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RESEARCH AND ANALYSIS

Regional analysis of aluminum and steel flows into the American automotive industry

Nate P. Hua[1] | Jarod C. Kelly[2] | Geoffrey M. Lewis[1] | Gregory A. Keoleian[1]

[1]Center for Sustainable Systems, School for Environment and Sustainability, University of Michigan, Ann Arbor, Michigan, USA

[2]Argonne National Laboratory, Lemont, Illinois, USA

Correspondence
Geoffrey M. Lewis, Center for Sustainable Systems, School for Environment and Sustainability, University of Michigan, Ann Arbor, Michigan, USA.
Email: glewis@umich.edu

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Abstract

Aluminum and steel represent the two most dominant metals in light-duty vehicles, yet the flows of these materials into the American automotive industry have not been well characterized. This study proposes and implements a method for analyzing the flow of these metals into the automotive industry. We create a framework for performing regionally linked, sector-specific material flow analyses and use this framework to trace flows of aluminum and steel entering the American automotive industry, focusing on flows downstream from raw material production. We show that automotive aluminum sheet and extrusions are sourced primarily from the NPCC (23%), SERC (20%), MRO (18%), and RFC (13%) North American Electric Reliability Corporation (NERC) regions, and a spatially unresolved local region within the United States and Canada (18%). We determine that primary aluminum is largely from Canada (70%), nearly all from Quebec (69%). Further upstream, alumina and bauxite originate mostly from Brazil, Australia, and Jamaica. We also show that finished automotive steel is sourced primarily from the RFC (63%) and SERC (20%) regions. The crude steel supply similarly originates mainly from the RFC (69%) and SERC (7%) regions. Upstream raw materials including coke, coking coal, iron ore, lime, and steel scrap are primarily sourced from the United States with only direct reduced iron and pig iron used in electric arc furnace steel production coming mostly from outside the United States. The framework developed here allows for increased spatial resolution of material flows, which can be used to develop more specific life cycle impact factors for life cycle assessments.

KEYWORDS
aluminum, automotive industry, industrial ecology, material flow, regional analysis, steel

1 | INTRODUCTION

Aluminum and steel are the two most dominant metals in light-duty vehicles (LDVs), representing 12% and 54% of an LDV's curb weight in 2018 (Ducker FSG Holdings, LLC, 2018), and significantly influencing its life cycle impacts. Aluminum use in LDVs is projected to continue increasing (Ducker FSG Holdings, LLC, 2017b) as automakers seek to further improve fuel economy by reducing vehicle weight, primarily through expanded use of aluminum sheet and extrusions (S&Es) (Ducker FSG Holdings, LLC, 2017a). While vehicle lightweighting with aluminum can provide benefits in reducing operational emissions, the strategy is not without consequence since automotive-grade aluminum S&Es often require a high fraction of primary aluminum (ANL, 2018), which is very electricity intensive (World Aluminum, 2017).

Steel has long been the predominant metal used in LDVs and will maintain that status in the near future (Ducker FSG Holdings, LLC, 2017b). While automotive-grade steel has traditionally been produced via basic oxygen furnace (BOF), which is heavily coal dependent, the lower energy but electricity-intensive electric arc furnace (EAF) production method of melting steel scrap, pig iron, and direct reduced iron (DRI) is projected to increase (Tolomeo et al., 2019).

There is a long-standing interest in characterizing flows of aluminum and steel. Beginning in the early 2000s, researchers used material flow analysis (MFA) to study stocks and flows of aluminum (Hatayama et al., 2007; Martchek, 2006) and steel (Müller et al., 2006; Wang et al., 2007). Researchers subsequently studied the flows of these two metals at the global level (Cullen & Allwood, 2013; Cullen et al., 2012; Global Aluminum Recycling Committee [GARC], 2009; Hatayama et al., 2010; Menzie et al., 2010; Yellishetty et al., 2010) and country level for the United States (Chen & Graedel, 2012; Pauliuk et al., 2013), Austria (Buchner et al., 2014), the United Kingdom (Geyer et al., 2007), Japan (Hirato et al., 2009), Korea (Park et al., 2011), Australia (Yellishetty & Mudd, 2014), and China (Chen & Shi, 2012; Ding et al., 2016; Reck et al., 2010). While these studies account for major flows of aluminum and steel into large economic sectors such as transportation, they do not resolve the supply locations of these flows. More specific aluminum MFAs have created trade-linked maps of the contemporary global flows of aluminum (Liu & Müller, 2013), have combined trade-linked multilevel MFA with life cycle assessment (LCA) to develop country-level impact factors for primary aluminum consumption and production (Milovanoff et al., 2021), 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 US passenger vehicles and their implications for energy use (Cheah et al., 2009), but these MFAs do not define regional sources of aluminum entering a specific sector. Steel MFAs have helped inform circular economy theory (Pauliuk et al., 2012; Wang et al., 2013), identified regional distribution of steel scrap to be dependent on quality and application (Pauliuk et al., 2017), and developed a physical input–output method to identify a steel product and its location in an LDV (Nakamura et al., 2011), but literature on the regional distribution of steel material flows into a particular sector is lacking.

LCAs of LDVs have used aggregate greenhouse gas (GHG) impact factors for aluminum and steel production (Dai et al., 2017; Kelly et al., 2015), but the reality is that these impact factors vary across space, primarily due to regional differences in electricity fuel sources (Colett et al., 2016). Illustrating these differences, estimates for North American Electric Reliability Corporation (NERC) region GHG emission factors range from 283 g/kWh in NPCC to 638 g/kWh in MRO (ANL, 2018). The American automotive industry's supply chains are also incredibly complex, with materials and components being sourced from a large variety of suppliers and locations. These factors, and the current and projected dominance of aluminum and steel in LDVs, motivate the need for higher spatial resolution of material flows. Such regionality could be used both to better characterize the GHG impacts of aluminum and steel in LDV production through use of localized energy parameters, and to better understand a region's energetic relationship to the automotive industry.

This paper addresses the gap in spatial resolution of MFAs in general and aluminum and steel flows into the American automotive industry in particular. The work described here aims to: (1) develop a framework to regionalize the flows of a given material entering a specific sector; (2) apply that framework to regionalize aluminum and steel flows entering the American automotive industry to the NERC level in the United States, whenever possible, and to the country level outside the United States, and (3) inform the development of more specific life cycle impact factors for LCAs, particularly for automotive aluminum and steel.

