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Material Use and its Sustainability in the Automotive Industry

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by

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Ph.D. DEGREE DISSERTATION

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ABSTRACT

Among sectors in the United States, the transportation sector contributes the most to greenhouse gas emissions (USEPA, 2018) at 28%. A complex mix of market dynamics, demographics, and technological changes like material type (e.g. lightweighting techniques), fuel type (e.g. biogas), vehicle mode (e.g. internal combustion) and recyclability (Lewis et al., 2019) is employed to combat theses emissions. While these changes presumably effect linear level contributions and impacts, it is important to objectively determine their effects and impacts at a systems level.

This research studied the material use implication of two major technological changes – lightweighting and electrification. The study involved the quantification and analysis of losses attributed to the dissipation of critical and strategic metals – e.g., copper (Cu), magnesium (Mg), chromium (Cr), etc. – and examined the attendant accumulation of tramp elements in the recycled lightweight material stream. The increasing demand for Cu in the adoption of electric vehicles was also analyzed. Finally, the study analyzes the impacts of these transitions on other industries that may be directly or indirectly connected to the automotive industry at different life cycle stages of the typical vehicle.

Results show that the "losses" associated with these transitions are not insignificant and occur throughout the life cycle of the vehicle. They are particularly concentrated at the end-of-life stage of the vehicle and thus technological and operational strategies need to be employed to abate these losses and improve material circularity. In addition, the transition to electrification results in an increase in the demand for Cu that will, in the long-term, lead to a strain in copper supply. Therefore, enhancing alternative sourcing for Cu from post-consumer scrap is imperative for a long-term sustenance of vehicle electrification. Further observation of the flow of Cu, at its

end-of-life, shows that while an alarming volume of copper may be recorded as “loss”, and thus not achieving a closed copper cycle loop, a significant portion of it should more appropriately be characterized as “unusable in the copper stream” as it is technically not lost, but trapped in other material stream. Therefore, while non-circularity might linearly exist for copper, an elevated point of view might show an interconnected circularity with other material stream that is acceptable from a sustainability standpoint. Secondly, the trade ban on scrap export to China – the largest importer of U.S. copper scrap – has presumably impacted the usual modus operandi in scrap processing, causing a disruption in the flow of copper and a local accumulation of copper scrap that is normally not domestically processed for recycling. This, as a result, has led to an increase in the recent volumes that are recorded as “lost” in the copper cycle. Regardless of the lift (or not) of the trade ban, it is important to incorporate improved recycling technologies to eliminate losses because of abandoned, but recyclable material to ensure a robust secondary copper supply. It is also acknowledged that policy mandates and interventions will play a huge role in achieving this goal.

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INTRODUCTION TO MATERIAL USE AND SUSTAINABILITY IN THE AUTOMOTIVE INDUSTRY

Sustainability Efforts in the Automotive Industry

As the demand for and consumption of products and services grow in the US, so does the concern for sustainable material usage. In the automotive industry, major sustainability issues revolve around advocating for improved fuel economy and the incorporation of materials with higher recyclability in order to reduce greenhouse gas (GHG) emissions. Among sectors in the United States, the transportation sector contributes the most to greenhouse gas emissions. In 2019, emissions from light vehicles (USEPA, 2021) account for 58% of total emissions from the transport sector , but the contribution to total emissions by light vehicles is on a gradual decrease (US EPA, 2020b). This decrease is due to a complex mix of market dynamics, demographics,

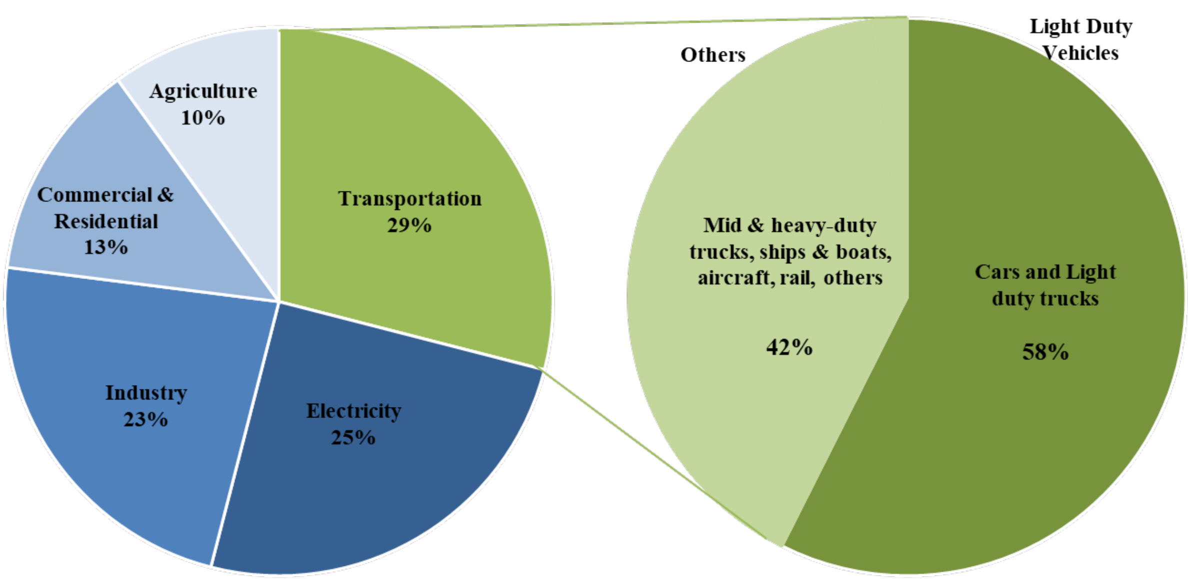


Figure 1.1: 2019 Fraction of total U.S greenhouse gas emissions by economic sector and by source for the transportation sector

and technological changes like material type (e.g. lightweighting techniques), fuel type (e.g. biogas), vehicle mode (e.g. Internal combustion) and recyclability (Lewis et al., 2019).

The automotive industry employs lightweighting as a means of abating greenhouse gas (GHG) emissions where studies show a 5 -10% improvement in fuel economy when curb weight is reduced by 10% (Miller et al., 2000). Lightweighting, in very simple terms, means the replacement of traditional steel structures in vehicles with lighter materials like aluminum, magnesium, plastics, and composites. In North America, aluminum is a top choice material for lightweighting as it has the potential to reduce vehicle weight by 20 – 30% compared to steel (Miller et al., 2000). It is used in a wide range of vehicle parts ranging from heat exchangers to closures. Each part will require unique functional properties for these differing automotive applications and therefore include a range of alloying elements. Many of these alloying elements are dissipatively lost and are also deemed critical. In addition, lightweighting, as a solution to improving fuel economy (Brooker, Ward, & Wang, 2013) can create complexities for circular economy strategies, particularly recycling, in the automotive industry. Continuous recycling can result in the accumulation of tramp or unwanted elements in the aluminum stream (Gaustad, Olivetti, & Kirchain, 2010), thereby resulting in secondary aluminum that is rich in impurities.

Also, the intensified push to attain clean mobility (ICCT, 2018; Ministry of Heavy Industries and Public Enterprises, 2019; Natural Resources Canada, 2020; The European Parliament and Council of the European Union, 2009), has ignited the drive towards zero emission, thereby encouraging the transition to alternative fuel vehicles. As a result of this, automotive manufacturers now have, among their fleet, vehicles with alternative powertrains that include batteries, electric motors and electronics in lieu of the ICEV's fuel storage tank, combustion engine, and transmission components. These vehicles come in different types –

hybrid electric vehicles (HEV), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV) – and are generally called electric vehicles (EVs).

An Overview of Critical and Strategic Materials

Critical metals are those metals that are highly demanded, strategic, have few or no known substitutes or replacement and/or are vulnerable to supply disruptions. Though a handful of governing bodies have differing lists of critical metals (Energy, 2011; European Commission & Industry, 2013), the National Research Council (NRC) (National Research, 2008) defines the criticality of metals based on their "importance in use" and "potential supply restrictions". For instance, rhenium (Re) is used in strengthening super alloys for various applications like turbine engines in aircrafts. It is not found or mined by itself, but as a by-product of copper (Cu) mining and thus, Re is vulnerable to supply disruptions based on market for Cu (Duclos, Otto, & Konitzer, 2010). Cobalt, Co, is another example of a critical material. It is one of the elements (together with lithium, nickel, manganese, and natural graphite), that constitute a lithium-ion battery (LIB). Co, like Re, is also a by-product of Cu mining (Cu accounts for 35% of Co production), but the bulk of Co production (50%) is associated with nickel (Ni) mining. Furthermore, over 50% of the production of Co is geographically constrained, and so any political unrest in that region will affect the supply of Co (Olivetti, Ceder, Gaustad, & Fu, 2017). In the automotive industry, platinum is an example of a critical material whose criticality is as a result of its cost of extraction due to its diminishing ore grade and geographic constraint (Alonso, Field, & Kirchain, 2012).

