts	7.5%	medium
	S1-7334	Invalid carriages	5.0%	high
	S1-7351	Warships of all kinds	1.0%	high
	S1-7353	Ships and boats, other than warships	1.5%	medium
	S1-7358	Ships,boats and other vessels for breaking up	2.0%	high
	S1-7359	Special purpose ships and boats	0.5%	high

Figure A 16: The SITC codes for transportation related ACPs, ACP aluminum percentages, and uncertainties used by Liu and Müller in 2013 (Liu and Müller Sept. 2013, p. S10)

To calculate the aluminum concentrations of bauxite, bauxite ore grades by country and the world average bauxite grade were used. These grades are shown in Figure A 17. Furthermore, the aluminum content in alumina was assumed to be 52% according to the chemical composition and IAI. Aluminum contents in unwrought aluminum, wrought products, and castings were assumed to be 99.7%, 95%, and 90%, respectively, and were based upon a previous study (Liu et al. 2011).

Figure A 17: Bauxite ore grades for different countries and the world average bauxite ore grade used by Liu and Müller in 2013 (Liu and Müller Sept. 2013, p. S9)

Table S4. Bauxite ore grade of different countries and the world average.

Countries	Bauxite ore grade	Countries	Bauxite ore grade
Australia	0.42	Bosnia and Herzegovina	0.50
Brazil	0.46	Montenegro	0.57
China	0.54	Iran	0.47
Domin. Republic	0.44	Hungary	0.50
Ghana	0.50	Azerbaijan	0.44
Greece	0.53	Russia	0.42
Guinea	0.49	Kazakhstan	0.42
Guyana	0.50	Crotia	0.49
India	0.47	France	0.47
Indonesia	0.49	Guinea-Bissau	0.46
Jamaica	0.44	Malawi	0.43
Malaysia	0.47	Mozambique	0.47
Sierra Leone	0.50	Romania	0.47
Suriname	0.47	Saudi Arabia	0.47
Turkey	0.55	Serbia	0.47
Venezuela	0.48	Spain	0.52
Vietnam	0.45	USA	0.47
all others	0.41		

Finally, the historic change of aluminum content in passenger cars was extracted from data provided by Ducker Worldwide.

A.7.4 LIU AND MÜLLER MARCH 2013

A production driven top-down approach was used by Liu and Müller to simulate the historical aluminum cycle and stocks in use between 1900-2010. All stocks and flows were calculated in aluminum metallic equivalents and starting data points were either domestic shipment data of aluminum semis (for nineteen countries, including the USA) or primary and recycled aluminum production statistics (all of the other 144 countries covered in this study). UN Comtrade data was used to isolate nearly 130 ACPs that were reviewed using the algorithm mentioned in (Liu and Müller Sept. 2013) before applying aluminum content percentages to identify the aluminum within each ACP.

In total, 50,000 production, consumption, and coefficient data points and over 20 million trade data points were compiled and analyzed. Sensitivity and uncertainty analysis were conducted including a Monte Carlo simulation, which was applied to address the uncertainty of aluminum concentrations in commodities (that were derived from a literature review), and a Gaussian expansion method to calculate aggregated uncertainties of all parameter variations.

Data on aluminum domestic end-use shipment for the USA was calculated from Metallgesellschaft (1889-2007) while data for bauxite, alumina, and aluminum production were obtained from USGS, like was done in (Liu and Müller Sept. 2013).

Life cycle and end-use manufacturing process fabrication yields were the same as in (Liu and Müller Sept. 2013). Aluminum concentration in bauxite, alumina, unwrought aluminum, wrought products, and castings were also the same as in (Liu and Müller Sept. 2013). The mean values of product lifetime assumptions by product category and world region (explicitly identifying the USA product lifetimes from previous literature) used by the study are shown in Table A 20.

Table A 20: The mean values of product lifetime assumptions by product category and world region used by Liu and Müller in 2013, with the USA product lifetimes from previous literature highlighted (Liu and Müller March 2013, p. S14)

Table S7. Mean values of product lifetime assumptions in the literature and our life assumptions by product category and by world region (countries within the same region are assumed to have the same lifetimes).

Categories	BC	TR	C&P	M&E	EE	CD	OT	Source
Europe	**50**	**13**	**1**	**15**	**20**	**8**	**10**	Proposed assumptions in the regional model
North America	**75**	**20**	**1**	**30**	**20**	**12**	**10**	
Developed Asia & Oceania	**40**	**10**	**1**	**20**	**20**	**10**	**10**	
China	**40**	**15**	**1**	**20**	**20**	**12**	**10**	
Rest of the world	**50**	**15**	**1**	**20**	**20**	**12**	**10**	
Germany	31.5 [23,40]	13 [10,16]	1	15 [15,20]	17.5 [10,25]	8.6 [5,8]	8.6 [5,8]	(Melo 1999)
UK	35 [10,60]	13 [12,15]	1	17 [15,20]	17 [15,20]	7 [5,8]	10 [0,10]	(Dahlström et al. 2004)
Europe	[16,95]	[11,15]				[8,10]	[24,30]	(Murakami et al. 2010)
Europe	31.5	13	1	15	17.5	10	10	(Hatayama et al. 2012)
Europe	37.5	[15.5, 27.5]	[0.3, 0.6]	11	22.5	5		(GARC 2011)
USA	75 [50,100]	20 [15,30]		30 [20,40]		15 [10,20]		(Müller et al. 2006)
USA	[45,90]							(Kapur et al. 2008)
USA	50 [31.5,75]	20 [13,40]	1	30 [15,40]	[17.5,40]	12 [8.6,15]	15 [8.6,20]	(Liu et al. 2011)
USA	75	20	1	30	15	10	15	(Hatayama et al. 2012)
USA	32.5	[12.5, 27.5]	[0.3, 0.6]	22.5	30	7.5		(GARC 2011)

A.8 KEY FINDINGS: ALUMINUM

Calculating accumulation of aluminum in automotive stocks can be done using a top-down MFA method given domestic production and product shipment data (that can be acquired from AA or GARC or USGS) into the automotive industry, import and export data of automotive ACPs from UN Comtrade (systematically reviewed and revised to address inconsistencies using the algorithm provided in Figure A 15), aluminum content of automotive ACPs from Ducker Worldwide, aluminum loss rates during fabrication and manufacturing, ACP lifespans, and the equations used by Chen and Graedel in 2012 (Table A 19). Additionally, aluminum in automotive stocks can also be calculated by a bottom-up and flow-based monetary data method as described by Chen in 2017 (Chen 2017). Furthermore, the trade-linked map of global aluminum along its life cycle creates a platform and reference for future regionally linked aluminum material flow analysis studies.

China is the global leader in both aluminum production and consumption and has recently created tension as such in the aluminum industry. Moreover, the USA 10% tariff on international aluminum (including Canada and Mexico) and newly increased primary aluminum capacity in the USA will likely cause both domestic aluminum production and USA aluminum spot prices to increase in the coming years. The recent signing of the USMCA dictates that automobiles must contain at least 70% North American sourced aluminum and steel. While this may not be a problem for major USA based automotive OEMs like Ford, FCA US, and GM, it could pose a serious challenge to foreign automotive companies that operate manufacturing plants in the USA

Secondary aluminum production is the dominant source of aluminum supply in North America. This is of particular interest as the aluminum industry seeks to be more sustainable, but also as the potential for a scrap surplus could loom. Secondary castings for automotive applications hold the potential to act as a bottleneck for EOL vehicle scrap, a dominant source of scrap, and if the supply of EOL vehicle scrap exceeds the demand for secondary castings, then a scrap surplus could be feasible. Additionally, although it has been asserted that 57% of automotive aluminum is from recycled metal, uncertainty still exists in the end-use distribution and sources of secondary aluminum—posing an interesting automotive aluminum research inquiry.

Finally, the evolution of internal scrap handling in the USA automotive industry could create a more sustainable aluminum supply chain for major automotive OEMs. Ford already has three closed-loop internal scrap recycling systems that it asserts recycles 20 million pounds of aluminum per month, enough to produce 37,000 F-Series trucks.