2 | METHODS

2.1 | Regionally linked, sector-specific MFA framework

MFAs are traditionally conducted using a top-down or bottom-up approach. While each of these approaches accounts for material flows into defined categories such as mining and raw material production, they lack the ability to regionally allocate the flows of a material into a specific sector. To address this shortcoming, we have developed a general framework to disaggregate and regionalize material flows entering the process of product fabrication and subsequent upstream steps. This method is outlined in Figure 1.

Our method begins by establishing spatial and temporal boundaries for the system of interest. Industry shipment data of a specific material product to a specific sector are gathered and material product producers and their locations are identified through market research. Regional flows of material products (the fifth step in Figure 1) are then disaggregated primarily through proxy schemes that use sales, shipment, production capacity, and investment data since market share and facility-level production data are often not publicly available. These proxy schemes are described further in the Supporting Information (SI) as well as in Hua et al. (2019). This disaggregation procedure is then repeated for upstream material inputs.

Our framework can be viewed as a hybrid MFA approach marrying statistical data and pathway weighting with trade information across a large spatial extent to model unique paths of material flows into a specific sector. It will require tailoring for a specific material and sector, but we present it as a guide to future regionally linked, sector-specific MFAs. To demonstrate how the framework can be used effectively, we apply it here to aluminum and steel entering the American automotive industry and describe our procedure in detail.

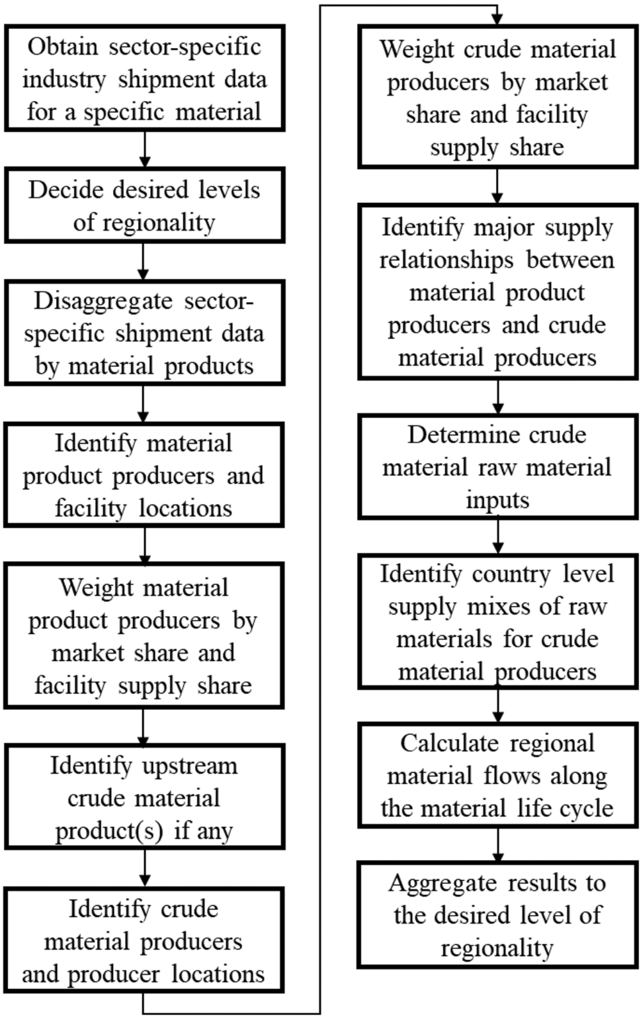

FIGURE 1 Regionally linked, sector-specific framework and process flow diagram

2.2 | Regionally linked automotive aluminum MFA

The system boundaries (Figure 2) for the automotive aluminum system were dictated by the resolution of industry data from the Aluminum Association (AA, 2017). We defined the spatial boundary of the American automotive industry to include the United States and Canada and the temporal boundary was 2016.

Mass flows analyzed only include those associated with S&E wrought aluminum to the American automotive industry. This decision was based upon the assumption that aluminum S&Es are expected to grow in LDV application while use of aluminum castings in LDVs is projected to remain flat (Ducker FSG Holdings, LLC, 2017a). We recognize that aluminum scrap and secondary aluminum are growing in automotive S&E application, but our data did not enable us to incorporate these materials into our analysis, and flows of these materials into the American automotive industry were not included in this study. Further research into regionalizing aluminum scrap and secondary aluminum flows is recommended as the aluminum industry and automotive manufacturing innovation continue to evolve. The regional units for this analysis, largely determined by data availability, were NERC regions for the United States (emphasizing the influence of electricity fuel mix on environmental impacts), provinces for Canada, and countries elsewhere. Additionally, the focus was placed downstream of alumina production given the availability of industry data and relative environmental impacts (ANL, 2018).

2.2.1 | Automotive aluminum sheet and extrusions

Data on aluminum S&E shipments to the American automotive industry were obtained from AA's industry statistics. Market research was conducted to identify automotive aluminum S&E producers (AAS&EPs) and their locations through consultation with a variety of resources, which are

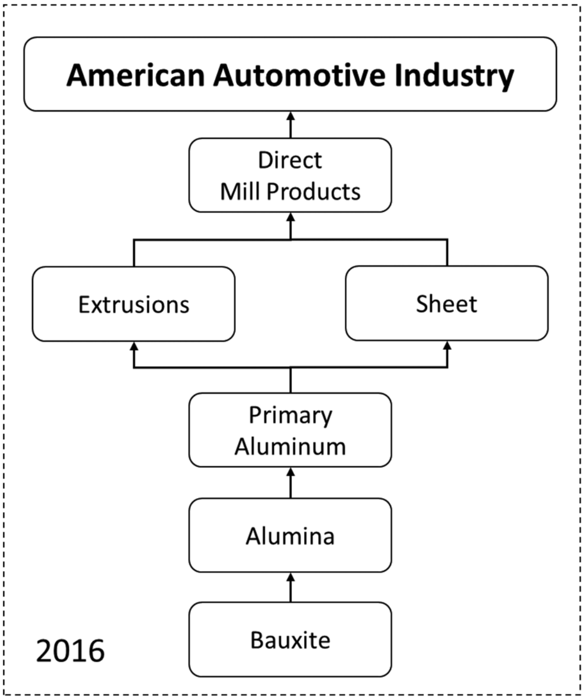

FIGURE 2 System boundary for automotive aluminum

listed in Section S1.1 of Supporting Information S1. Aluminum S&Es to the American automotive industry can be assumed to originate wholly from within the geographic boundaries of the United States and Canada. A Local region was established for automotive aluminum extrusions because, aside from four major producers, the supply of aluminum extrusions comes from producers near automotive original equipment manufacturers (OEMs) and tier 1 and tier 2 suppliers (SAPA, 2017).