Research Objective and Questions

While these transitions may result in positive contributions on a linear scale, it is important to objectively determine their effects and impacts on other industrial sectors and aspects of the economy, i.e., analyze their effects at a systems level. The overarching objective of this research is thus, <u>to inform how the transition to clean mobility impacts the use of materials and its sustainability</u>. The study involves the quantification and analysis of both material and economic losses attributed to the dissipation of critical metals and examined the attendant accumulation of tramp elements in the recycled aluminum stream. A model is also developed to forecast the demand for copper given the push for the adoption of electric vehicles, coupled with their relatively high copper intensity. Finally, the study attempts an end-of-life (EOL) substance flow analysis for one of the strategic materials in the automotive industry, copper. This is done to have a better understanding of how to improve secondary copper supply, amidst the recent reports of high volume of copper loss at EOL and the relatively high price of copper metal.

Therefore, the ensuing chapters focus on studying the material use implication of these transitions – from traditional internal combustion (ICE) vehicles to lightweight ICE vehicles to electric vehicles – and answering the following questions.

1. How much critical material is lost in the automotive stream?

   The analysis carried out in answering this question focuses on the automotive aluminum stream as a case study. It involves quantifying the dissipative and economic losses attributed to critical metals in automotive aluminum alloys.

2. How can the surge in the demand for strategic materials required in an EV be sustained?

   Here, copper is the selected strategic material and the impact of accelerated EV adoption on its demand is estimated.

3. What can be done to enhance alternative supply of copper?

This analysis is a follow-up of the previous question and to adequately answer this question, this study fills a literature gap in the form of a substance flow analysis of copper at its EOL to optimize the flow of secondary copper.

CHAPTER 2

ESTIMATING INCREASING DIVERSITY AND DISSIPATIVE LOSS OF CRITICAL AND STRATEGIC METALS IN THE ALUMINUM AUTOMOTIVE SECTOR

As the demand for and consumption of products and services grow in the US, so does the concern for sustainable material usage. In the automotive industry, major sustainability issues revolve around advocating for improved fuel economy and the incorporation of materials with higher recyclability in order to reduce greenhouse gas (GHG) emissions. A popular strategy to achieve this in the automotive industry is lightweighting. Many studies in this field are focused on the environmental benefits of lightweighting, that is, how replacement of traditional steel in the automotive industry with aluminum, for instance, will help reduce the amount of CO2-eq emissions in the environment. However, the increasing use of aluminum in the industry for differing automotive applications broadens the range of alloying elements, and so this study investigates the diversity and losses of critical and strategic materials in the aluminum automotive industry.

Introduction

Among sectors in the United States, the transportation sector contributes the most to greenhouse gas emissions (USEPA, 2018) at 28%. Data from 2009 to 2016 show about a 6% increase in emissions from the transport industry (USEPA, 2021). Emissions from light vehicles account for over 60% of total emissions from the transport sector, but the trend observed (2009 to 2016) show that the contribution to total emissions by light vehicles is on a gradual decrease. This decrease is due to a complex mix of market dynamics, demographics, and technological change; one such technological change that may be contributing is the move toward lightweighting strategies. Lightweighting, in very simple terms, means the replacement of traditional steel structures in vehicles with lighter materials like aluminum, magnesium, plastics, and composites. In North America, aluminum is a top choice material for lightweighting as it has the potential to reduce vehicle weight by 20–30% compared to steel (Miller et al., 2000). Researchers estimate that every 10% savings in curbside weight results in a 5–10% improvement in vehicle fuel economy (L. W. Cheah, 2010; Miller et al., 2000). While this contributes to abating tailpipe emissions, aluminum production is very energy intensive and has an emission factor (9.45 kg CO2-eq/kg Al) of about 4 times that of steel (2.2 kg CO2-eq/kg steel) (Kim, McMillan, Keoleian, & Skerlos, 2010). On the other hand, aluminum production from scrap (secondary aluminum production) has an emission of about 0.9 kg CO2-eq/kg Al, so to justify lightweighting with aluminum, efficient aluminum recycling is necessary, where there is little dependence on primary aluminum.

Aluminum is used in a wide range of vehicle parts ranging from heat exchangers to closures. Each part will require unique functional properties for these differing automotive applications and therefore include a range of alloying elements. The key alloying elements will differ by alloy family as shown in Table 1, but these additions are copper, manganese, silicon, magnesium, zinc, and tin. The alloy families are called series with 4-digit nomenclature (for the wrought alloys; the cast alloys have 3-digit nomenclature), such that 1XXX is the 1000 series, 2XXX is the 2000 series, etc. The first digit in the series signifies the major alloying element as identified in Table 2.1, the third and fourth digit are arbitrary numbers that identify the specific alloy, and the second digit indicates a special modification to the specific alloy. For example, alloys 2024, 2124, 2324, 2424, 2524, 2624, 2724 and 2824 are aluminum alloys that have copper as the major alloying element, but alloys 2124 to 2824 are modifications of alloy 2024. Same is true for alloys 2018, 2218 and 2618. These modifications may be in the amount of the major alloying element or amounts of other alloying elements. These may include nickel, lead, chromium, titanium, bismuth, vanadium, lithium, scandium etc. (European Aluminium Association, 2002).

Table 2.1: Aluminum Association alloy family designations showing major alloying elements for each series.

	Wrought	Cast
Pure Al 99% or higher	1XXX	1XX
Major alloy elements:		
Copper	2XXX	2XX
Manganese	3XXX	
Silicon	4XXX	4XX
Magnesium	5XXX	5XX
Magnesium & Silicon	6XXX	
Zinc	7XXX	7XX
Other & Specialized	8XXX	9XX
Tin		8XX
Si + Cu + Mg		3XX

Many of these alloying elements are considered critical. Critical metals are those metals that are highly demanded, strategic, have few or no known substitutes or replacement and/or are vulnerable to supply disruptions (National Research Council, 2008). Chromium is an example of a critical metal used in metallurgical applications for its excellent resistance to corrosion and high temperature properties (Barnhart, 1997). Chromium is often included as critical (Nuss, Harper, Nassar, Reck, & Graedel, 2014) due to its high demand and lack of substitutes for most major industrial applications. Vanadium, like chromium, is also widely used in metallurgical applications for added strength properties. Approximately 80% of its global production is as a companion metal, i.e., a byproduct of other base (or host) metals, like iron and bauxite (Nassar, Graedel, & Harper, 2015; Nuss et al., 2014). In recent years, the U.S. has solely relied on imports of vanadium whose production has been in very few countries (U.S. Geological Survey, 2018). Thus, vanadium is one of such elements deemed critical based on its supply risk.

While a handful of organizations have differing lists of critical metals (Department of the Interior, 2018; European Commission, 2017), the National Research Council (NRC) (National Research Council, 2008) defines the criticality of metals based on their "importance in use" and "potential supply restrictions". Recycling restriction based on stock and recyclability has also been used as a measure of criticality (Hatayama & Tahara, 2015).

Lightweighitng, as a solution to improving fuel economy (Brooker et al., 2013) can create complexities for circular economy strategies, particularly recycling, in the automotive industry. Continuous recycling can result in the accumulation of tramp or unwanted elements in the aluminum stream (Gaustad et al., 2010), thereby resulting in secondary aluminum that is rich in impurities. In most cases, if aluminum is being recycled into aluminum this would be considered closed loop, however, in practice the aluminum is not going into the same type of alloy in most cases. This then causes reduced utilization rates of secondary aluminum since metal batches have to be diluted with primary aluminum in order to meet required specifications of the desired new alloy. With their dissipative losses and their accumulation in the aluminum stream, an open loop is observed with these alloying elements and thus loss of material, as well as loss of embodied energy, both alluding to economic losses. Recycling end of life vehicles (ELV) is a well-established and profitable industry but is mostly suited to steel-structured vehicles. The process starts out with disassembling the vehicle to separate hazardous fluids from reusable components and valuable parts. Next, the materials are typically shredded to liberate valuable materials and then separation techniques such as eddy currents are employed to move scrap into different material streams, ferrous, non-ferrous (metallic non-ferrous) and automotive shredder residue (non-metallic non-ferrous) (Cui & Roven, 2010). These preparation stages of recycling ELVs (disassembly and shredding) are roughly 75% efficient in the U.S. (Boon, Isaacs, & Gupta, 2000). Typically, aluminum in processed ELVs are bulky castings that are easily removed from the vehicles and are comparably easily recyclable into castings used in automotive industry, the largest consumer of secondary aluminum (Modaresi & Müller, 2012). Soon, aluminum intensive vehicles will have more wrought alloys in the form of sheets, forged alloys and extrusions. With the current recycling technologies, recycling efficiencies are bound to reduce due to:

1. Incompatibility between existing recycling technologies, geared towards aluminum cast alloy recycling, and next generation vehicles comprising of more wrought alloys than cast alloys.
2. Surplus scrap that will be created with a reduced demand in automotive castings, the largest consumer of secondary castings (Modaresi & Müller, 2012). Unlike cast aluminum alloys, wrought aluminum alloys have tight specification allowances (Cui & Roven, 2010) that limit their production from secondary aluminum. Secondary aluminum has a wide range of impurities like Fe, Si or Zn in varied amounts, present as a result of intentional alloy modification or introduced along the way through applications of mechanical processes.