A.9 MFA KNOWLEDGE GAP: ALUMINUM

Although extensive research has been conducted on stocks and flows of aluminum, including research that has identified trade-linked patterns of aluminum and product level distributions of aluminum, specific locality of aluminum that goes into various industries industrial remains unclear. Restated, the major knowledge gap in aluminum material flow analysis is the lack of specific regionality of flows. Even for a major aluminum market such as the automotive market, the source locations of the aluminum that flows into the automotive industry remain unclear. While methods exist to identify the amount of semis being imported into the USA, there does not exist a level of detail that communicates how much of the imported semis from a given country goes into the automotive industry. Similarly, while domestic end-use distribution of semis exist and describe the amount of semis going into the automotive industry, there are no locations attached to said amount; one aggregate number of semis flowing into the automotive industry is presented and not broken down by source locations. Additionally, although the amount of automotive aluminum in-use stock can be calculated by a bottom-up material flow analysis method, no information regarding where the automotive aluminum in-use stock comes from is obtained in the application of this method at this boundary.

A.10 MFA METHOD OVERVIEW: STEEL

Material flow analyses of steel and iron were, until recently, relatively under explored areas of research. As the economic and environmental impetus to incorporate secondary iron and steel strengthened and concerns for environmental impacts grew, a requirement to understand the flow pattern of these metals increased. Research has since been conducted on a number of aspects regarding steel and iron material flows. Key research has focused on the material flow of anthropogenic iron and steel across markets such as the United States, Japan, China and the global market, while more targeted research has focused on the development of recycling and circular economies. Lastly, this memo highlights a study focused on the regionality of stainless steel material flows.

A.10.1 MULLER ET AL. 2006

The research team at the School of Forestry and Environmental Studies at Yale University has led the way regarding material flow analyses of the United States iron and steel industries. "Exploring the engine of anthropogenic iron cycles" by Muller et al. 2006 is considered the first in-depth analysis of the material flow of iron and steel. The study established a new framework for resource cycles, which includes two components: (1) all relevant metal stocks: raw materials, production, manufacturing, in-use and scrap; and (2) all flows of metallic iron: movement from one market to another (Muller 2006, p. 16112 – 3). The purpose of this framework is to assess present and future iron sources and sinks. The study applied the framework to the USA iron cycle from 1900-2004.

Muller et al. developed a system definition to differentiate between two key processes: transformation and market processes (Muller 2006, p. 16112 – 4). Transformation processes balance inputs and outputs of industrial facilities (blue boxes) (Figure A 18). Market processes balance domestic and foreign supply and demand in physical terms (yellow boxes) (Figure A 18). These processes are connected by iron-containing flows between them (grey arrows) (Figure A 18).

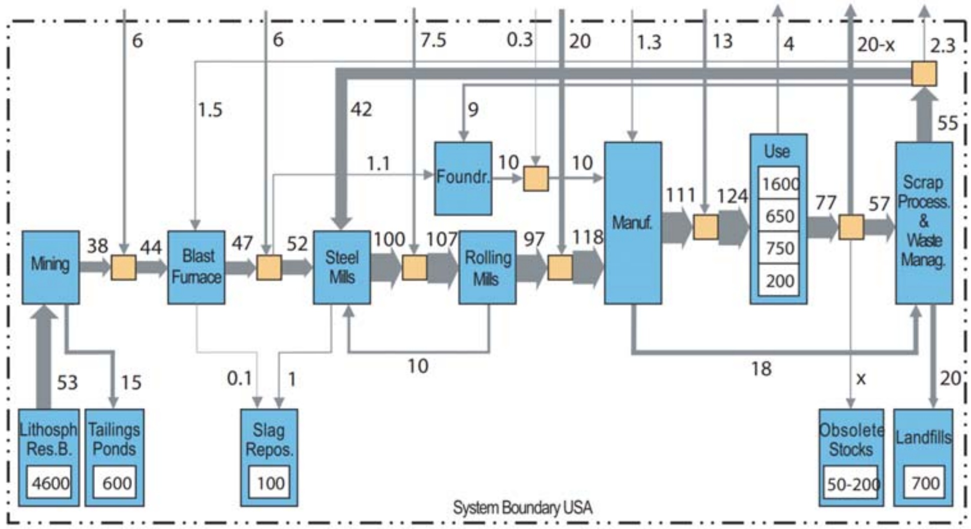


Figure A 18: USA Steel and Iron Cycle, 2000, flows in Tg/a, stocks in Tg (Muller 2006, p. 16114)

Transformation processes include raw materials (lithosphere, tailings, slag), production processes (mining, blast furnace, steel mills, rolling mills), manufacturing, use and scrap processing & waste management. Both manufacturing and use are divided into four product categories: (1) construction – buildings and infrastructure; (2) transportation – automobiles, railways, ships and airplanes; (3) machinery and appliances – industrial and domestic; and (4) other – containers, furniture, cans (note: industry stocks are neglected because negligible size; also excludes iron incorporated in minerals not used for metallurgical purposes) (Muller 2006, p. 16116-1).

When data is available, flows and stock calculations are determined using mass flows in combination with the iron concentration of the materials flowing through each process. When data is incomplete or unavailable, mass balances and assumptions were used to arrive at the mass flow of iron and steel (Muller 2006, p. 16116-2). For manufacturing breakdowns, domestic shipments of finished steel were broken down into 22 sectors (steel wholesale center were assumed to have the same split). This data was sourced from AISI's *Annual Statistical Report of the American Iron and Steel Institute* (Muller 2006, p. 16116-3). Imported shipment data is lacking, and thus, the same sectoral breakdown of finished steel is applied to all imported steel (Muller 2006, p. 16116-3). More specifically, UN Comtrade data used to determine import and export flow data for steel and casting, while iron concentrations were similarly applied to the trade flows (data sources detailed later). As the UN Comtrade data does not distinguish between new and used products, a correction was applied to the integrated data. USA Department of Commerce *USA Trade Online* data was used to identify the proportion of used products in 5% of iron-containing product categories across all available data (Muller 2006, p. 16116-4). The proportion of used products was applied to 100% of products, resulting in 3% of imports being removed as used products and 40% of exports being removed as used products (Muller 2006, p. 16116-4).

In-Use product stock was calculated across three broad categories: (1) products that remain in the USA, (2) products that were imported, and (3) products that were exported. For imported and exported products, products were assumed to remain in the USA for half of their lifetime. Stock lifetime for products that remain in the country were calculated based on a normal lifetime distribution model. Sensitivity analyses were conducted to determine effects of different lifetime assumptions, but impacts were minimal and thus not included (Muller 2006, p. 16116 – 5).

Recycling and recovery rates were largely estimated, as only data was available only for iron entering landfills through municipal solid waste. Municipal solid waste data was estimated using the EPA's report *Municipal Solid Waste Generation, Recycling and Disposal in the United States: Facts and Figures.* Additional *r*ecycling rates were estimated using USGS data in combination with expert interviews (Muller 2006, p. 16116 – 6).

Data sources fall into two categories for this study: those used to determine mass flows, and those used to determine iron concentration (Muller 2006, p. 16115 – Table 2). Total Mass flows were identified and determined from: USGS *Mineral Commodity Summaries*, USGS *Minerals Yearbook,* USA Bureau of Census *Historical Statistics of the United States, Colonial Times to 1970,* USA Bureau of Census *Historical Statistics for Mineral and Material Commodities in the United States,* American Metal Market Metal Statistics 1942, USGS *Historical Statistics for Mineral and Material Commodities in the United States,* UN Statistics Division *UN Commodity Trade Statistics Database* (UN Comtrade), and USA Department of Commerce *USA Trade Online.*

Iron Concentrations were calculated using: USGS *Mineral Commodity Summaries,* USGS *Minerals Yearbook,* EPA *Technical Resource Document, Extraction, and Beneficiation of Ores and Minerals,* International Iron and Steel Institute *The Management of Streel Industry By-Products and Waste, and* Shackelford JF, Alexander W *CRC Materials Science and Engineering Handbook.*

A.10.2 PAULIUK ET AL. 2011

As China's economy continues to expand and become a dominate global economic force, increased focus has been put on the steel industry. In particular, as the first large waves of steel stock begin to reach end-of-life, studies are focusing on the development and quantification of the potential circular economy. Furthermore, the desire is born out of a need to balance economic development with environmental protections and resource limitations. (Pauliuk 2011, p. 148-1). Pauliuk et al. conducted a study to analyze the full steel material flow cycle to forecast raw material use, production, and recycling in 2100. Under the assumption that per-capita steel stock saturates at 8-12 tons (based on studies in developed nations), Chinese consumption is likely to peak by 2020, with a subsequent 40% drop by 2050. The study estimates that up to 80% of iron ore could be replaced by scrap materials by 2050 in the Chinese cycle. (Pauliuk 2011, p. 149-3).