AAS&EPs within the United States and Canada were assigned to their appropriate NERC region or Canadian province. AAS&EP market shares and intraproducer location supply shares were estimated either by using proxy schemes that use different sources of market data that can reasonably be associated with production, or by assuming uniform distributions. Detail on proxy schemes can be found in Section S1.2 of Supporting Information S1. Regional automotive aluminum mill product mass flows $M(\text{mill})_{j,l}$ were then calculated by multiplying the total mass of a given aluminum mill product M_j by its respective AAS&EP market share $A_{j,k}$ and intraproducer location supply share $B_{j,k,l}$, as seen in Equation (1):

$$M(\text{mill})_{j,l} = M_j \left(A_{j,k} \times B_{j,k,l}\right) \tag{1}$$

2.2.2 | Primary aluminum

Automotive aluminum S&E primary aluminum composition was assumed to be 89%, as in the GREET model (ANL, 2018). Applying the primary aluminum composition percentage and respective fabrication efficiencies to automotive aluminum sheet (77.36%) and extrusions (77.52%) (AA, 2013) yields the amount of primary aluminum required for these mill products.

We adapted a previously published US and Canadian supply mix for primary aluminum (Bushi, 2018) to provide detailed NERC region and Canadian province detail by marrying industry statistics from AA with production information from primary aluminum producers (PAPs). Details on this supply mix can be found in Section S1.3 of Supporting Information S1. Regions outside of the United States and Canada were kept at the country level due to lack of higher spatial resolution data.

To provide a more robust description of primary aluminum sourcing by AAS&EPs, we looked to identify supplier relationships. If a major supply relationship such as corporate spin-off or vertical integration was identified between an AAS&EP and PAP, that AAS&EP was assumed to source primary aluminum only from that PAP. The total amount of primary aluminum required by these AAS&EPs was then removed from the aluminum supply mix for the United States and Canada. Remaining AAS&EPs that did not mention major relationships with specific PAPs were assumed to source primary aluminum from the resulting primary aluminum supply after these modifications. Mass flows of primary aluminum were then calculated with Equation (2):

$$M(\text{primary})_n = \frac{M_j\,(A_{j,k} \times B_{j,k,l} \times C_j)}{D_j} \times E_m \times F_{m,n} \tag{2}$$

In Equation (2), $M(\text{primary})_n$ is the mass of primary aluminum from location n, M_j is the total mass of aluminum mill product j shipped to the American automotive industry, $A_{j,k}$ is the estimated market share of aluminum mill product j from producer k, $B_{j,k,l}$ is the estimated supply share of aluminum mill product j from producer k's location l, C_j is the primary aluminum content of aluminum mill product j, D_j is the fabrication efficiency of aluminum mill product j, E_m is the estimated market share of primary aluminum from producer m, and $F_{m,n}$ is the estimated supply share of primary aluminum from producer m's location n.

2.2.3 | Alumina and bauxite

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 the country level to the identified sources and mass flows of primary aluminum. These ratios can be found in Section S1.5 of Supporting Information S1. This determined the amount of alumina required by each PAP for automotive aluminum S&Es. Country-level alumina supply mixes were compiled for each primary aluminum-supplying country using United States Geological Survey (USGS) data (Bray, 2018), the United Nations (UN) Comtrade database for import and export data (UN, 2019a), and the rules in Equation (3) where P, E, and I represent production, exports, and imports, respectively. Though additional methods for resolving discrepancies in UN Comtrade import and export data exist (Milovanoff et al., 2021), the use of Equation (3) effectively illustrates the application of our novel MFA framework. Further, the focus of our study was on products downstream of raw materials. Future studies may expand upon our work for raw materials, but this focus was outside the scope of this study. Applying alumina supply mixes to each primary aluminum-supplying country's respective primary aluminum mass flow resulted in regionalized flows of alumina, as shown in Equation (4) where G is the units of alumina required to produce one unit of aluminum, H_o is the estimated market share of alumina from producer o, and $I_{o,p}$ is the estimated supply share of alumina from producer o's location p. A "Rest of World" alumina supply was calculated based on country-level alumina production and was assigned to primary aluminum-supplying countries that lacked UN Comtrade data:

$$\begin{aligned} &\text{If } P = 0 \text{ or } P < E : \text{Supply Mix} = I \\ &\text{If } P > E : \text{Supply Mix} = P - E + I \end{aligned} \tag{3}$$

$$M(\text{alumina})_p = \frac{M_j\,(A_{j,k} \times B_{j,k,l} \times C_j)}{D_j} \times E_m \times F_{m,n} \times G \times H_o \times I_{o,p} \tag{4}$$

Country-level bauxite supply mixes were determined following a similar procedure. These mixes were applied to country-level alumina mass flows to identify regionalized flows of bauxite following Equation (5), where J is the units of bauxite required to produce one unit of alumina, K_q is the estimated market share of bauxite from producer q, and $L_{q,r}$ is the estimated supply share of bauxite from producer q's location r:

$$M(\text{bauxite})_r = \frac{M_j\,(A_{j,k} \times B_{j,k,l} \times C_j)}{D_j} \times E_m \times F_{m,n} \times G \times H_o \times I_{o,p} \times J \times K_q \times L_{q,r} \tag{5}$$

2.2.4 | Scenario and sensitivity analysis

A scenario analysis was conducted to examine how different sourcing patterns and supply mixes of primary aluminum for automotive application influence regional flows of primary aluminum, alumina, and bauxite. The base scenario assumed the supply relationships between AAS&EPs and PAPs described earlier. The first alternative scenario assumed that each AAS&EP sourced primary aluminum from the adapted United States and Canada primary aluminum supply mix described in Section 2.2.2 to examine how a uniform sourcing pattern would affect regional flows. The second alternative scenario assumed the same primary aluminum sourcing pattern as the first alternative scenario but adapted the United States and Canada primary aluminum supply mix further by assuming that all aluminum ingot imports to the United States in 2016 were primary aluminum. Ingot imports to the United States were assumed to represent the imported ingot supply of both the United States and Canada since Canada is a large net exporter of aluminum ingots. This scenario analyzes the effect that increased primary aluminum imports has on the automotive aluminum supply chain. Estimated production at each PAP location in the United States and Canada was not changed in either alternative scenario.