The historic and futuristic use of aluminum and its alloys as lightweight materials have been analyzed and predicted respectively by Ducker Worldwide, a global consultancy firm that helps companies and industries strategize and make decisions based on intensive data analyses. The analysis shows an increasing trend as pressure on original equipment manufacturers (OEMs) to increase fuel economy continues (L. Cheah & Heywood, 2011; Ducker Worldwide, 2017). If this trend is to continue as predicted (see Fig. 2.1), then these critical metals, and other alloying

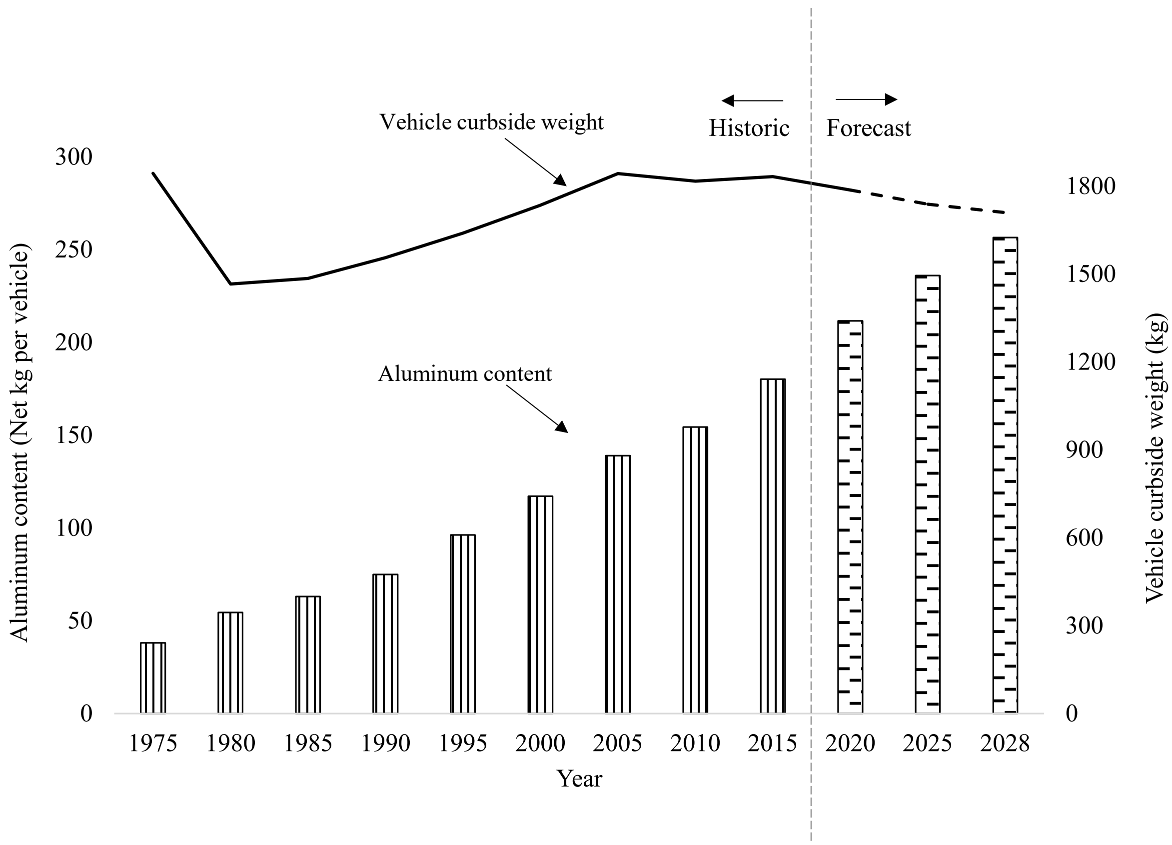


Figure 2.1. Average vehicle curbside weight (USEPA, 2018) and aluminum use in vehicles in North America (Ducker Worldwide, 2017)

elements need to be tracked to inform of the different avenues to possibly close the loop and thus, reduce the negative economic impact. This research quantifies these material flows to a) inform the dissipative losses of these economically important alloying elements, and b) inform the recycling process to potential challenges of increased diversity of alloying additions. While losses as energy expended may not be easily quantified, economic losses in terms of material input can be quantified in dollar values based on the market price of these materials. While quantifying the economic loss requires the knowledge of the current market price, quantifying the dissipative losses requires a material flow analysis (MFA) to understand the inflow and outflow of aluminum and its alloying elements. A key barrier to performing an MFA for this sector is that most data sources track total aluminum by production type (wrought, cast, extruded, etc.) (U.S. Geological Survey, 2018) and not by specific alloys, so it is quite difficult to quantify the alloying elements that are a part of these material flows. Another barrier is the lack of readily available data specifying actual automotive components and the alloys used. Previous studies have investigated the use of rare earth metals and platinum group metals in the catalytic converters of internal combustion vehicles (Alonso et al., 2012; Nansai et al., 2014; Peiró, Méndez, & Ayres, 2013); however, there is a lack of work examining other critical metals contained in automotive. While the amount of critical metals present in a lightweight vehicle might seem relatively negligible, the aggregate mass flow, considering total lightweight vehicle production in North America, possibly has an impact on the demand of these critical metals.

Graedel et al. (2011), discuss the recycling rates of metals and mention barriers to closing the open circle of material flow, particularly in consumer products like vehicles. These include complicated product designs that discourage disassembly, uncontrollable material flows because of high product mobility, lack of knowledge on the attributed economic losses, and lack of recycling infrastructures and updated recycling technologies.

Beyond creating awareness on resource loss, achieving a closed loop for critical metals is faced with other challenges. As discussed by Zimmermann and Gößling-Reisemann (2013), these critical metals are dissipatively lost. Their dissipation occurs all the way from cradle-to grave, i.e., from their production to their disposal. In-use dissipation and a lack of robust recycling technologies accounts for the loss of over 50% of annual input flow of critical metals. They also discuss the different types of dissipation exhibited by critical metals at their different lifespan stages – Dissipation into the environment (type A), into other material flows (type B) and into landfills (type C). While type A is the most difficult to recover the metals from and poses the most health hazard, type B is the most dominant of all the categories as more critical metals are used as alloying elements in the enhancement and modification of properties of other materials. Type B dissipation might not be as difficult as type A dissipation in terms of metal recovery, but the critical metals dissipated into other material streams are in such small amounts that it is not economically feasible to recover them. Recycling of the host material, on the other hand, is a common practice across industries, including the automotive industry. Unfortunately, continuous recycling of the host materials results in the accumulation of these alloying metals as tramp "unwanted" elements in the host material stream. Tramp element accumulation is a problem in many recycled material streams like steel, plastic, copper, etc., however due to thermodynamics, aluminum has the most accumulation challenges with magnesium, nickel, lead, chromium, iron, vanadium, silicon, copper and zinc cited as some of the possible tramp elements that increase with the recycling of aluminum (Gaustad, 2009). Copper and zinc (listed above) and other alloying elements like manganese, tin, titanium and bismuth used in the aluminum industry (European Aluminium Association, 2002) are also seen to exhibit different amounts of in-use dissipation, ranging from approximately 1%–20 % by mass of the element dissipated in-use (Ciacci, Reck, Nassar, & Graedel, 2015)

With the dissipative characteristics of these alloying elements and their accumulation as tramp elements, continuous recycling hits a barrier where the material continuously gets downcycled until it is eventually disposed of. So ultimately, a type B dissipation, over time, ends up being a type C dissipation. Along with other material flow analysis results, this paper aims to quantify and analyze the dissipative losses of critical metals and the accumulation of tramp elements in the recycled aluminum stream as well as the attributed economic losses.

Methodology

In order to quantify dissipative losses of critical alloying elements in automotive aluminum, a material flow analysis that included resolution to the compositional level was conducted. Different aluminum vehicle parts employed for lightweighting were compiled from a variety of sources. Scenarios were built from assumptions on which specific alloys were the most likely to be used for each vehicle part application. Forecasts for light vehicle sales in North America were used to extrapolate total materials usage and resultant dissipative losses as shown schematically in figure 2.2.