The study focuses on an in-use stock driven material flow analysis (Pauliuk 2011, p. 150-3). For the purposes of understanding future scrap availability, focusing on in-use stock provides the clearest forecast of end-of-life scrap that will be available. First the study completed a historical analysis of iron stocks in China from 1900 to 2009, which will be the focus of this discussion.

The system defined in Pauliuk et al. 2011 mirrors the the process breakdown used in Muller et al. 2006 with both transformation processes and market processes for both domestic and international resource flows (Figure A 19). As with Muller et al. 2006 and as is typically done across steel and iron material flow analysis, the study breaks down the material flow into production (e.g., foundries, EAF, BOF), consumption or use (e.g., construction, transportation, etc.) and scrap (e.g., home scrap, tailings, slag) (Pauliuk 2011, 150-5).

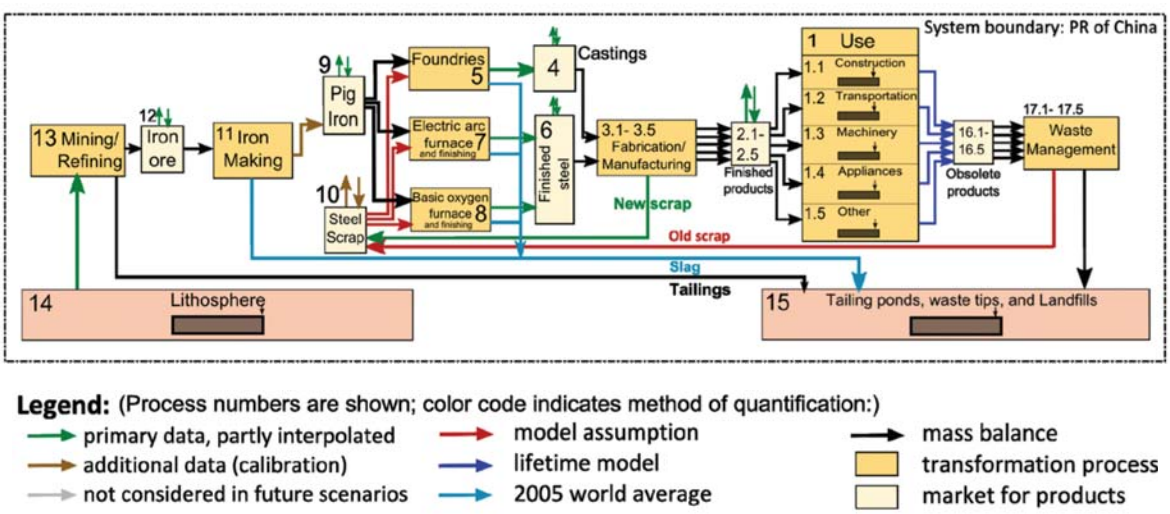


Figure A 19: Iron and Steel Cycle in China, 1900-2009 (Pauliuk 2011, 149)

The study centers around the use phase as it links stock to steel consumption via a mass balance and because it connects end-of-life products to historical consumption. Detailed equations and Matlab programming can be found in the supporting materials as needed (Pauliuk 2011, 150-6). Historical cycle was determined using mass balances around: (1) castings (market – 4), (2) finished steel (market – 6); manufacturing (transformation process – 3.1-3.5); and (4) finished products (market – 2.1-2.5). These balances allowed the final consumption by sector to be determined. Lifetime distribution of in-use stock was determined using normal distribution models except for a log-normal distribution for building stock (Pauliuk 2011, p. 150-7).

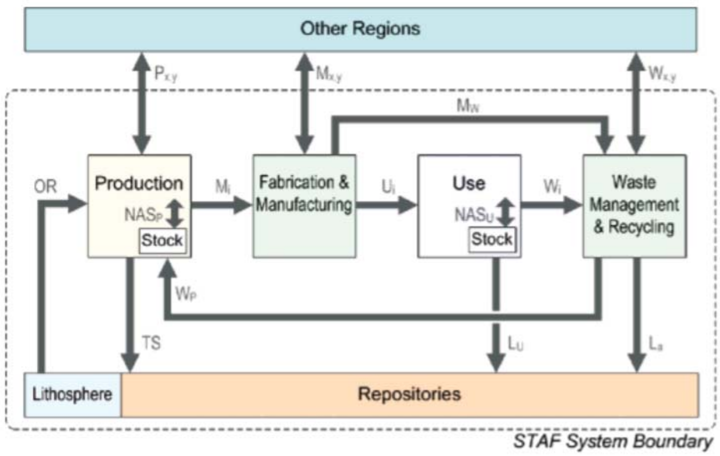
Key data sources consisted of top down sources providing country specific steel production and consumption details. These included: International Iron and Steel Institute *World Steel in Figures 2008*; World Steel Association *World steel in figures*, 2009; State Statistical Bureau, China (2008). Statistical yearbook of China; and USGS data sources.

A.10.3 WANG ET AL. 2007

Following their study in 2006 regarding the USA steel and iron material flow, Wang et al. 2007 (working directly with Muller and team) presented the first global perspective on iron and steel flows. Their new study focused particularly on developing nations and in-use steel stocks (Wang 2007, p. 5120-5). This study was conducted for the year 200 across three spatial levels: 68 countries and territories, nine world regions, and global (Wang 2007, p. 5120-1). The study found that Asia is the world leader in iron production and use, scrap contributes to a quarter of the system, and 24% of iron / steel use is destined for transportation uses (Wang 2007, p. 5120-1).

Wang et al. leveraged market and transformation processes developed by Muller et al. 2006 (Wang 2007, p. 5120-7). Similarly, the follow these same four key life stages: production, fabrication and manufacturing (F&M), use, and waste management and recycling (Figure A 20) (Wang 2007, p. 5120-1). While production concerned the typical stages and steps, the F&M

breakdowns differed slightly. F&M consisted of seven product groups: (1) steel angles, shapes, and sections; (2) steel bars and wire rods; (3) steel plates, sheets, and strips, excluding tin-coated plates; (4) tinplate; (5) steel rails; (6) castings; and (7) steel tubes and pipes (Wang 2007, p. 5121-4). These seven product groups flowed into five end use categories, which followed the traditional in-use breakdown (Wang 2007, p. 5121-5).



OR	Crude ore mined	L_U	In-use dissipation
P	Flow relevant to Production life stage	L_a	Landfill and dispersion to environment
M	Flow relevant to F&M life stage	M_W	Industrial scrap from F&M
U	Flow relevant to Use life stage	W_P	Purchased scrap to Production
W	Flow relevant to WM&R life stage	i	In-flow
TS	Tailings, slag, and other production by-products	x	Export
NAS_P	Net addition to industrial and governmental stock	y	Import
NAS_U	Net addition to in-use stock		

Figure A 20: Schematic Diagram of the Iron and Steel Material Lifecycle (Wang 2007, 5121)

Data is based on estimates of iron amounts entering each end use category. Country specific data for iron use is available for the USA, Japan, Canada, Europe, India and China. (Wang 2007, p. S7-1). Then product-to-use-matrices (PTUMs) are used to estimate the end use consumption of steel and iron based on average breakdowns of iron products by end use. “Global Steel Mill Product Matrix: 1989 to 2001” by P.F. Marcus is used to determine the PTUM breakdowns (source access restricted) (Wang 2007, p. S7-2).

Import and export data of semis and finished products (indirect trade) was also analyzed using UN Comtrade data (Wang 2007, p. 5121-7). Nearly 220 categories of products which contained iron were examined and included in the analysis (Table A 21).