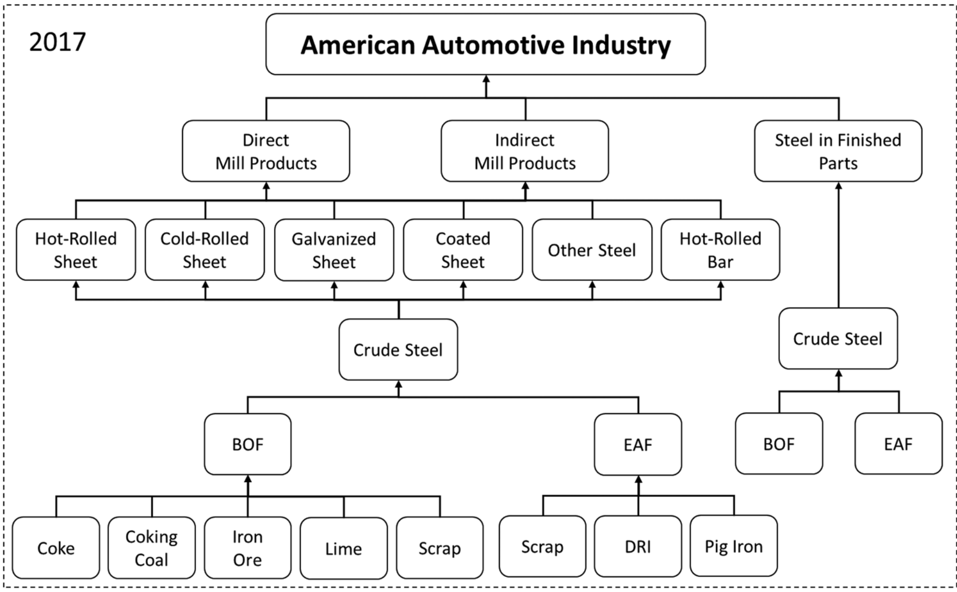

FIGURE 3 System boundary for automotive steel

Scenario and sensitivity analyses were also conducted for regional distributions of aluminum S&Es. The base case scenario weighted the regional distributions of automotive aluminum S&Es using a combination of proxy schemes informed by market data and uniform distribution methods. An alternative scenario assumed all AAS&EPs held equal market shares (by product category) to examine how a uniform sourcing pattern would affect regional flows. From this alternative scenario, a ± 10% sensitivity analysis was conducted for each AAS&EP market share to represent "reasonable" market share variation. Given its minimal impact on results, further exploration of this sensitivity was deemed unnecessary.

2.3 | Regionally linked automotive steel MFA

The system boundaries for the automotive steel system (Figure 3) were dictated by the resolution of industry data from the American Iron and Steel Institute (AISI, 2018). The spatial boundary of the American automotive industry was defined to be the United States and the temporal boundary was the year 2017.

The scope of the automotive steel system includes automotive steel mill products (ASMPs, which includes hot-rolled sheet, cold-rolled sheet, galvanized sheet, other coated sheet, hot-rolled bar, and other steel) as well as the steel contained in finished parts (SFP) like electronics and powertrain parts. Upstream materials—crude steel and its raw materials—are also included.

Ratios of ASMP to SFP are difficult to determine since vehicle teardowns, the primary source of these data, are rare. Estimates for the percentage of steel in an LDV for this study, 91% ASMP and 9% SFP, were averages of previous studies conducted by MEGA Associates (MEGA Associates, n.d.; Schnatterly, 2010, 2012).

The inclusion of both ASMP and SFP in our automotive steel system allowed us to estimate a total amount of steel entering the American LDV industry. This procedure, including a comparison to a bottom-up estimate, can be found in Section S1.7 of Supporting Information S1.

2.3.1 | Steel in finished automotive parts

Country shares of finished automotive parts supplied to the American automotive industry were obtained from Miles (2017). Due to supply chain complexity, inability to isolate flows of specific automotive parts, and uncertainties in steel content of automotive parts, we assumed that regional flows of SFP mimic those of finished automotive parts.

To obtain NERC region estimates for the SFP entering the American automotive industry, we assumed that steel was produced from BOF or EAF crude steel in the same ratio (32% BOF and 68% EAF) as for overall crude steel production in the United States (AISI, 2018). Steel produced via BOF and EAF crude steel was then assigned to the NERC regions of BOF and EAF crude steelmakers, respectively. The NERC level regionalization of BOF and EAF crude steelmakers is illustrated in Figure 4 and discussed further in Section 2.3.3. Data for countries supplying SFP to the American automotive industry were kept at country level but split by BOF and EAF crude steel production to trace raw materials (World Steel Association, 2018). Regional distribution percentages were applied to the total mass flow of SFP to obtain regional mass flows.

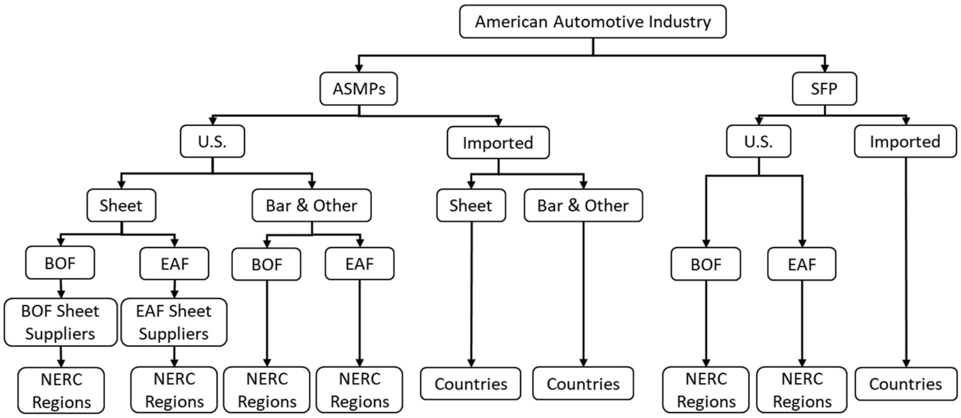

FIGURE 4 Regionalization of automotive steel flows

2.3.2 | Automotive steel mill products

ASMP can enter the American automotive industry directly or indirectly. The direct pathway involves automotive steel mill product producers (ASMPPs) shipping ASMPs directly to the American automotive industry. The indirect pathway involves ASMPPs shipping ASMPs to steel service centers or converters for further processing before they enter the American automotive industry. A direct-to-indirect ratio of ASMP shipments to the American automotive industry, 75% direct and 25% indirect, was an average of information extracted from MEGA Associates studies (Schnatterly, 2010, 2012; MEGA Associates, n.d.). Due to a lack of supply chain information regarding indirect shipments of ASMPs to the American automotive industry, the regionalization scheme of ASMPs discussed in this section was applied to both direct and indirect shipments.