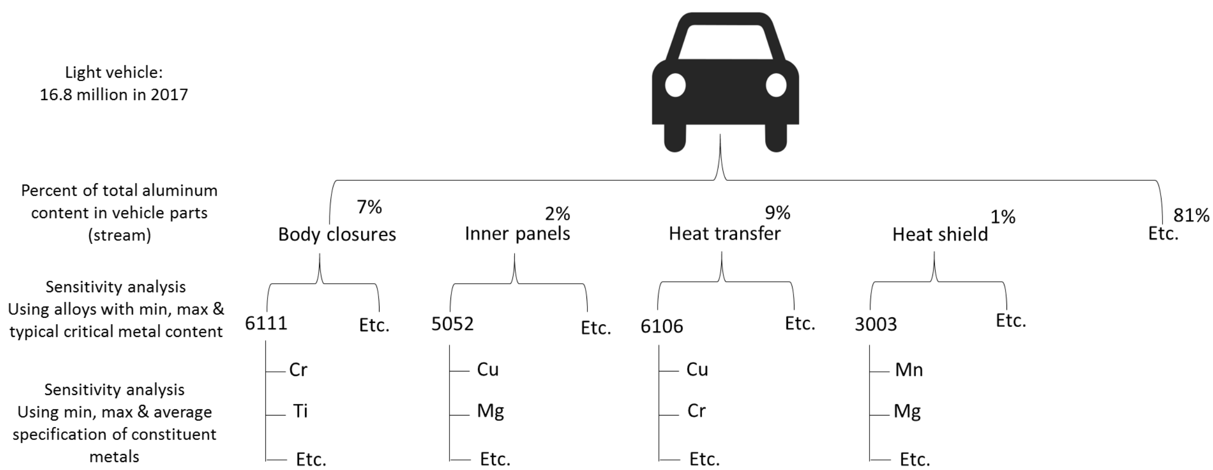


Figure 2.2: Schematic diagram of methodology

Compositional characterization

Using the Aluminum Association's teal books, we characterized the maximum and minimum potential elemental composition according to the specification for each alloy, and by extension, each aluminum vehicle part. The total aluminum content for a representative lightweight vehicle were derived from the Ducker analysis (Ducker Worldwide, 2017); this analysis provides historical aluminum content as well as future projections. Vehicle parts that were likely to be aluminum alloys were identified from industry and academic literature; these potential aluminum car parts and alloys were combined to create scenarios detailed in the **scenario analysis** section. As shown in flow of Fig. 2.2, first the total amount of aluminum in a lightweight vehicle is identified, then the vehicle parts made of aluminum are identified. For example, in a generic North American lightweight vehicle, 45% of the aluminum use is in the cast engine and cylinder heads. Then, the typical alloys used for these parts are identified. For engine castings, the alloy can either be alloy A380 or alloy A319. At this point, scenarios are developed as the alloy selection will vary for different makes and models of vehicles. If silicon was the element of interest for this case, the Aluminum Association indicate a specification window of 7.5%–9.5% weight percent for A380 and 5.5%–6.5% weight percent for A319. We would then select the minimum specification of 7.5% for Si in A380 (and subsequently for all constituent metal in A380) and calculate the total critical metal content in A380. Same would be done for A319. Whichever one of A380 and A319 has the lesser total critical metal content is selected as the minimum content scenario. The same selection process is followed for maximum content scenario but this time, the maximum specification for each constituent metal is used and the alloy with the greater total critical metal content is selected as the maximum content scenario.

Material flow analysis

Material Flow Analysis (MFA) is a tool used to quantify the flows and stocks of a material, substance or product. Depending on defined parameters, it considers processes such as extraction, fabrication, waste, transformation, use, and end of life (EOL), i.e., reuse, recycling and/or disposal. There are two (2) approaches to carrying out an MFA: a) the top down and b) the bottom-up approach. The top-down approach estimates the material in stock by considering the net flows (inflow less outflow) over a defined period of time; while the bottom-up approach estimates the material in stock by identifying all relevant material streams and summing up the material in each stream (Laner & Rechberger, 2016). For this research, i.e., to analyze and quantify the amount of each alloying element present in each alloy specification, we used a combination of both methods to build a model where we identified two sets of material streams; the vehicle parts that contain aluminum and the aluminum alloys that contain the constituent elements. Figure 2.2 gives a schematic of the approach where car parts like body closures, inner panels, etc. were identified to contain aluminum alloys in which about 7% of total aluminum content of a car is in the body closure. Also, each car part was found to be made from different aluminum alloys, e.g., the body closures could be made of alloy 6111, 6010, etc. Finally, each alloy is characterized based on its constituent element. For instance, alloy 6111 contains chromium, titanium, etc.

Scenario analysis

The critical metals considered in this study were manganese, magnesium, chromium, titanium, tin and vanadium (Department of the Interior, 2018; Moss et al., 2013; Wagstaff, 2018). The total critical metal content in a typical lightweight vehicle was calculated by summing up the amounts of each of the listed critical metals above that are present in the aluminum alloy employed in the car part. Two extreme scenarios and a midpoint scenario as shown in Table 2.2, were analyzed based on the range of specification provided by the Aluminum Association for each alloy and the multiple alloys that can be utilized for a car part:

- Alloy with maximum critical metal (CM) content using maximum specification limit of
- Alloy with minimum critical metal (CM) content using minimum specification limit of alloy constituents.
- Typical alloy used in the industry using midpoint of specification range of alloy constituents.

Where there is no specification range for a constituent metal, the value specified was used across the three scenarios.

Table 2.2: Description of scenarios explored for sensitivity analysis

Aluminum in vehicle parts (Ducker Worldwide, 2017)		Alloys used in Sensitivity Analysis		
Vehicle part	Content of total aluminum in vehicle (%)	Max CM using max spec limit	Min CM using min spec limit	Typical Alloy using midpoint of spec range
Engine & Cylinder heads	30	A380	A380.2	A380.2
Trans & Driveline	21	A380.2	A380.2	A380.2
Heat Shields	1	5182	1050	1050
Heat Exchangers	9	5049	1050	3003
Wheels	11	6082	A356	6082
Steering system	5	6082	7108	6082
Suspension Parts				
(knuckles)	3	6013	6013	6013
(control arms)		6082	6082	6082
Brake System	2	F3N20S	F3N20S	F3N20S
Body Closures	7	6010	6111	6061
Body frame & Inner Panels	2	5182	5052	5182
Collision Mgt.	7	6013	6013	6013
Cradles, Frames	2	5182	5182	5182
Total	**100**			

While a synthesis of the literature provided an average of aluminum parts by weight in lightweight vehicles, the proportion can differ widely for each make and model. Therefore, a general case was used to represent an average light-weight passenger vehicle in North America. A specific make and model case study was also carried out on the 2015 Ford F-150 pick-up truck. The F-150, known for being aluminum intensive compared to the average vehicle, has a curb weight in the range 4069 lbs. (1846 kg) – 5697 lbs. (2584 kg). Depending on the model, the engine size ranges from a 2.7 l (V6) to 5.0 l (V8) with in-city fuel mileage ranging from 15mpg – 20mpg and highway fuel mileage ranging from 18mpg – 26mpg.1 The case study analyzes the differing amounts of critical materials present in the aluminum sheet alloys used as skin alloys for closures and outer panels as a function of time from 1962 to 2005 Chappuis (2019). This case study was selected as the Ford F-150 has garnered a significant amount of publicity for the design team's decision to go with an aluminum body compared to traditional high-strength steel designs for pick-up trucks. The skin alloys analyzed for each year in review corresponds to the skin alloys registered as automotive skin alloys for that year.

Results and Discussion

Identifying aluminum vehicle parts

Table 2.3 lists the various aluminum alloys used in each aluminum containing vehicle part. The difficulty in performing an MFA of this scope is seen in i) the various alloy series that can be present in a vehicle part and ii) the implicit uncertainty created by the content specification range of each alloying element in the alloy. This can be illustrated by considering an example from literature (Gaustad, 2009). Two aluminum manufacturers, company A and company B, each produce alloy 6061, a very common automotive sheet alloy. Table 2.4A shows the AA guidelines to the minimum and maximum amount specification of individual alloying elements. "Other each" is the maximum allowable amount for any other individual alloying

Table 2.3: Typical Alloys in the Automotive Industry (European Aluminium; Fridlyander et al., 2002; Miller et al., 2000; J. T. Staley & Lege, 1993; James T. Staley, Van Horn, & Bridenbaugh, 2018)

Body & Inner Panel	**Body Closures**	**Heat Exchangers**	**Heat Shields**	**Misc Engine**
2008, 5030, 5052, 5182, 5454, 6009, 6016, 6111	2008, 2036, 6009, 6016, 6010, 6383, 6061, 6111	6060, 6061, 6063, 6106, 5049, 7072, 1145, 4047, 4004, 4045, 4343, 3003, 8079, 6006, 1200, 1050, 1100	1056, 3003, 5052, 5182	226, AlSn20Cu, AlZn5Bi4
Cradles & Frames	**Wheels**	**Steering system**	**Fuel system**	**Engine/Cylinders**
5182	356, 6081, 6061	6082, 7108, 7021	6063, 3103, 5049, 5754	380, 319, Al-Si
Collision	**Brake System**	**Suspension parts**	**Trans**	**Pistons**
6013, 7021, 7029	359 or 360 +SiC	AlSi7Mg, 6013, 6082	380.2	4032

element not listed and "other total" is the maximum allowable amount for all these other unlisted alloying elements combined. Company A has a customer whose application of the alloy requires most of the alloying elements to be near the maximum specification while company B has a customer that requires the alloy to be produced at minimum specification. While the resulting alloys from both companies are designated as 6061, Table 2.4B shows that their composition differs as much as observing a 3% difference in total aluminum content.