Table A 21: International Trade of Final Products (Wang 2007, S8)

SITC-1 Code	Parts or Final Products	% Fe[a]	Accumulative Global Import (Gg Fe/a)
S1-7321	Passenger motor cars, other than buses	65%	23,220
S1-719	Machinery and appliances non electrical parts	75%	20,285
S1-7328	Bodies & parts motor vehicles ex motorcycles	70%	19,710
S1-698	Manufactures of metal	90%	11,115
S1-729	Other electrical machinery and apparatus	55%	8,327
S1-718	Machines for special industries	75%	7,746
S1-7323	Lorries and trucks, including ambulances, etc.	80%	6,899
S1-735	Ships and boats	90%	5,551
S1-722	Electric power machinery and switchgear	55%	5,082
S1-7250	Domestic electrical equipment	65%	4,725
S1-69421	Nuts, bolts, screws, rivets, washers of iron/steel	98%	4,553
S1-7115	Internal combustion engines, not for aircraft	50%	3,881
S1-693	Wire products ex electric & fencing grills	90%	3,236
S1-7333	Trailers & other vehicles not motorized, & parts	50%	2,637
S1-861	Scientific, medical, & optical instruments	55%	2,333
S3-8213	Metal furniture	70%	1,984
S1-7316	Rail. &tram. cars ,not mechanically propelled	85%	1,947
S1-69221	Casks, drums, etc. used for transport of iron/steel	96%	1,933
S1-715	Metalworking machinery	65%	1,892
S1-714	Office machines	22%	1,648
S1-724	Telecommunications apparatus	25%	1,627
S1-712	Agricultural machinery and implements	70%	1,561
S1-894	Perambulators, toys, games and sporting goods	20%	1,515
S1-695	Tools for use in the hand or in machines	85%	1,499
S1-6291	Rubber tyres & tubes for vehicles and aircraft	15%	1,362
S1-717	Textile and leather machinery	65%	1,206
S1-7325	Road tractors for tractor trailer combinations	80%	1,164
S1-69721	Domestic utensils of iron or steel	95%	1,078
S1-69411	Nails, tacks, staples, spikes, etc. of iron or steel	98%	1,049

a: The main data source of iron concentrations in final products is IISI *(25)*.

Use phase masses are calculated using the mass balance of F&M based on the determined PTUM (Table A 22).

Table A 22: World iron and steel products-to-uses matric, 2000 (Wang 2007, S7)

	Castings	Shapes	Bars	Plates (ex. tinplate)	Tinplate	Rails	Tubes
Construction	0.400	0.952	0.674	0.450	0.000	0.900	0.627
Consumer Durables	0.100	0.000	0.017	0.076	0.000	0.000	0.011
Industrial Machinery	0.150	0.013	0.141	0.106	0.000	0.100	0.293
Transport Equipment	0.350	0.035	0.168	0.344	0.000	0.000	0.070
Others	0.000	0.000	0.000	0.024	1.000	0.000	0.000
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000

The study also considered changes to in-use stock, stock of obsolete products, trade of used products, and in-use dissipation through corrosive losses (Wang 2007, p. 5122-9). Changes to in-use stock were calculated as the input from F&M minus the mass of recycled products, discarded products and the mass of waste sent to landfills (Wang 2007, p. 5122-9). Discarded products consist of: municipal solid waste, construction and demolition debris, end-of-life vehicles (ELV), waste from electronics and other obsolete waste. Trade of obsolete products could not be categorized and thus was not included, while corrosive losses were estimated to be negligible.

Home and industrial scrap can be estimated based on the production of crude and finished steel (Wang 2007, p. 5122-10). Obsolete scrap is determined as described above as part of the use phase mass balance. Using UN Comtrade data to subtract net scrap import, along with home and industrial scrap, the recovered obsolete scrap is determined. Finally, using mass balances, the portion of scrap not recovered and sent to the landfill can be identified (Wang 2007, p. 5122-10).

To move to a global iron cycle, all country specific data are aggregated and trade “remaineders” and “phantom flows” were eliminated (). Phantom flows are assumed to be negligible in the study. Mass balances were then recalculated to determine the estimated overall global flow of iron and steel products (Wang 2007, p. S11-2). On the global level, approximately 75% of material input was met by crude ore, while 25% was met by recycled scrap (Wang 2007, p. 5125-5). The study itself acknowledges a lack of maturity around the study of in-use stocks and stock / trade of used and obsolete products, as well as a lack of understanding of the flows into repositories (Wang 2007, p. 5126-1).

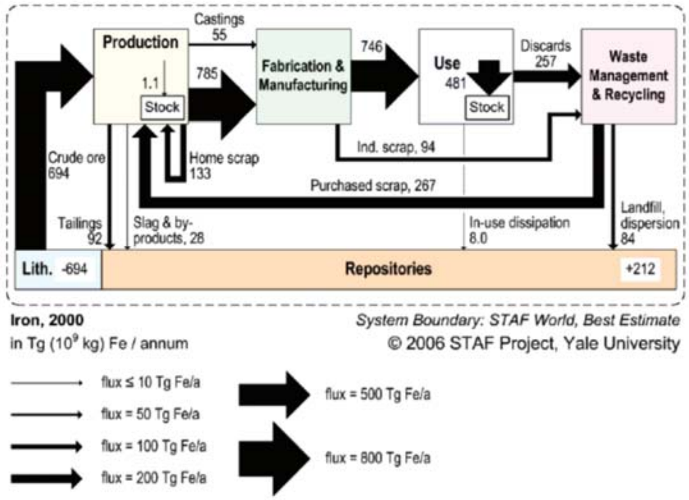


Figure A 21: Global-level Iron Cycle, 2000, values in Tg Fe per annum (Wang 2007, p. 5128)

A.10.4 RECK ET AL. 2010

The final study highlighted uses many of the same approaches discussed previously; however, it takes a more detailed look at the stainless steel industry. In "Global stainless steel cycle exemplifies China's rise to metal dominance" Reck et al. explore the global stainless steel cycle at various spatial levels from 2000 to 2005. The study is the first to conduct such a study at the global level for any steel alloy (Reck 2010, p. 3940-5). The study found a 30% increase in the amount of stainless steel flowing into industry between 2000 and 2005, mainly driven by production ramp up in China (China accounted for half of the global production) (Reck 2010, p. 3940-1). China surpassed the USA, Germany, Japan, and South Korea in terms of stainless steel production. However, similar to steel more broadly, it had little to no end-of-life recovery as the stainless steel in-use stock is too new (Reck 2010, p. 3940-1).

The study follows the same material flow analysis as discussed, citing similar studies, such as Muller et al. 2006 (Figure A 22). The methodology includes the four main processes of steel production and end-use: production, manufacturing, use, and recycling and waste management (Reck 2010, p. 3940-6). The production process is dominated by EAF with inputs from both primary materials (e.g., ferrochromium, ferronickel, and others) and secondary materials (e.g., scrap of stainless steel, alloy steel and carbon steel) (Reck 2010, p. 3940-7). The molten stainless steel is either case into a semi-finished product (semi) or continuously cast before being rolled into either “flat” or “long” products (Reck 2010, p. 3940-7). Manufacturing is considered to products good for the typical five end use sectors (except “other” is characterized more descriptively as “metal goods”) (Reck 2010, p. 3941-1). To account for the trade of manufactured goods, the study examined 64 relevant commodities and estimated the steel content within each category. The trade values were determined using UN Comtrade data (Reck 2010, p. 3941-1). As with the other studies, the use phase stock addition is determined from a mass balance by sector accounting for: net imports, manufacturing output, end-of-life flows and flow to landfills (Reck 2010, p. 3941-2). Finally, the end-of-life flow was determined based on an analysis of each sector’s product residence time model and a determination (a portion of the scrap is carbon/alloy steel-scrap, while the majority is stainless steel scrap) (Reck 2010, p. 3942-2).

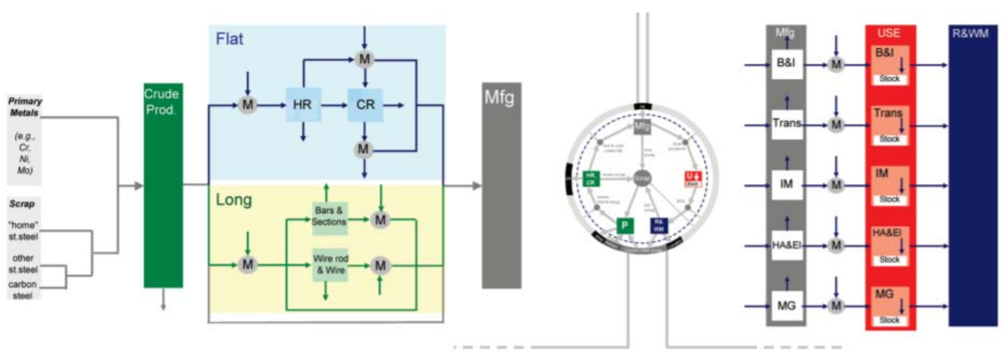


Figure A 22: Stainless Steel Flowchart from Production to End Use (Reck 2010, p. 3941)

Through the use of regional and country-specific data, the study determined a spatial breakdown of flows and stocks at each stage of the cycle (Figure A 23).