We first determined the domestic US supply share of ASMPs using the American Automotive Policy Council's (AAPC's) conservative estimate of 85% (AAPC, 2017). Once disaggregated by country, we divided ASMPs by BOF or EAF crude steel input (see Figure 4). Steel sheet products followed the 94/6 BOF/EAF ratio detailed by the Steel Recycling Institute (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 and proxy method.

US automotive steel sheet producers were identified through consultation with industry professionals (Sebastian et al., 2019), steel industry reports and presentations, steel sheet producer websites, steel sheet producer annual reports, 10-K Securities and Exchange Commission (SEC) filings, steel industry news articles, and automotive industry news articles. For US hot-rolled bar and other steel, regional distributions are assumed to be the same as the distributions for BOF and EAF crude steel production, which is discussed in Section 2.3.3. For a comprehensive list of these sources, see Section S1.8 in Supporting Information S1. Weighted mass flows for ASMPPs and producer locations were calculated through proxy methods using data related to production and uniform distributions (see Section S1.9 of Supporting Information S1).

International ASMPs were assumed to have the same weighting scheme as US ASMPs. International distributions of ASMP sources by mill product were extracted from AISI's industry statistics (AISI, 2018) by weighting countries based on US import volume. The BOF/EAF ratios for international ASMPs were assumed to be the same as those for US ASMPs.

Regional mass flows of ASMPs were then calculated using Equation (6), where $M_{l,m}$ is the mass of steel mill product l from location m, M_T is the total mass of steel entering the American automotive industry, X is the estimated percentage of steel mill products entering the American automotive industry, D_n is the estimated direct or indirect share of steel mill products, E_o is the estimated share of American or international steel mill products, F_l is the estimated share of steel mill product l, $G_{l,p}$ is the estimated share of steel mill product l produced via BOF or EAF, $H_{l,q}$ is the estimated market share of steel mill product l from producer q, and $I_{l,p,q,m}$ is the estimated supply share of steel mill product l from producer q's location m if produced via BOF (this term is ignored if produced via EAF):

$$M_{l,m} = M_T \times X \times D_n \times E_o \times F_l \times G_{l,p} \times H_{l,q} \times I_{l,p,q,m} \tag{6}$$

2.3.3 | Crude steel

To determine the amount of crude steel required for automotive hot-rolled sheet, cold-rolled sheet, galvanized sheet, and hot-rolled bars, fabrication efficiencies were taken from GREET (ANL, 2018). The fabrication efficiency for other coated sheet products was assumed to be the same as galvanized sheet. The material input of crude steel for other steel mill products and SFP was assumed to be 1.05 based on GREET 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.

BOF crude steelmaker locations were determined by first identifying the number of BOF crude steelmakers (Fenton, 2018a), then identifying these BOF crude steelmakers through market research, and finally extracting facility locations through company websites and annual reports. Each BOF crude steelmaking facility was then assigned to its appropriate NERC region.

EAF crude steelmaker locations were identified by consulting USGS to identify a total number of facilities (Fenton, 2018a) and then using a state facility distribution map of EAF crude steelmakers from IBISWorld (Hadad, 2017) to determine the number of locations by state. If most of a state was within the boundaries of a NERC region, then all EAF crude steelmaker locations within that state were attributed to that NERC region. We then created a NERC-level distribution of EAF crude steelmakers weighted by number of facilities.

Company-level vertical integration was assumed when regionalizing the supply of crude steel to US automotive steel sheet producers, as well as for US hot-rolled bar and other steel produced via BOF crude steel. For US hot-rolled bar and other steel produced via EAF crude steel, crude steel sourcing was assumed to be intra-NERC.

2.3.4 | Steel raw materials

Raw materials for steel considered by this study include coke, coking coal, iron ore, lime, steel scrap, DRI, and pig iron. Where possible, NERC-level regionality within the United States was maintained for raw material supply mixes. Otherwise, regionality was country level.

BOF crude steel input requirements for coke, coking coal, iron ore, lime, and steel scrap were obtained from World Steel (World Steel Association, 2019) and the Industrial Efficiency Technology Database (IETD) from the Institute for Industrial Productivity (IPP, 2019a, 2019b). Due to variability in material composition of EAF crude steel, especially in automotive applications, EAF crude steel input requirements for DRI and pig iron were assumed to vary, from 0% each for hot-rolled bar to 25% each for all other ASMPs, leaving steel scrap to account for 100% of the material composition for hot-rolled bar and 50% for all other ASMPs. Because of this uncertainty, fabrication loss factors between mill products and EAF crude steel were not considered.

Steel raw material supply mixes were created following the procedure like the one outlined in Section 2.2.3 for alumina and bauxite. Production, import, and export data for steel raw materials were collected from the US EIA (U.S. EIA, 2018a, 2018b), UN Data (UN, 2019b), UN Comtrade (UN, 2019a), the International Energy Agency (IEA) (IEA, 2019), USGS (Corathers, 2018a, 2108b; Fenton, 2018a, 2018b; Fenton & Tuck, 2019; Tuck, 2018a, 2018b; USGS, 2018), Bureau of International Recycling (BIR, 2018), and Midrex Technologies (MIDREX, 2018). Country-level export data from UN Comtrade was used to determine the Rest of World region raw material supply mixes. Section S1.11 of Supporting Information S1 outlines additional details.

2.3.5 | Scenario and sensitivity analysis

A ±10% sensitivity analysis was performed on the ratio between direct and indirect shipments of ASMP to the American automotive industry to explore “reasonable” variation in these pathways. Further exploration of this sensitivity was deemed unnecessary given its minimal impact on results. A 10% increase in the US supply of ASMP to the American automotive industry was also done. Only an increase in this parameter was used since the base case is a conservative estimate and conversations with industry professionals indicated that the actual US supply of ASMPs is about 95%.