Table 2.4: Implicit uncertainty created by vehicle specification range; A) Aluminum Association weight percent specification for 6061 and B) Comparison of alloy 6061 specifications (wt %) across companies A & B.

A

Alloying Elements	Min	Max
Si	0.4	0.8
Fe	0	0.7
Cu	0.15	0.4
Mn	0	0.15
Mg	0.8	1.2
Cr	0.04	0.35
Zn	0	0.25
Ti	0	0.15
Other each	0	0.05
Other total	0	0.15

B

Alloying Elements	Company A	Company B
Si	0.8	0.4
Fe	0.7	0
Cu	0.4	0.15
Mn	0.15	0
Mg	1.2	0.8
Cr	0.35	0.04
Zn	0.25	0
Ti	0.15	0
Ni	0.05	0
Ga	0.05	0
V	0.05	0
Total alloying elements	4.15	1.39
Aluminum content	95.85	98.61

The above illustration shows the possible difference in amount of constituent metals in a particular alloy. Further into the uncertainty of constituent metal amount, is the different possibilities of alloys used. A typical heat exchanger in a lightweight vehicle could be made from nearly any of the alloying families, which have different major alloying elements as reported in Table 2.1.

The analysis in figure 2.3 shows that for a typical heat exchanger, if the assumption is that it is made of 1050, there would be very few alloying elements with a total of 0.04 kg/vehicle of critical metals. However, the assumption of an alloy like 5049 means that the magnesium content would be quite high. Alloy 5049 would result in 0.70 kg total critical metals per vehicle. Assuming 17 million lightweight vehicles produced per year, this would mean a range of about 700 metric tons to 12,000 metric tons of total critical metals resulting from just variations in heat exchanger assumptions.

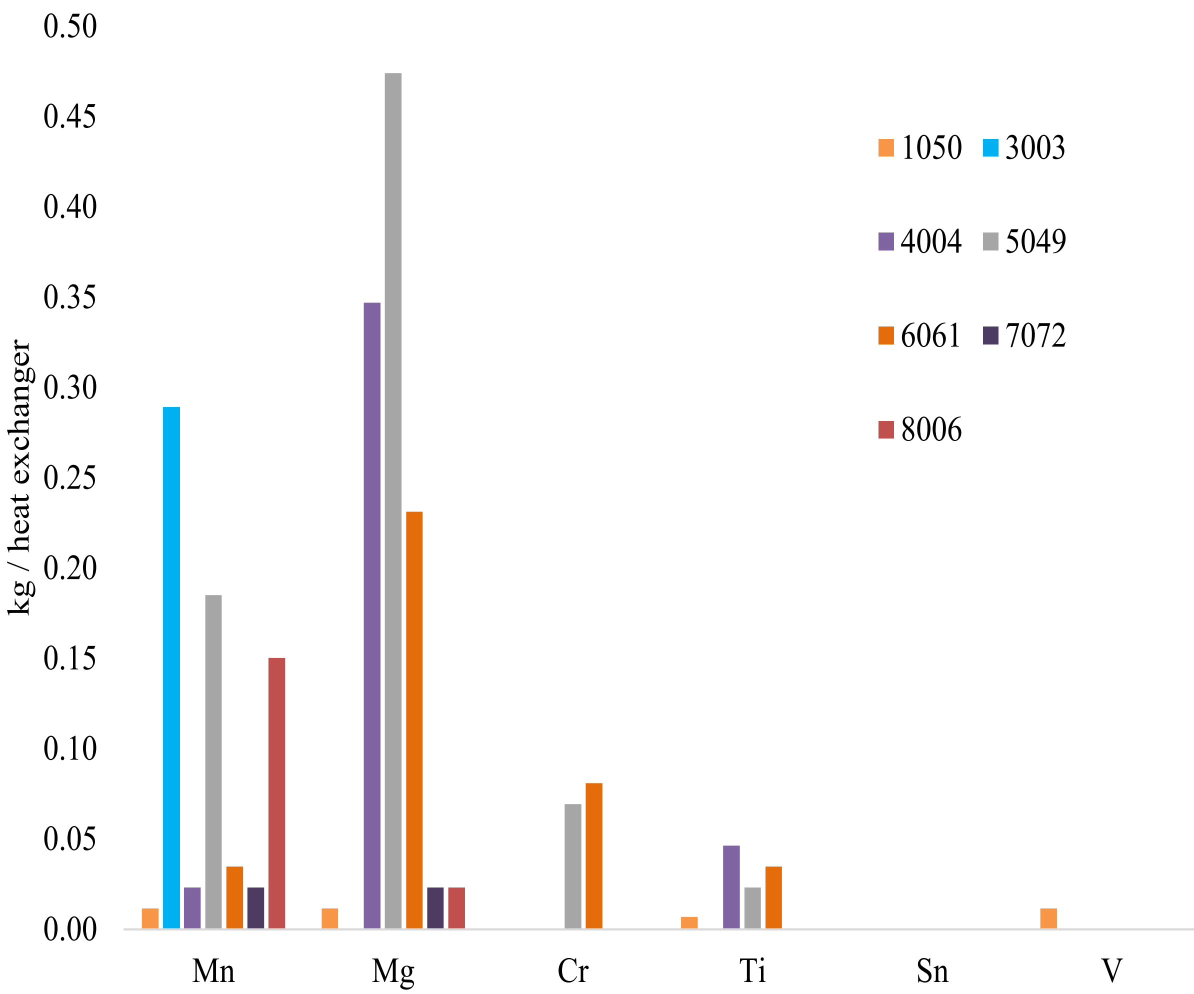


Figure 2.3: Diverse range of elemental amount in heat exchanger alloys.

Estimating critical metal content per lightweight vehicle

Individual variation in alloy for lightweight vehicle parts was synthesized into scenarios to explore the total critical element content per typical lightweight vehicle; results were explored for each constituent metal. Results (fig. 2.4) show that total critical metal content per lightweight vehicle is in the range of about 0.6 kg to 3.6 kg per vehicle. It also shows results for each critical metal across the three scenarios that were described in the methodology. The top of each high-low line signifies the maximum critical metal content scenario, the bottom signifies the minimum critical metal content scenario and the red marker signifies the typical scenario. Translating this to total North America lightweight vehicle production of 16.8 million for 2017 (Petit, 2018), and using the typical scenario value of approximately 2.0 kg critical metal per vehicle, approximately

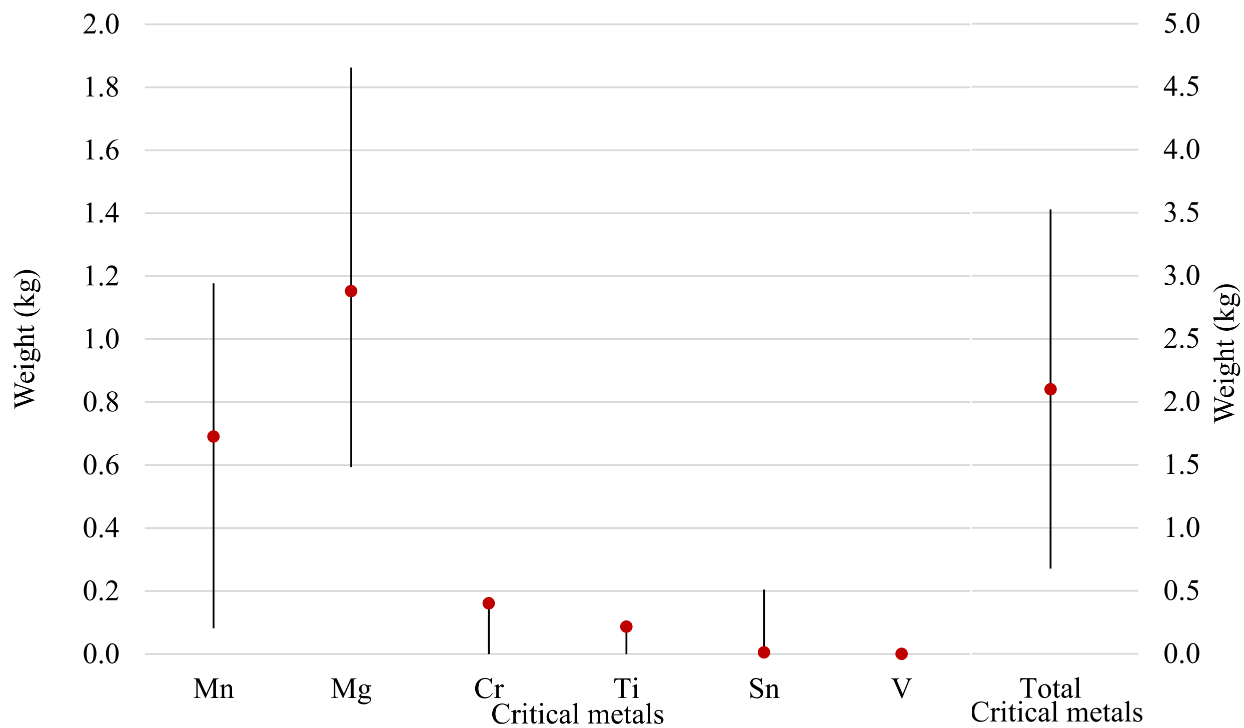


Figure 2.4: Predicted range of critical metal content per representative lightweight vehicle; Total critical metal content on right.