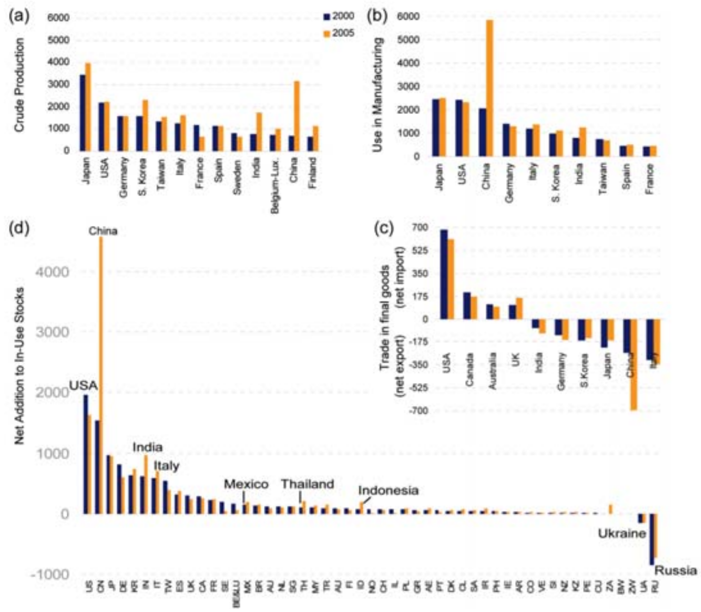


Figure A 23: Stainless Steel Flow compared by Country in 2000 (blue) and 2005 (orange) (Reck 2010, p. 3943)

The study leveraged a number of private and publicly available data sets. Crude production was determined from industry data provided by Vale Inco for 2000, which is not publicly available, while 2005 data was determined from data provided by the International Stainless Steel Forum (ISSF) (Reck 2010, p. S10-3). Manufacturing data and scrap input were already provided by ISSF. Additional data elements such as yield losses were estimated based on expert interviews.

A.11 KEY FINDINGS: STEEL

Material flow analyses regard steel and iron are typically done using a hybrid approach that varies in terms of timeframe and spatial boundaries. The methodologies typically take a top-down approach for production, while using a hybrid approach when considering in-use stocks. The most common sources of production data and shipment data include AISI, IISI, and other industry group data sets. These sources of data have proven highly beneficial for industry wide data analyses that do not consider directly end use destinations. Furthermore, country specific data can be found, but often varies in quality and reliability. In the USA the main data source for production data is USGS, while China, Japan, and Europe have reliable sources as well. Trade flows are typically leveraged to determine additions to in-use stocks for each end use. Using an estimated concentration of steel in the product and the total amount of goods being traded, the studies determine an approximate increase to in-use metals.

From the MFAs conducted, the increase in production and consumption in China is a stark shift in the industry. From an environmental and recycling perspective, this creates immense danger and opportunity for the industry. China's production has been limited to almost exclusively primary materials, as their stocks are too new and the amount of recycling metals is highly limited. However, as their automobiles and other iron and steel products begin to retire in the next 5-10 years, there is a immense opportunity to increase the market share of recycled steel, particularly in China. If this market is able to develop and mature fast enough, China's environmental efficiency will increase dramatically.

Meanwhile, in the USA iron usage per-capita leveled off in the 1980s, leading to the theoretical possibility that raw material extraction could be eliminated with perfect recycling of iron and steel goods in the USA industry. This is in part due to the decrease in iron-content in finished products. Furthermore, the USA has been increasingly importing more and more iron containing goods, offsetting decreased domestic production. The USA industry is shifting towards high quality steel products, as the industry attempts to keep up with the light weight properties of plastics and aluminum. In the USA steel consumption has been flat or decreased since 1980 and there is no signs of growth. The fate of the steel industry, particularly in the automotive sector, depends on its ability to innovate and develop new materials.

A.12 KNOWLEDGE GAP: STEEL

A detailed review of the previously discussed academic articles, along with additional studies, industry reports and numerous industry expert interviews, has revealed a number of research gaps regarding the availability and understanding of data regarding the flow of iron and steel into the USA automotive industry. As discussed in the studies above, in-use stock of iron and steel can be easily obtained from existing data sources. While, none of the studies highlighted break down the use-phase beyond transportation, automotive stock in the USA can be estimated using both top-down and bottom-up approaches (Hirato et al. 2009). Furthermore, through industry data sources and the methods described previous, the amount of steel and iron flowing into the automotive industry and be calculated. Lastly, it is important to highlight that import and export data for steel and iron is accessible through international trade databases such as the UN Comtrade database.

The key gap in current knowledge and research exists in the connection between each of these key sources of data. As of yet, no publicly obtainable data set includes data outlining the regionality of automotive steel and iron. Import data into the USA for raw steel and iron and semis cannot be easily tracked to a specific sector or industry. Previous studies examine the steel and iron industry as a whole, and do not breakdown the production flows or import flows by sector. In order to examine the automotive industry specifically, estimations will be required to determine the regional flow of the metals unless additional industry data is uncovered.

A.13 PROPOSED METHODS

In this section, three initial proposed methods to identify regionality of automotive metals (steel and iron and aluminum) are presented: A top-down method that applies the domestic end-use distribution of metal semis to imported semis in order to estimate at a country level who the automotive industry imports metal semis from and how much, a hybrid approach that calculates metal contents of imported automotive final products and relates said contents to the country of export, and a bottom-up approach that relies on pinpointing contracts between major automotive OEMs and metals manufacturers to estimate automotive steel and iron and aluminum source location.

A.13.1 TOP DOWN APPROACH

A top-down approach, visualized in Figure A 24, to capture source locations of steel and iron and aluminum semis that go into the automotive industry is presented here and suggests that the USA domestic end-use distribution of metals semis be applied to country level semis import amounts. Doing so would estimate the amount of imported semis from a country that goes into the USA automotive industry, obtaining regionality. Major limitations of this proposed approach include assumptions that it would only be able to be applied to semis, each country adheres to the domestic end-use distribution of semis, and each country exports semis to the USA automotive industry. Further, a method to calculate uncertainty in this approach remains uncertain.

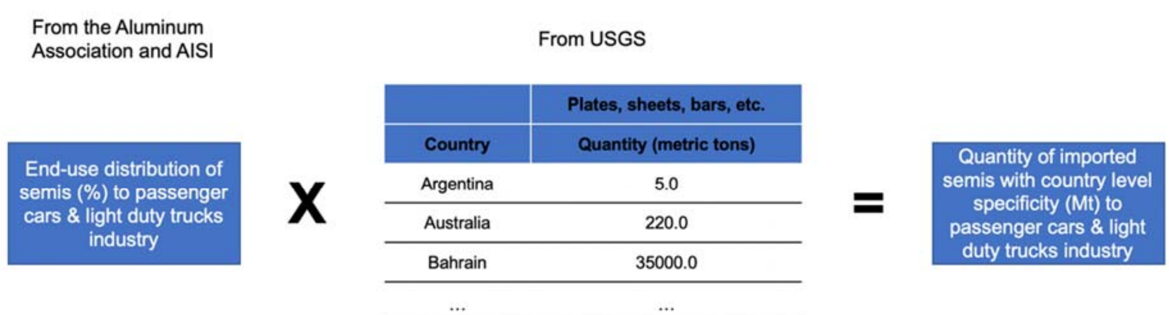


Figure A 24: The proposed top-down approach to identify source location and amount of imported metals semis into the USA automotive industry at a country level by applying the USA domestic end-use distribution to all imported metals semis

A.13.2 HYBRID APPROACH

A hybrid approach can be employed to determine the quantity and regionality of imported stel and aluminum finished goods bound for the automotive industry (Figure A 25). Using UN Comtrade data, trade flow quantities into the USA can be obtained on a country-specific basis. For automotive specific finished products, HS codes can be used to obtain the import data. For each finished product, the composition of steel, iron and aluminum must then be estimated to determine the mass of metal per product. The product of the finished good quantity by country and the good's composition can be used to determine the amount of metal flowing into the industry. This approach is limited in that it only applies to trade codes that are specific to the automotive industry. It also depends on the ability to determine average compositions and mass estimates for all parts.