The BOF/EAF crude steel input ratios for ASMPs were evaluated with scenario analysis. The percentage of automotive steel sheet products made from BOF crude steel was reduced from 94% to 85%, and for all other ASMPs, the BOF crude steel input percentage was reduced from 50% to 10% to explore a scenario of increased EAF penetration.

3 | RESULTS AND DISCUSSION

3.1 | Automotive aluminum

By applying our regionally linked, sector-specific MFA framework to aluminum entering the American automotive industry, we find that the regional distribution of AAS&E mass flows is 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 5.[1] AAS&E flow from the Local region is all extrusions. The Local region accounts for 58% of extrusion mass flows, though extrusions represent only 31% of the total AAS&Es by mass. A potential strategy to further disaggregate the Local region is to weigh American automotive OEM assembly facilities, tier 1, and tier 2 supplier facilities by NERC region and apply those weights to the Local region. In our scenario analysis, uniformly distributing both the automotive aluminum mill product producer market shares by mill product and the supply shares of automotive aluminum mill product producers resulted in notable decreases in mass flows from the MRO, NPCC, and Local regions and significant

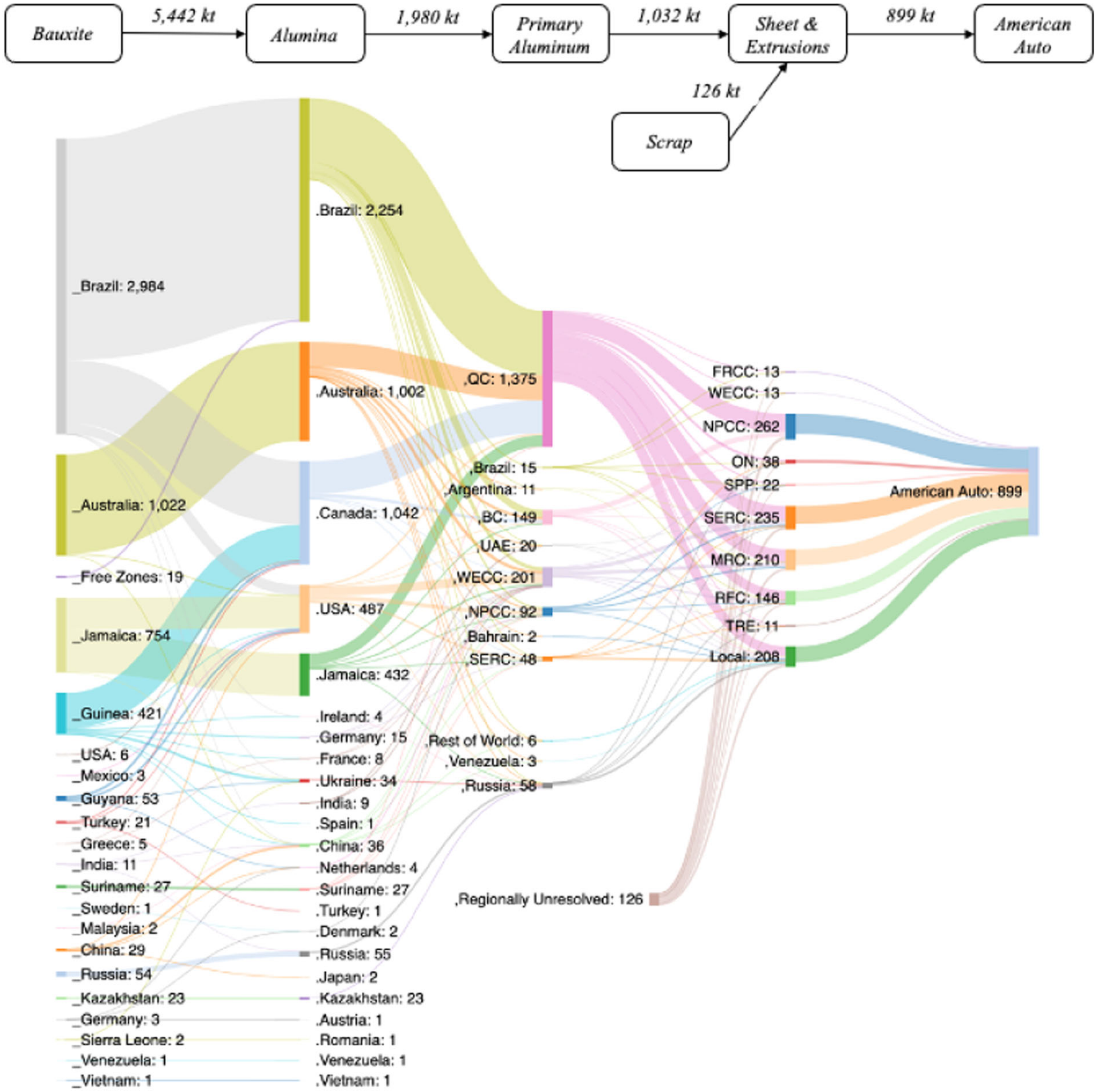

FIGURE 5 Spatially resolved flow of upstream materials and aluminum into the American automotive industry (all units are kt, underlying data are in Supporting Information S3)

increases in mass flows from the TRE, SPP, RFC, and ON regions. Sensitivity analysis on automotive aluminum mill product producer market shares resulted in only slight changes to the regional distribution of mass flow.

Primary aluminum used for AAS&Es is predominantly sourced from Canada (70%), almost exclusively Quebec (69%). Together, the United States and Canada supply 94% of the primary aluminum for AAS&E production. The regional flows of primary aluminum supply can be seen in Figure 5. The combined US and Canadian supply of primary aluminum decreased by 13% (from 94% to 81%) in our first alternative primary aluminum sourcing scenario and decreased by 27% (from 94% to 67%) in our second alternative primary aluminum sourcing scenario. Changing automotive aluminum mill product producer market shares had minimal effect on the regional distribution of primary aluminum supply.

From these results, we observe that if the sourcing of primary aluminum for the American automotive industry were to change and the amount of Canadian primary aluminum decreases, there is potential for a large increase in embodied GHG emissions. Since the Hall–Héroult process for primary aluminum production is largely dependent on electricity and regional electric grids have differing emission factors, regional variation of primary aluminum production could cause extreme variations in GHG emissions in primary aluminum production. The bulk of primary aluminum entering the American automotive industry comes from Quebec, which has an electrical grid powered primarily by hydroelectric sources and therefore low GHG emissions. At a regional level, decreasing the relative sourcing of this primary aluminum from Quebec could dramatically increase

GHG emissions embodied by primary aluminum entering the American automotive industry since other regions and countries supplying primary aluminum have grid emission factors that are orders of magnitude greater than Quebec's (Carbon Footprint, 2020). However, we recognize that aluminum smelting facilities tend to concentrate near abundant and inexpensive electricity, locations that are often collocated with hydroelectricity even if a region's aggregate grid may not be explicitly hydro-based.