35 Gg (35,000 metric tons) of critical metals were used in lightweight vehicle production in 2017. Magnesium makes up more than half of this amount, 19 Gg (19,000t) with manganese at 12 Gg (12,000t), chromium at 3 Gg (3000t), and titanium, tin and vanadium at 1 Gg (1000t), 0.1 Gg (100t) and 0.02 Gg (20t) respectively as shown in figure. 2.5. Figure. 2.6 shows the sensitivity analysis depicting the increasing trend of total critical metal content per vehicle across the years based on the forecasted aluminum content per vehicle. We also observe an increasing

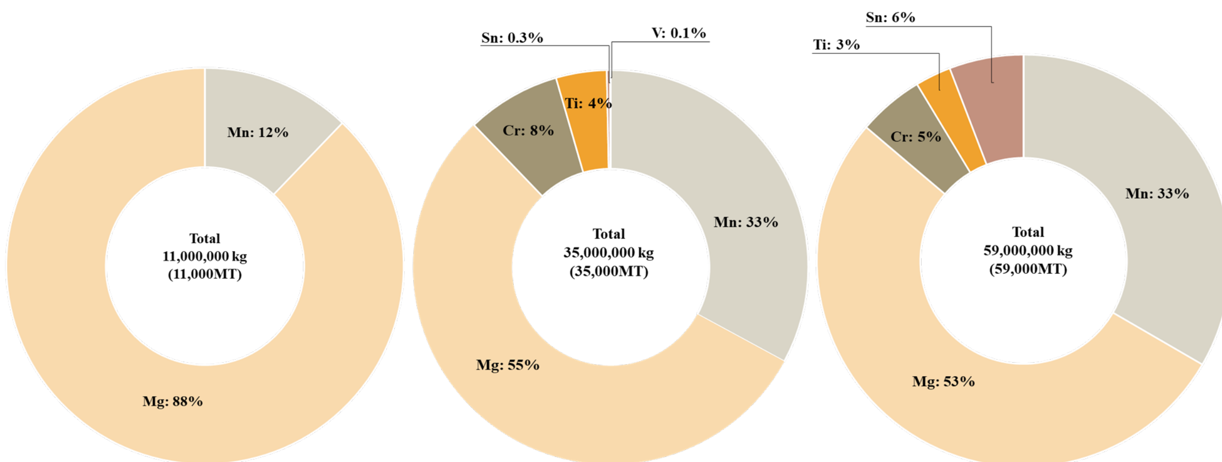


Figure 2.5: Total critical metal content distribution by alloying element showing 3 scenario analyses; from left to right: minimum, average and maximum.

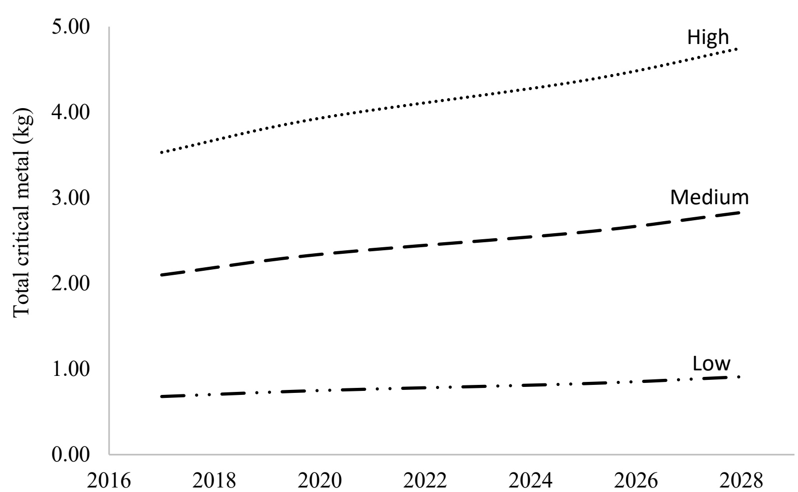


Figure 2.6: Trend in total critical metal content per vehicle across scenarios.

range of uncertainty from 0.6 kg (minimum case scenario) to 3.6 kg (maximum case scenario) per vehicle in 2017 to about 0.91 kg (minimum case scenario) to 4.75 kg (maximum case scenario) in 2028. The result is further resolved into critical metal content by part. Table 2.5a shows the critical metal content per part as a fraction of total critical metal content in the vehicle. Here, the most critical metal content is found in the wheels, followed by the collision management parts and suspension knuckles. Table 2.5b refines the total critical metal content into each critical metal under study. For example, in the body frame and inner panels with 5182 as the typical aluminum alloy, there is a total of 192 g of critical metal content consisting of 13 g of manganese, 171 g of magnesium, 4 g of chromium and 4 g of titanium. Another result read off here is the distribution of each critical metal across the aluminum parts in the vehicle. Take titanium as an example; approximately 87g of titanium is used per lightweight vehicle and most of it is in the wheels and body closures.

Table 2.5a: Critical metal content distribution by part as a fraction of total critical metal content per vehicle.

Al content per vehicle		Typical Alloy	Critical metal content
Parts	kg		(%)
Wheels	20.9	6082	19
Collision Mgt.	13.3	6013	11
Suspension-Knuckles	3.7	6013	11
Body Closures	13.3	6061	10
Heat Exchanger	17.1	3003	10
Body frame & inner panel	3.8	5182	9
Steering	9.5	6082	9
Cradles, Frames	3.8	5182	9
Engine & Cylinder heads	57	380.2	5
Trans, Driveline	39.9	380.2	2
Suspension-Control arm	2	6082	2
Brake system	3.8	360 + SiC	2
Heat Shields	1.9	1050	0
Total	**190**		**100**

Table 2.5b: Individual critical metal content distribution by part; values rounded off.

Parts	Typical Alloy	Aluminum content (g)						
		Mn	Mg	Cr	Ti	Sn	V	Total
Wheels	6082	146	188	52	21	0	0	408
Collision Mgt	6013	67	133	13	13	0	0	226
Suspension-Knuckles	6013	67	133	13	13	0	0	226
Body Closures	6061	20	133	47	20	0	0	219
Heat Exchangers	3003	214	0	0	0	0	0	214
Body frame & inner panel	5182	13	171	4	4	0	0	192
Steering	6082	67	86	24	10	0	0	185
Cradles, Frames	5182	13	171	4	4	0	0	192
Engine & Cylinder heads	380.2	57	57	0	0	0	0	114
Trans & Driveline	380.2	0	40	0	0	0	0	40
Suspension-Control arm	6082	14	18	5	2	0	0	39
Brake system	360+SiC	13	23	0	0	6	0	42
Heat Shields	1050	1	1	0	1	0	1	3
	Total	691	1153	162	87	6	1	2100

While some of the critical metals are small in amount compared to the major alloying elements, they are much higher in value. Potential economic impact resulting from dissipative losses were calculated based on reported prices of each metal and are shown in Table 2.6. Results show that the dollar value from the critical metals used in total lightweight vehicle production in 2017 is approximately 167 million USD. Fig. 2.7 compares the weight of each critical metal to their value (dollars). Results show that tin has the highest value to weight ratio, followed by vanadium, chromium, titanium, magnesium and manganese. These values represent a maximum potential loss and these elements will not be fully lost in certain recycling loops as some blending algorithms will comprehend the alloying elements present and take advantage in the batch recipe, although dilution is likely to still occur (Gaustad, Li, & Kirchain, 2007). However, down-cycling is also very likely to occur in other recycling systems for example wrought aluminum alloys will be used to produce cast aluminum alloys or specialty steels will be recycled into rebar (Brooks et al., 2019). For these cases, the functionality of these elements will indeed be fully lost.