Figure A 25: The proposed hybrid approach to identify location and amount of imported finished goods into the USA automotive industry at a country level by analyzing the UN Comtrade databae

A.13.3 BOTTOM UP APPROACH

Finally, a bottom-up approach can be leveraged to estimate national regionality and international trade flows from specific supplier contracts (Figure A 26). First, key automotive manufacturer contracts for steel, iron and aluminum can be identified, along with specific supplier mill location and distribution centers. The vehicle specific research can then be applied as an estimate across the industry by estimating the stock of automobiles (e.g., passenger cars and light duty trucks) in the United States. By applying the specific contract regionality to the entire market, the overall quantity of flow from specific locations can be estimated. The major limitation to this method is the assumption that a specific contract is representative of the industry as a whole. Furthermore, it may be difficult, through publicly available information to identify contracts and specific suppliers.

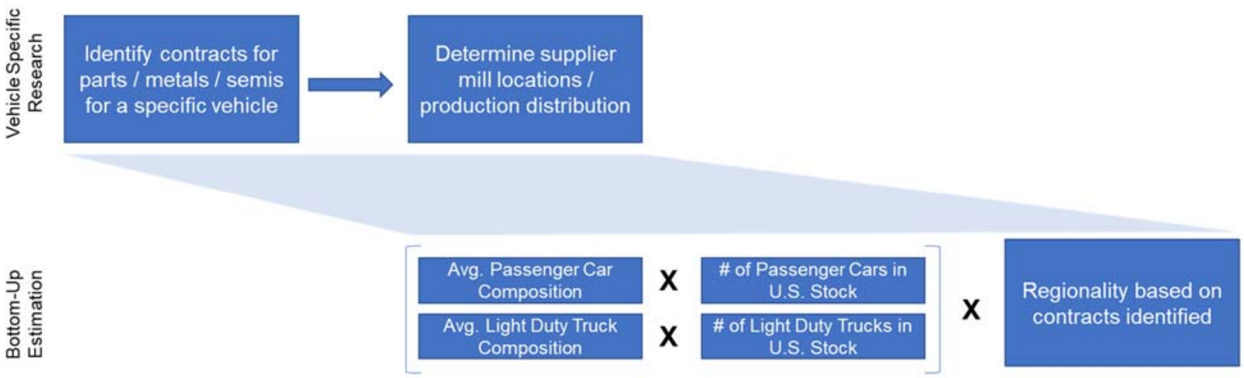


Figure A 26: The proposed bottom-up approach to identify location and amount of metals used in the USA automotive industry by considering specific vehicle contracts and total USA automobiles in stock

A.14 CONCLUSION

The information provided in this report, from reviewing steel and iron and aluminum material flow analyses literature, will hopefully inform the development of a method to account for the regionality of automotive metals sourcing.

Motivating the need for a regionally linked, dynamic automotive metals material flow analysis is a trade-off that automotive OEMs face. In order to maximize profit margins and maintain competitive advantage in the market, automotive OEMs must make economic metals sourcing decisions which may be at the expense of environmental stewardship as different metals manufacturers operate on different grids with varying energy and GHG intensities. With the recent special report from the IPCC on the impacts of global warming of 1.5C—released in October 2018—and the Fourth National Climate Assessment—released in November 2018—detailing imminent consequences of climate change caused by anthropogenically accelerated

GHG emissions to the atmosphere, the need to accurately characterize the energy pain points along automotive metals supply chains is eminent in order to understand the domestic and global impacts of these automotive metals and help the automotive industry mitigate said impacts moving forward, especially as the industry continues to innovate its metal usage in vehicles

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Regional-level analysis for the material flows and process energy demands of aluminum and steel in the American automotive industry

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APPENDIX B

B.1 HS CODES USED FOR TRACKING IMPORTS OF UPSTREAM MATERIAL PRODUCTS ALONG ALUMINUM LIFE CYCLE

Table B 1: The UN Comtrade HS codes used to track trade flows of alumina and bauxite.

Material Product	HS Code(s)
Alumina	281820 281830
Bauxite	2606

B.2 PROXY METHODS AND EXAMPLE CALCULATIONS

B.2.1 NORTH AMERICAN PRIMARY ALUMINUM MIX

To determine USA primary aluminum locational production, Producer H's 10-K SEC filing was consulted and production values at each of Producer H's smelter locations were extracted. Producer G's primary aluminum production was then back calculated according to Equation B 1 as there were only two primary aluminum producing companies in the USA in 2016. The back calculated production of primary aluminum by Producer G barely exceeded the combined capacity of each identified Producer G smelter location. Each smelter location for Producer G was first assumed to produce at capacity and then scaled up by capacity weight following Equation B 2 in order to meet the back calculated production value from Equation B 1.

Equation B 1: Back calculating company level production of primary aluminum in the USA

$$Primary\ Aluminum\ Production_{Producer\ G} = Primary\ Aluminum\ Production_{USA\ Total} - Primary\ Aluminum\ Production_{Producer\ H}$$

Equation B 2: Capacity scaling primary aluminum smelters for Producer G

$$Primary\ Aluminum\ Production_{Location\ G1} = Primary\ Aluminum\ Production\ Capacity_{Location\ G1} + \left(\frac{Primary\ Aluminum\ Production\ Capacity_{Location\ G1}}{Primary\ Aluminum\ Production\ Capacity_{Producer\ G}}\right)(Primary\ Aluminum\ Production_{Producer\ G} - Primary\ Aluminum\ Production\ Capacity_{Producer\ G})$$

To determine Canadian primary aluminum locational production, the capacity at each smelter location was first identified. Similar to the situation in the USA, the cumulative capacity of Canadian primary aluminum at all smelter locations is barely less than the reported production by The Aluminum Association (AA, 2017), henceforth referred to as AA. Equation B 2 is therefore used to determine the production at each Canadian primary aluminum smelter location.

Primary aluminum producer market shares are calculated via Equation B 3. Within each primary aluminum producer, location supply shares are calculated following Equation B 4.

Equation B 3: Determining primary aluminum producer market shares of the total NA primary aluminum supply mix

$$Primary\ Aluminum\ Producer\ Market\ Share_{Producer\ A} = \frac{Primary\ Alumium\ Production_{Producer\ A}}{Primary\ Aluminum\ Production_{Total}}$$

Equation B 4: Determining a primary aluminum producer's location supply share

$$Primary\ Aluminum\ Producer\ Location\ Supply\ Share_{Location\ A1} = \frac{Primary\ Aluminum\ Production_{Location\ A1}}{Primary\ Aluminum\ Production_{Producer\ A}}$$

B.2.2 CREATING THE VERTICAL INTEGRATION SUPPLY MIX

Using production values of each vertically integrated mill product producer, the total amount of primary aluminum required from the vertically integrated primary aluminum producer was calculated following Equation B 5. The post vertical integration supply of primary aluminum by the vertically integrated primary aluminum producer was then calculated using Equation B 6 and that producer's share of the total North AAmerican (NA) primary aluminum supply was calculated following Equation B 7. Pre vertical integration primary aluminum producer location supply shares from Equation B4 were then applied to the primary aluminum required from the vertically integrated primary aluminum producer, calculated from Equation B 5, and the resulting amounts were subtracted from each respective location. These values were then used to calculate post vertical integration primary aluminum producer location supply shares using Equation B 4.