Countries that supply greater than 1% of the alumina entering the American automotive industry are shown in Figure 5 and represent 96% of the total alumina by mass. Countries in North and South America dominate the alumina supply, providing 80% of the total. Brazil accounts for 43% of the total supply while the United States and Canada combined represent 29%. Additionally, we find alumina supply is dominated by countries with large bauxite reserves—Brazil, Australia, and Jamaica most notably—which suggests vertical integration with respect to alumina refining. These three countries supply 91% of the total bauxite entering the American automotive industry, with Brazil accounting for 57%, Australia 20%, and Jamaica 14%. All countries responsible for over 1% of the total bauxite supply are shown in Figure 5 and represent 95% of the total bauxite by mass. The decreases in US and Canadian supply of primary aluminum in our alternative sourcing scenarios resulted in decreases in supply shares of alumina and bauxite from North and South America and allowed for additional countries to meet the 1% cutoff relative to the base scenario. Changing automotive aluminum mill product producer market shares had a minimal effect on the regional distributions of alumina and bauxite. Our scenario analysis shows that a decrease in American primary aluminum use also decreases the relative supply of alumina and bauxite sourced from North and South America. This indicates that proximity is a primary factor in the sourcing of alumina and bauxite. Additional detail on our scenario and sensitivity analyses can be found in Section S1.6 of Supporting Information S1.

Our analysis focused on supply chains associated with primary aluminum, but we recognize that increased efforts have been made to integrate scrap into AAS&Es. These efforts could result in major changes in regional aluminum material flows. Continued integration of scrap could create major reductions in total process energy embodied by AAS&Es. 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 AAS&EPs could dramatically reduce the need for raw materials associated with primary aluminum. We acknowledge 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 in this area.

Our results provide spatial resolution of aluminum entering the American automotive industry and demonstrate the importance of incorporating spatial resolution into GHG analyses. Therefore, we recommend that future development of automotive aluminum life cycle impact factors consider and incorporate our results to help support LDV LCAs. Though out of our scope here, we recognize the importance of temporal resolution and recommend use of our framework to map aluminum flows into the American automotive industry over time.

3.2 | Automotive steel

Through the application of our regionally linked, sector-specific MFA framework, we find that the split between the United States and international supply of SFP is nearly 50/50. Within the United States, the RFC (27%) and SERC (17%) regions dominate total supply. Mexico is the dominant international source of steel in finished automotive parts, providing 19% of the total supply.

The regional flows can be seen in Figure 6. The supply of ASMPs is heavily dominated by the RFC (63%) and SERC regions (20%), which is where all BOF steel in the United States is produced. The only other regions that supply over 1% of the total are Canada (4.5%) and Turkey (1.1%). Isolating hot-rolled bar and other steel products, we find that the WECC, TRE, MRO, and FRCC regions exceed 1% of the supply of these products since they are produced in large part using EAF crude steel, which while produced in significant amounts in the RFC and SERC regions, is more distributed in production location.

Moving upstream, the regional distribution of crude steel for automotive application is dominated by the RFC (62%) and SERC (14%) regions. The only international crude steel producers supplying over 1% of the total mass are Japan (5.0%), Canada (4.7%), Mexico (2.5%), and Turkey (1.0%). Of the total crude steel supply, EAF crude steel accounts for only 18%. The dominance of the RFC and SERC regions in supplying ASMPs and crude steel aligns with the location of American OEMs, tier 1, and tier 2 suppliers, which suggests that the American automotive industry has short supply chains.

Our results for raw materials show that the United States dominates supply of coke, coking coal, iron ore, lime, and scrap. Only DRI and pig iron show significant international supplies (regional flows of steel raw materials are depicted in additional Sankey diagrams in Section S1.11 of Supporting Information S1). A general US region appears for some mixes because raw materials for some imported crude steel originates in the United States. We find that the future supply of DRI from the United States can be reasonably assumed to increase as US DRI infrastructure increases (Tolomeo et al., 2019). Pig iron is likely to continue to be dominated by international supply since 95% of the pig iron produced in the United States goes directly into BOF crude steel production (Fenton, 2018a). Because of this, EAF steelmakers turn toward international sources of pig iron to use as EAF crude steel feedstock. Growth in EAF crude steel for automotive application would necessitate the increased utilization of DRI and pig iron for quality assurance. This has implications not only in steel raw material flows but also in energy impacts. Because EAF crude steel production