Table 2.6: Market price and value of alloying elements used in the aluminum sector of the automotive industry ((U.S. Geological Survey, 2018); *Price of manganese and chromium obtained from Fastmarkets AMM: Daily Metal Price (October 19, 2018)

	Amount/2017 production (million kg)	**Price ($/kg)**
Mn	11.61	2.53*
Mg	19.37	4.78
Cr	2.72	11.20*
Ti	1.95	8.60
Sn	0.10	20.78
V	0.02	11.56
Total	35.28	

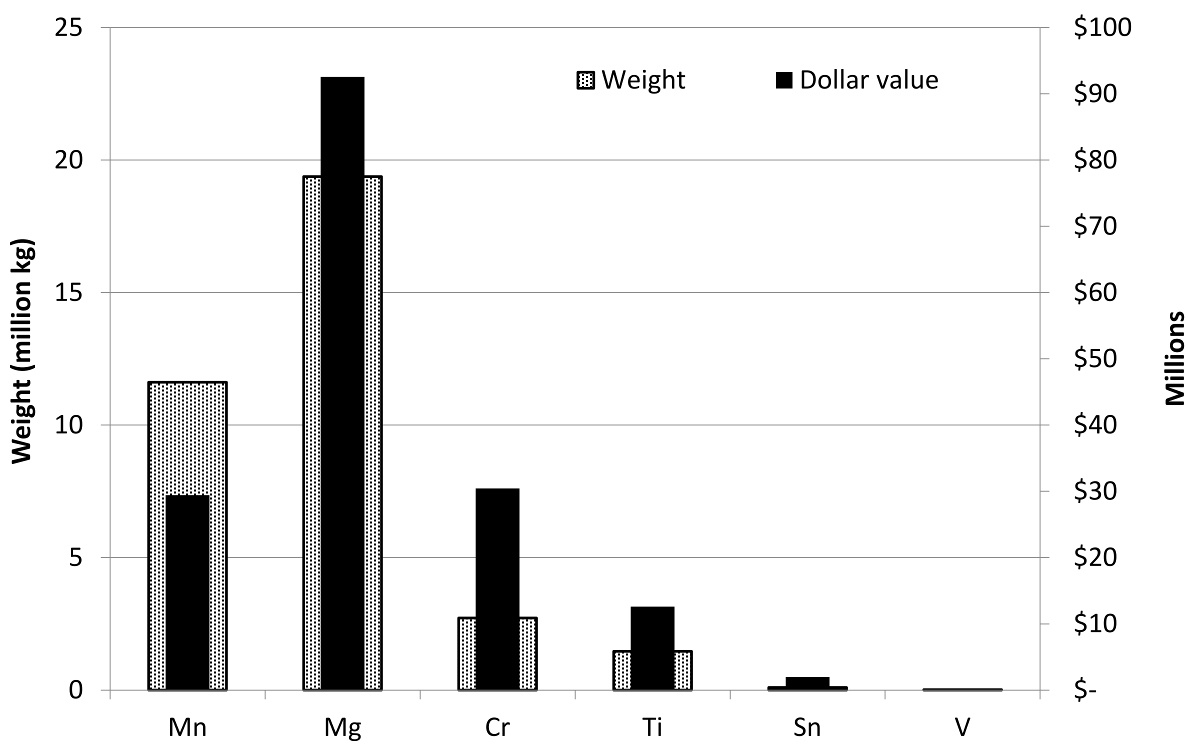


Figure 2.7: Weight (million kg) compared to value (million dollars) of individual alloying elements; U.S. 2017 values.

Critical metal usage over time: Ford F150 skin alloy case study

Increasing the aluminum content in vehicles is increasing the total alloying element content in a lightweight vehicle. Getting data to illustrate this is challenging as most original equipment manufacturers (OEMs) do not release specific alloys used in specific makes and models. However, some data are available for the Ford F-150 Chappuis (2019), a vehicle that is widely advertised for its aluminum autobody. Looking at alloy use over time shows that total alloying elements present in the skin alloys (closures) of the pick-up truck will increase over time. We show mass forecasts of total alloying elements per F-150 skin alloys over time using five (5) different scenarios: the five different aluminum alloys still in use as skin alloys.

Each year's data shown in figure 2.8 correspond to the different alloys that were registered as skin alloys. From 1962 to 2005, ten (10) alloys – 6005, 2036, 6009, 6010, 6111, 6014, 6016, 2008, 6022 and 6451 – were registered, in that order, as automotive skin alloys and only five (5) of them – 6005, 6014, 6016, 6022 and 6451 – are still in use at present (scenario on skin alloys in use zoomed out). The forecast carried out considered the historic and forecasted amounts of aluminum per vehicle, as well as the mass of aluminum in skin alloys (closures) from the Ducker analysis (Ducker Worldwide, 2017). Historic and forecasted skin alloy data was available for 2016 and 2020 respectively. Data prior to 2016 and after 2020 for skin alloys were extrapolated in proportion to the aluminum content per vehicle corresponding to each year. These data, from 1962 to 2028, were used to calculate the total critical metal content in the skin alloy corresponding to each year. From 2016 to 2020, aluminum content in closures is forecasted to increase by over 100%. This is reflected in the rapid increase in critical metal content across all 5 scenarios from 2016 to 2020.

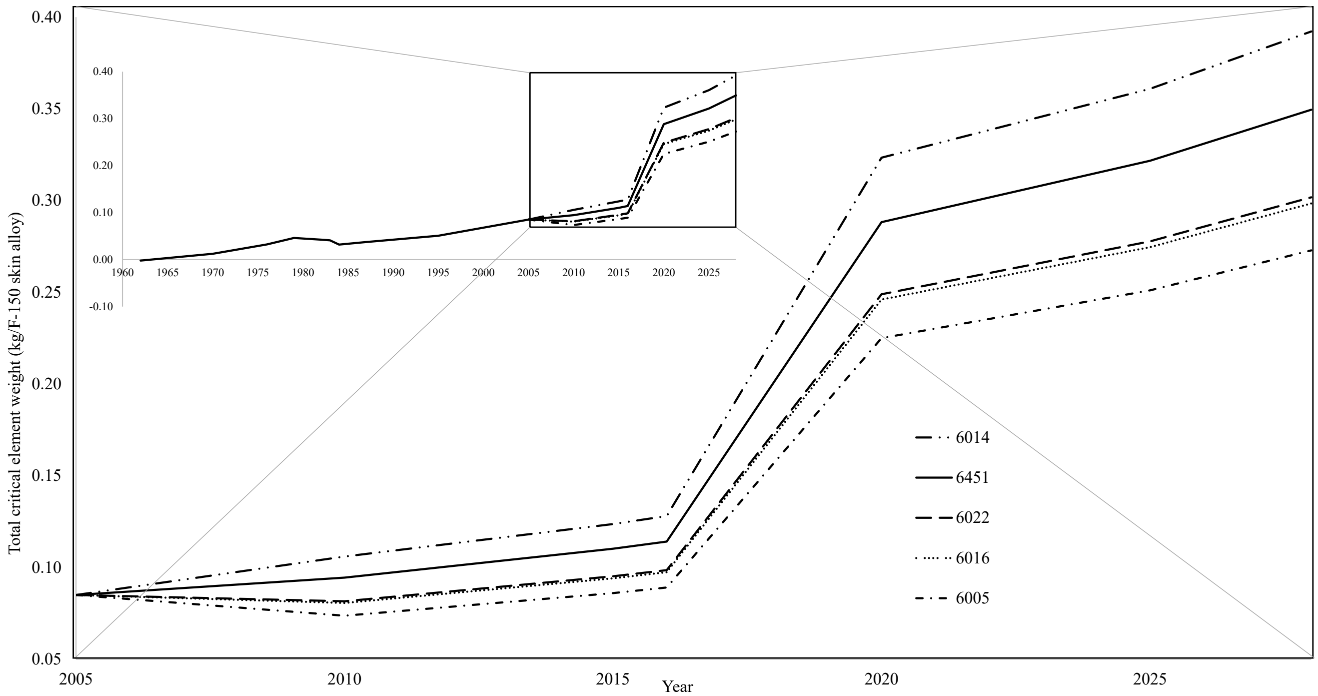


Figure. 2.8: Increase in total critical element per F-150 skin alloy; 5 scenarios based on alloys currently in use.

Though the analysis is based on Ford F150 skin alloys, and the uncertainties involved will differ from one auto manufacturer to the other, the results show that whichever one of the alloys are used in a lightweight vehicle as skin alloys, there is an unavoidable increase in critical metal content over time. While this research work focuses on metals that make up the frame of the vehicle, the authors acknowledge that the significant increase of electronics within the car will also greatly contribute to an increase of overall critical metals contained (Restrepo et al., 2017). The result from the F150 case study can even more so be generalized for lightweight vehicles, seeing that the greatest increase in the projected use of aluminum is seen in the use of aluminum sheets for body closures (Ducker Worldwide, 2017). The result also highlights how choice of skin alloy will impact the degree of critical metal content. This emphasizes how policy could be influential in this space; design for recycling approaches may incentivize one alloy use over another where function remains unchanged. This analysis points to the conclusion that increasing the aluminum content in vehicles (as seen in lightweight vehicles), increases the amount of alloying element (and thus potential tramp elements) and the critical metal content.