Equation B 5: Identifying the primary aluminum required

$$\frac{Mill\ Product\ Production_{Producer\ A}}{Mill\ Product\ Fabrication\ Efficiency} * Mill\ Product\ Primary\ Aluminum\ Content = Primary\ Aluminum\ Required_{Producer\ A}$$

Equation B 6: Post vertical integration supply of primary aluminum of a primary aluminum producer

$$Primary\ Aluminum\ Production_{Producer\ A} - Primary\ Aluminum\ Required_{Producer\ G} = Post\ Vertical\ Integration\ Primary\ Aluminum\ Production_{Producer\ A}$$

Equation B 7: Post vertical integration primary aluminum producer share of total NA primary aluminum supply

$$\frac{Post\ Vertical\ Integration\ Primary\ Aluminum\ Production_{Producer\ A}}{Post\ Vertical\ Integration\ Primary\ Aluminum\ Production_{Total}} = Post\ Vertical\ Integration\ Primary\ Aluminum\ Producer\ Market\ Share_{Producer\ A}$$

B.2.3 FABRICATION EFFICIENCY OF AUTOMOTIVE ALUMINUM SHEET

Automotive aluminum sheet is assumed to be first hot rolled and then cold rolled. Given this sequenced process, the fabrication efficiency of automotive aluminum sheet from aluminum ingots is calculated using hot and cold rolling efficiencies from AA (AA, 2013) to be ~0.774.

B.2.4 MILL PRODUCT PRODUCER MARKET SHARE USING FINANCIAL INVESTMENT PROXY

Financial investment information into aluminum mill product production capacity was one method used to proxy mill product producer market shares. The general formula used for this proxy is shown in Equation B8.

Equation B 8: Mill product producer market share using financial proxy

$$Mill\ Product\ Producer\ Market\ Share_{Producer\ A} = \frac{Mill\ Product\ Production\ Capacity\ Investment_{Producer\ A}}{Total\ Mill\ Product\ Production\ Capacity\ Investment\ By\ All\ Producers}$$

B.2.5 MILL PRODUCT PRODUCER MARKET SHARES USING OTHER PROXIES

If a mill product producer reported a market share for the NA extrusions market in a 10-K SEC filing, investor presentation, or on their website, it was used directly as the producer's market share. If a mill product producer reported a total mass of automotive aluminum extrusions shipped in a 10-K SEC filing, investor presentation, or on their website, that value was divided by the total amount of automotive aluminum extrusions shipped given in AA's industry statistics to determine the mill product producer's market share. If a mill product producer reported a general amount of aluminum extrusions shipped in a 10-K SEC filing, investor presentation, or on their website as well as information on the percentage of their aluminum extrusion sales to the automotive market, the automotive aluminum sales percentage was applied to the general amount of aluminum extrusions shipped to determine the mill product producer's market share.

For automotive aluminum extrusions specifically, it is reported that aside from four major producers, the market is highly local (Sapa, 2017). Therefore, a Local region was established to capture the rest of the market share after the four major producers.

B.2.6 MILL PRODUCT PRODUCER LOCATION SUPPLY SHARE USING EPA GHGRP PROXY

Facility level emissions data for select mill product producer locations can be collected via the USA Environmental Protection Agency's (USA EPA) Greenhouse Gas Reporting Program (GHGRP) (USA EPA, 2019). Using process energy intensities for a given mill product from AA (AA, 2013), NERC region emission factors, and fossil fuel combustion emission factors, an amount of mill product production at a given location can be estimated. This proxy process is reflected in Equation B 9-Equation B 11.

Equation B 9: Automotive aluminum sheet emissions from natural gas

$$Automotive\ Aluminum\ Sheet\ Production\ Emissions\ Factor_{NG} = \left(\left(\frac{3812.315\ MJ}{mt\ Hot\ Rolled}\right)\left(\frac{1.244718\ mt\ Hot\ Rolled}{mt\ Cold\ Rolled}\right) + \frac{2196.06\ MJ}{mt\ Cold\ Rolled}\right)\left(\frac{0.102\ kg\ CO_2e}{MJ}\right)\left(\frac{1\ mt}{1000\ kg}\right)$$

Equation B 10: Automotive aluminum sheet emissions from electricity

$$Automotive\ Aluminum\ Sheet\ Production\ Emissions\ Factor_{Electricity} = \left(\left(\frac{113.424\ kWh}{mt\ Hot\ Rolled}\right)\left(\frac{1.244718\ mt\ Hot\ Rolled}{mt\ Cold\ Rolled}\right) + \frac{366.202\ kWh}{mt\ Cold\ Rolled}\right)\left(NERC\ Region\ Emission\ Factor\ in\ \frac{kg\ CO_2e}{kWh}\right)\left(\frac{1\ mt}{1000\ kg}\right)$$

Equation B 11: Estimated automotive aluminum sheet production using EPA GHGRP proxy method

$$Estimated\ Automotive\ Aluminum\ Sheet\ Production_{Location\ A1} = \frac{EPA\ GHGRP\ Reported\ Emissions_{Location\ A1}}{Combined\ Automotive\ Aluminum\ Sheet\ Production\ Electricity\ and\ Natural\ Gas\ Emissions\ Factor}$$

For mill product producer locations without USA EPA GHGRP data, 10-K SEC filings, investor presentations, and company websites were consulted to make estimates on the order of magnitude of production at the location.

B.2.7 MILL PRODUCT PRODUCER LOCATION SUPPLY SHARE USING FINANCIAL AND CAPACITY INVESTMENT PROXY

Financial investment information on mill product production capacity at mill product producer locations was leveraged to proxy mill product production when available. Old installed capacity and new installed capacity information was extracted to weight production between locations by new capacity. Equation B12 was used in for the calculation.

Equation B 12: Estimating mill product producer location supply shares using financial and capacity investment proxy

$$\text{Mill Product Producer Location Supply Share}_{Location\ B1} = \frac{\text{Mill Product Production Capacity}_{Location\ B1}}{\text{Total Mill Product Producer Production Capacity}_{Producer\ B}}$$

B.2.8 MILL PRODUCT PRODUCER LOCATION SUPPLY SHARE USING VEHICLE COMPOSITION DATA

The 2016 Ford F-150 used an aluminum body. Consulting mill product producer 10-K SEC filings, it was identified that Producer C's Location C2 contributed 6kg of aluminum extrusions per 2016 F-150. With an estimate that 850,000 F-150 trucks were produced in 2016 (Ducker, FSG Holdings, LLC [Ducker], 2016), it was determined that over 5 million kgs of aluminum extrusions came from Producer C's Location C2. This mass was divided by Producer C's total automotive aluminum extrusions supply to determine a supply share for Producer C's Location 2.

B.2.9 MILL PRODUCT PRODUCER LOCATION SUPPLY SHARE USING UNIFORM DISTRIBUTIONS

If no proxy methods were able to be used to estimate production at any mill product producer location within a mill product producer, a uniform distribution was applied where each location was determined to contribute an equal supply share.

In the case of Producer C, because a production estimate for Location C2 was able to be determined but not necessarily comprehensively, the remaining percentage of mill product supply after subtracting out Location C2's estimated supply hold was uniformly distributed to all Producer C locations, including Location C2.

B.2.10 CALCULATING SCRAP MASS FLOWS

While regional flows of aluminum scrap were not tracked in this study, general mass flows of scrap were calculated according to the generalized Equation 13.

Equation B 13: Generalized equation to determine mass flows of aluminum scrap

$$Mass_{scrap} = \frac{Mass_{primary\ aluminum}}{Mill\ Product\ Primary\ Aluminum\ Content} - Mass_{primary\ aluminum}$$

B.2.11 CALCULATING PROCESS ENERGY DEMAND BY ENERGY TYPE

Calculations to determine the process electricity delivered, process electricity required in terms of generation, process natural gas required, process heavy oil required, process diesel oil required, and process coal required for each mass flow of each material product used Equation B 14-Equation B 19. Higher heating values (HHV) used for diesel oil, heavy oil, and coal were extracted from USA EPA (USA EPA, 2018) where the HHV for diesel oil was assumed to be an average of distillate fuel oil number 1, 2, and 4, the HHV for heavy oil was assumed to be the same as for crude oil, and the HHV for coal was assumed to be for the industrial sector.