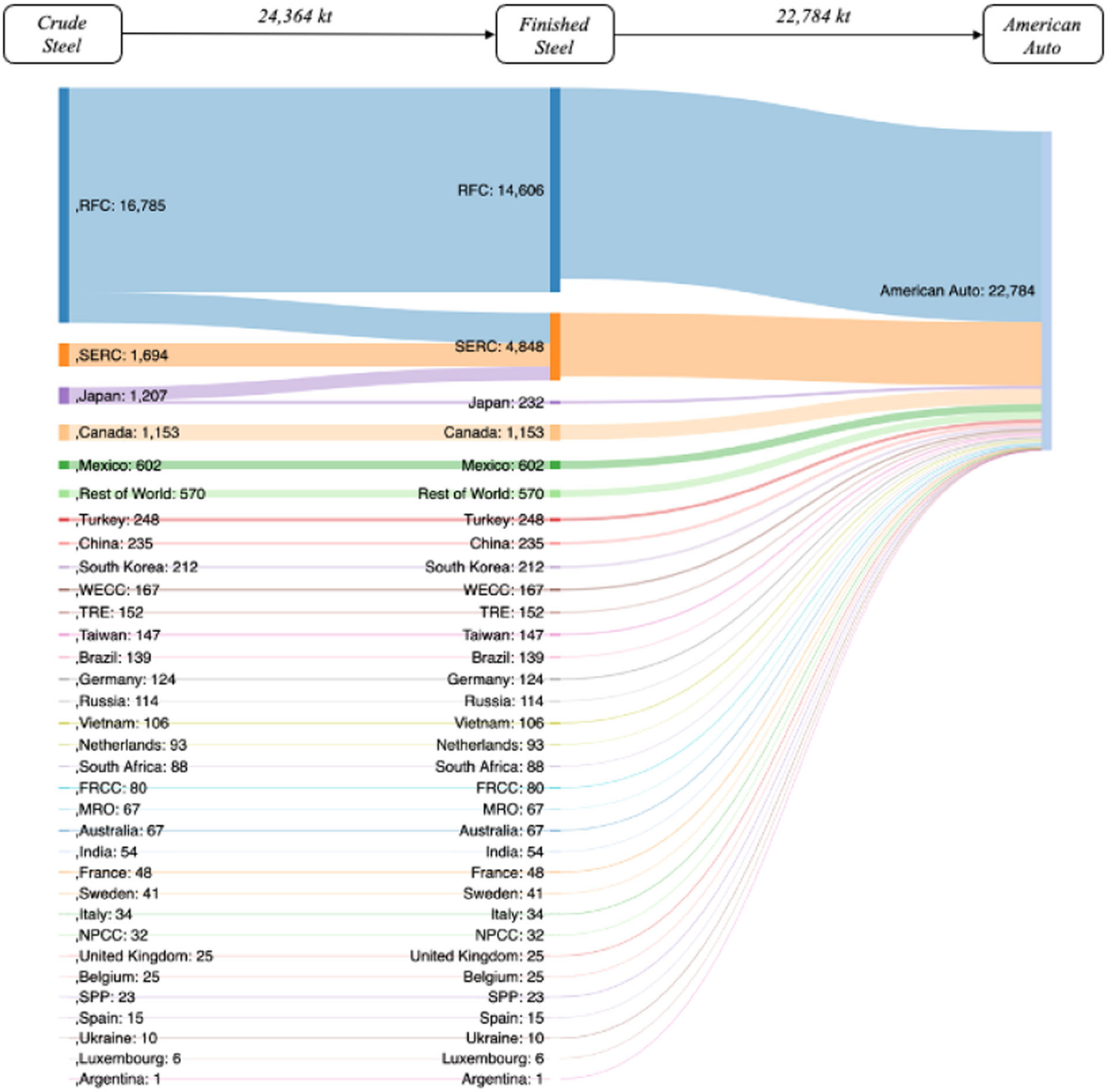

FIGURE 6 Spatially resolved flow of crude steel and finished steel into the American automotive industry (all units in kt, underlying data are in Supporting Information S2)

utilizes electricity as its primary energy input, regional variations and future grid mix changes will precipitate changes in GHG emissions to produce automotive steel.

In our scenario and sensitivity analyses, we find that decreasing the fraction of ASMPs produced via BOF crude steel decreases the supply of crude steel from RFC and increases the supply of crude steel from SERC since more EAF crude steel production occurs in that region. Additionally, we find that because our method holds constant the value of direct mill product shipments, changes to percentages in US ASMP supply and direct ASMP supply affect the total steel to LDVs. As the US ASMP supply percentage increases, the total steel to LDVs decreases. A similar result is observed when increasing the direct ASMP supply percentage. Further detail can be found in Section S1.12 of Supporting Information S1. We recognize the need for more reliable data on the amount of steel mill product from service centers and converters that ultimately reach the American automotive industry.

We provide spatial resolution of steel entering the American automotive industry. This spatial resolution will be of increasing importance if the use of EAF crude steel in automotive applications continues to grow, given production of EAF crude steel's dependence on electricity. Further, our results can help the development of detailed automotive steel life cycle impact factors and, though out of our scope here, we recommend future research applying our MFA framework to automotive steel across time to add temporal resolution.

4 | CONCLUSION

We developed a framework for regionally linked, sector-specific MFAs and applied it to identify regional mass flows associated with aluminum and steel entering the American automotive industry. This framework can be used to understand the GHG implications of future electricity grid decarbonization as well as shifts (or disruptions) in sourcing across the supply chain, both domestically and internationally.

We found that for aluminum, AAS&Es are largely sourced from the NPCC, SERC, MRO, and RFC NERC regions. Electricity GHG emissions intensity in these regions are 283 g/kWh in NPCC, 559 g/kWh in SERC, 638 g/kWh in MRO, and 609 g/kWh in RFC (ANL, 2018). Automotive aluminum extrusions are largely sourced locally, and we recognize the need for further disaggregation of a Local region. Primary aluminum comes largely from American and Canadian producers while alumina and bauxite are primarily sourced internationally from countries with large bauxite reserves. As use of secondary aluminum increases in automotive applications, regionalizing scrap flows and secondary aluminum production is necessary since this has serious implications for material production GHG emissions reduction.

For steel, we found that the majority of finished (ASMPs and SFP) and crude steel that enters the American automotive industry comes from the RFC and SERC regions (regional electricity GHG emissions intensity noted earlier). This narrowness in regional supply stems from the significant amount of vertical integration in the steel industry. Most of the raw materials required for crude steel production also come from the United States, with DRI and pig iron for EAF crude steel being exceptions. We also see that automotive steel is still dominated by crude steel produced via BOF, but crude steel produced via EAF is increasing in automotive application. Regional disaggregation of steel flows becomes increasingly important for EAF crude steel, as this process is electricity intensive.

The framework we developed for performing regionally linked, sector-specific MFAs can be used as a tool for MFAs across all industrial sectors and be used to support development of spatially specific life cycle impact factors and LCAs. The results presented here, which identify regional flows of automotive aluminum and steel, can help inform vehicule life cycle practitioners and the American automotive, aluminum, and steel industries in better understanding the spatial variability and associated GHG implications of their input resources.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study were derived from the following resources available in the public domain: UN Comtrade Database (https://comtrade.un.org/data/); ANL GREET model (https://greet.es.anl.gov/). The data that support the findings of this study are available from the Aluminum Association and the American Iron and Steel Institute. Restrictions apply to the availability of these data, which were used with approval for this study. Data are available directly from the third parties.

ORCID

Geoffrey M. Lewis https://orcid.org/0000-0001-6426-6068
Gregory A. Keoleian https://orcid.org/0000-0002-7096-1304

NOTE

[1] NERC regions include NPCC (Northeast Power Coordinating Council), SERC (South East Reliability Corporation), MRO (Midwest Reliability Organization), RFC (ReliabilityFirst Corporation), TRE (Texas Regional Entity), SPP (Southwest Power Pool), WECC (Western Electricity Coordinating Council), and FRCC (Florida Reliability Coordinating Council).

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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