Equation B 14: General equation to calculate process electricity required

$$Process\ Electricity\ Required = Mass\ (mmlbs) * \frac{453.60\ mt}{mmlbs} * Electricity\ Intensity\ \left(\frac{kWh}{mt}\right)$$

Equation B 15: General equation to calculate electricity generation required for a process

$$Generated\ Electricity\ Required\ For\ Process = \frac{Process\ Electricity\ Required}{T\&D\ Efficiency}$$

Equation B 16: General equation to calculate process natural gas required

$$Process\ Natural\ Gas\ Required = Mass\ (mmlbs) * \frac{453.60\ mt}{mmlbs} * Natural\ Gas\ Required\ \left(\frac{mmBtu}{mt}\right) * \frac{1055MJ}{mmBtu}$$

Equation B 17: General equation to calculate process heavy oil required

$$Process\ Heavy\ Oil\ Required = Mass\ (mmlbs) * \frac{453.60\ mt}{mmlbs} * Heavy\ Oil\ Required\ \left(\frac{kg}{mt}\right) * \frac{40.49\ MJ}{kg}$$

Equation B 18: General equation to calculate process diesel oil required

$$Process\ Diesel\ Oil\ Required = Mass\ (mmlbs) * \frac{453.60\ mt}{mmlbs} * Diesel\ Oil\ Required\ \left(\frac{kg}{mt}\right) * \frac{43.94\ MJ}{kg}$$

Equation B 19: General equation to calculate process coal required

$$Process\ Coal\ Required = Mass\ (mmlbs) * \frac{453.60\ mt}{mmlbs} * Coal\ Required\ \left(\frac{kg}{mt}\right) * \frac{25.99\ MJ}{kg}$$

Equation B 20: General equation to calculate total process energy demand

$$\begin{aligned} Total\ Process\ Energy\ Demand \\ &= Generated\ Electricity\ Required\ for\ Process + Process\ Heavy\ Oil\ Required \\ &+ Process\ Diesel\ Oil\ Required + Process\ Natural\ Gas\ Required \\ &+ Process\ Coal\ Required \end{aligned}$$

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APPENDIX C

C.1 HS CODES USED FOR TRACKING IMPORTS OF UPSTREAM MATERIAL PRODUCTS ALONG STEEL LIFE CYCLE

Table C 1: The UN Comtrade HS codes used to track trade flows of coke, coking coal, iron ore, lime, scrap, DRI, and pig iron.

Material Product	HS Code(s)
Coke	2704
Coking Coal	270112
Iron Ore	2601
Lime	251820 2522
Scrap	720441 720449
DRI	7203
Pig Iron	720110

C.2 PROXY METHODS AND EXAMPLE CALCULATIONS

C.2.1 AUTOMOTIVE STEEL SHEET PRODUCER MARKET SHARE USING SALES WEIGHTED PRODUCTION ESTIMATES.

Steel sheet shipments to markets in the USA by steel sheet producers were identified by consulting producer 10-K SEC filings. Splits of steel sheet shipments by sheet product and percentages of sales to the automotive market were also extracted. If splits of steel sheet shipments by sheet product were unavailable, producer websites were consulted to see if a given producer produced a given steel sheet product. These factors were combined in accordance with Equation C 1 to estimate steel sheet producer market shares by sheet product.

Equation C 1: Proxy calculation to determine the LDV share of automotive steel

$$BOF\ Steel\ Sheet\ Producer\ Market\ Share\ For\ A\ Given\ Sheet\ Product = \frac{Steel\ Sheet\ Shipments\ in\ USA * \%\ of\ Shipments\ to\ Automotive\ Sector *\ Given\ Sheet\ Product\ Shipment\ \%}{Total\ Given\ Sheet\ Product\ Shipments\ to\ American\ Automotive\ Sector}$$

C.2.2 AUTOMOTIVE STEEL SHEET PRODUCER LOCATION SUPPLY SHARES USING PRODUCTION ESTIMATE PROXY

When available, automotive steel sheet producer location level production data was extracted or extrapolated given contextual implications from producer 10-K SEC filings, investor presentations, and producer websites. Information about what steel sheet products each location producers was gathered from the same sources. A location's total production was allocated equally to the different types of steel sheet the location was identified to produce. Location supply shares were then weighted following Equation C 2.

Equation C 2: Proxy formula for estimating automotive steel sheet producer location supply shares via production estimates

$$Automotive\ Steel\ Sheet\ Producer\ Location\ Supply\ Share\ of\ a\ Specific\ Steel\ Sheet\ Product = \frac{\frac{Location\ Steel\ Sheet\ Production}{\#\ of\ Identified\ Steel\ Sheet\ Products\ Location\ Produces}}{Total\ Amount\ of\ Specific\ Steel\ Sheet\ Produced\ by\ the\ Automotive\ Steel\ Sheet\ Producer}$$

C.2.3 AUTOMOTIVE STEEL SHEET PRODUCER LOCATION SUPPLY SHARES USING UNIFORM DISTRIBUTION

When no information was available to proxy automotive steel sheet producer location production, uniform distributions were applied so that every location for a given automotive steel sheet producer held the same supply share.

C.2.4 USA ELECTRIC ARC FURNACE CRUDE STEEL REGION SUPPLY SHARES USING FACILITY LOCATIONS PROXY

In 2017, there were 54 companies producing electric arc furnace (EAF) crude steel at 110 minimills in the USA (Fenton, 2018a). The sheer number of EAF crude steel producing locations amplifies the difficulty in identifying location level production values. Because of this, a method weighting EAF crude steel production by NERC region based upon number of locations was used to identify EAF crude steel region supply shares. Knowing the number of BOF and EAF crude steel producing locations and utilizing a map from IBISWorld (Hadad, 2017) that identifies location distribution by state, a number of EAF crude steel producing locations was determined for each state. States were then aggregated by NERC region, where all of a state's EAF crude steel producing locations were allocated to the NERC region that the state was primary encompassed by on an area basis. This proxy method assumes that each EAF crude steel producing location produces the same amount of EAF crude steel.

C.2.5 USA DISTRIBUTION OF AUTOMOTIVE STEEL MILL PRODUCTS PRODUCED VIA EAF CRUDE STEEL USING FACILITY LOCATION PROXY

The distribution of EAF crude steel production by NERC region within the USA and described in section C.3.4 was applied to automotive steel mill products that were identified to having been produced via EAF crude steel.

C.2.6 REGIONAL DISTRIBUTION OF STEEL IN FINISHED AUTOMOTIVE PARTS USING COUNTRY LEVEL BOF AND EAF CRUDE STEEL PRODUCTION SPLITS

Steel in finished automotive parts entering the American automotive industry were assumed to be produced from both BOF and EAF crude steel and weighted by each supplying countries' percentage of crude steel production by both processes.

Within the USA, steel in finished automotive parts entering the American automotive industry that was identified to have been produced via EAF crude steel was further disaggregated by NERC region in accordance with the distribution scheme described in section C.3.4.

C.2.7 REGIONAL WEIGHTING SCHEME FOR USA COKE SUPPLY USING CAPACITY AND CENSUS DIVISION SUBTRACTION PROXY

Coke producing locations, identified from the American Coke and Coal Chemicals Institute (ACCCI, 2016) were associated with a NERC region and census division. The company websites for each coke production location were consulted to extract location coke production capacities where available. Information was also gathered from that estimated the capacity of coke production per coke oven (Haryanto, 2012). If a coke production location released its number of coke ovens in operation, capacity was able to be back calculated. The USA Energy Information Administration's (EIA) quarterly coal report was also consulted to identify coke production in the USA by census division. Three coke production locations were located in the SERC region, one in the NYPP region, and the rest in the RFC region. With respect to census divisions, two coke production locations were located in the East South Central division, eight in the East North Central division, three in the Middle Atlantic division, and two in the South Atlantic division. Through a combination of location production capacity identification and subtraction of identified production capacities from reported census division values, coke production was able to be identified and weighted by NERC region.

C.2.8 REGIONAL WEIGHTING SCHEME FOR USA IRON ORE USING PRODUCTION VALUES

Only two states produced iron ore in the year 2017 (Tuck, 2018a). The total iron ore production in the USA was given by the United States Geological Survey (Tuck, 2018b). The production of iron ore in one state was able to be identified using a report from Cleveland-Cliffs Inc. (Cleveland-Cliffs Inc., 2018). The production of iron ore in the other state was then able to be back calculated. The states were then assigned to their appropriate NERC region.

C.2.9 REGIONAL WEIGHTING SCHEME FOR USA DIRECT REDUCED IRON USING PRODUCTION VALUES

Three USA direct reduced iron (DRI) production locations were identified for the year 2017. The company websites for each of these DRI production locations were consulted to extract location production values. Each of the three locations were assigned to their appropriate NERC region and supply shares were weighted by production.

C.2.10 CALCULATING PROCESS ENERGY DEMAND BY ENERGY TYPE

Process energy demands for each energy input type and at each material product stage were calculated using equations similar to those (Equation B 14-Equation B 20) described in Appendix B.

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