Another study in this research sought to analyze the effect of increasing wrought aluminum content in vehicles. The analysis by Ducker (Ducker Worldwide, 2017) shows two mass reduction scenarios, where the cast aluminum content is reduced from about 70% to i) about 60% and ii) about 40%. This reduction scenario does not contradict the forecasted trend of increasing aluminum usage in vehicles. It simply captures the current trend of using more wrought aluminum in various vehicle parts and less cast aluminum in engines to continue the lightweighting trend (as cast is much denser than wrought). This is not substitution but a fundamental change in the alloy types used in a typical vehicle (Bayliss, 2019). Using this scenario, a what-if analysis was created to observe the tradeoffs in increasing the wrought aluminum content from 30% to 70%. This increase is likely to be in the body panels, body closures and bumpers as projected by Ducker (Ducker Worldwide, 2017). Figure 2.9 shows the total critical elements with increasing wrought aluminum content. As the trend moves from 30% to 50% wrought content, a total critical metal content increase from approximately 1.1 kg to approximately 2.1 kg can be seen, and from 50% to 70% wrought content, the total critical metal content increases to approximately 3.3 kg. Also, wrought content growing from 30% to 50% also shows the inclusion of new critical metals (tin and vanadium) introduced as alloying elements. These new critical metals are also present at 70% wrought content. It is concluded from this results that increasing the wrought content increases the number of alloying elements used. Of note, is the increase in the diversity of alloying elements, as seen in the inclusion of tin and vanadium at 50% wrought content.

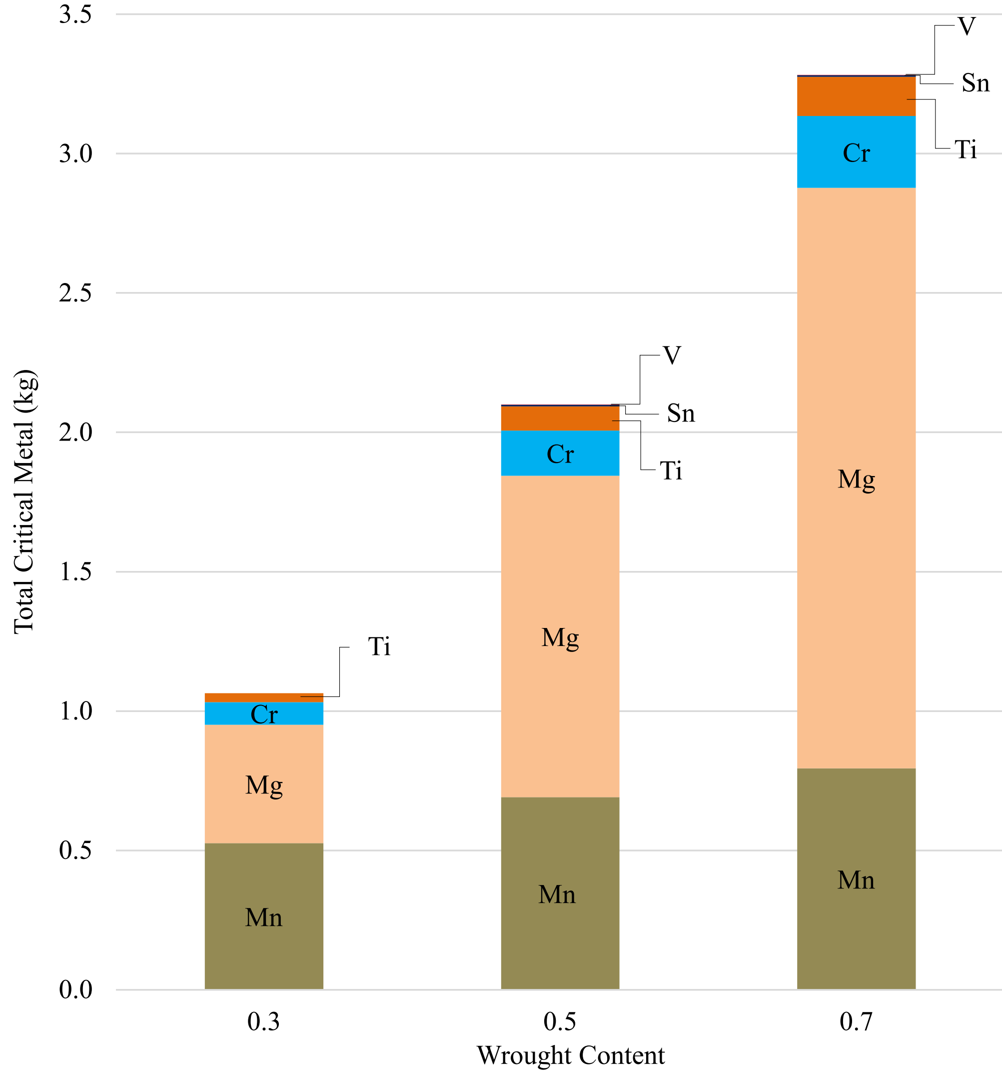


Figure. 2.9: Relationship between total critical metal content and wrought aluminum content.

Implications

Understanding how to make the automotive materials sector more circular requires quantifying uses and dissipative losses of those materials. Accumulation of alloying elements as tramp elements also negatively impacts recycling of aluminum automotive alloys in the circular economy. This work aimed to bridge a methodological and data gap in doing a material flow analysis of this sector, namely, a lack of elemental resolution of alloying elements in automotive aluminum. This challenge was highlighted by results illustrating the wide range of aluminum alloys present in a lightweight vehicle; the diversity of alloy family designations for specific parts (e.g., heat exchangers) leads to a large range in uncertainty for alloying material content and hence both critical and possible tramp elements; 0.7 kg to about 3.6 kg total critical metal content per representative lightweight vehicle. This may be an opportunity for policy in the automotive sector to push for certain alloy selections to aid in "design for recycling" (Gaustad et al., 2010). In 2017, total lightweight vehicle production was 16.8 million cars which translates to roughly 35 Gg (35,000t) of critical metals being utilized. Over 50% of this total was magnesium, the remainder being manganese, chromium, titanium, tin and vanadium in order of magnitude. The automotive aluminum industry is characterized by a nonfunctional recycling system, so these alloying elements are somewhat functionally lost in that system. Translating this into dollar values, approximately 167 million U.S. dollars are functionally lost in the system. Furthermore, data from USGS (U.S. Geological Survey, 2018) shows that the reliance on import for each of the critical metal analyzed here is on the high side – 100% for manganese and vanadium, 75% for Sn, 69% for chromium and 53% for titanium. Only magnesium has a less than 25% reliance on import. This large reliance on import is one factor for material criticality based on supply risk. In cases where a melt shop is using an advanced blending algorithm or batch plan, the alloying elements in the scrap are more efficiently used and therefore not lost. Sorting combined with positive material identification technologies enables this to be even more efficient. Again, the role of policy here could be influential. In the EU, the End-of-Life Vehicle Directive (The European Parliament and the Council of the European Union, 2000) requires high targets of recovery for automotive materials driving enhanced recycling. In the US, the solely profit-based recycling infrastructure is unlikely to be incentivized to prevent dissipative losses of alloying elements; dilution and down-cycling will likely continue.

The case study on registered automotive skin alloys used in the Ford F-150 show that newer vehicle models are pushing lightweighting to new levels and thus increasing the magnitude and variety of alloying elements contained in vehicles. This is likely to continue as the use of aluminum sheets for body closures is projected to increase if pressure on increasing corporate average fuel economy (CAFE) standards remains. The strategy for better fuel efficiency through light-weighting will also continue to drive down the automotive demand for castings which contributes to these trends. The trend of less demand for castings will also complicate the automotive aluminum circular economy as castings are a compositionally forgiving sink for recycled aluminum and the largest consumer of secondary aluminum (Modaresi & Müller, 2012).

CHAPTER 3

COPPER USE IN ELECTRIC VEHICLES AND IMPACTS ON THE RECYCLING SECTOR IN THE UNITED STATES

The transition from internal combustion engine (ICE) vehicles to electric vehicles (EV) is currently accelerating. The market for EVs is uncertain due to inter-related environmental, social, and economic parameters that drive adoption and market demand. EVs and ICEs differ greatly in the materials that are required to manufacture them. This chapter focuses on the increasing demand for copper, a strategic material, in ICEs as well as in EVs especially with the massive push for EV adoption and its dependence on copper.

Introduction

Both environmentalists and policy makers pushing to attain clean mobility (ICCT, 2018; Ministry of Heavy Industries and Public Enterprises, 2019; Natural Resources Canada, 2020; The European Parliament and Council of the European Union, 2009) have ignited the drive towards zero emissions, thereby encouraging the transition to alternative fuel vehicles. As a result of this, automotive manufacturers now have, among their fleet, vehicles with alternative powertrains that include batteries, electric motors and electronics. These vehicles come in different types – hybrid electric vehicles (HEV), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV) – and are generally called electric vehicles (EVs). Based on scenarios considering different policies and mandates, the global target for EVs on roads is between 130 million and 250 million vehicles by 2030 (IEA, 2019; UNFCCC, 2015) from a 2018 global stock of 5 million EVs (Ballinger et al., 2019). Figure 1 shows the dynamics in the sales of passenger vehicles in the U.S. where we see an increasing trend in the purchase of EVs. We observe about 30% increase in the total number of vehicle sales from 2011 to 2019, where the major portion is from increased purchase of light duty vehicles (LDVs) like pickup trucks and sport utility vehicles (SUVs). Though this results in about 20% in passenger car sales, EV sales (included in passenger car sales) however, increased by about 20%. At the end of 2019, the estimated EV stock on roads is approximately 1.4 million EVs in the US and a global stock of 7.2 million (IEA, 2020).

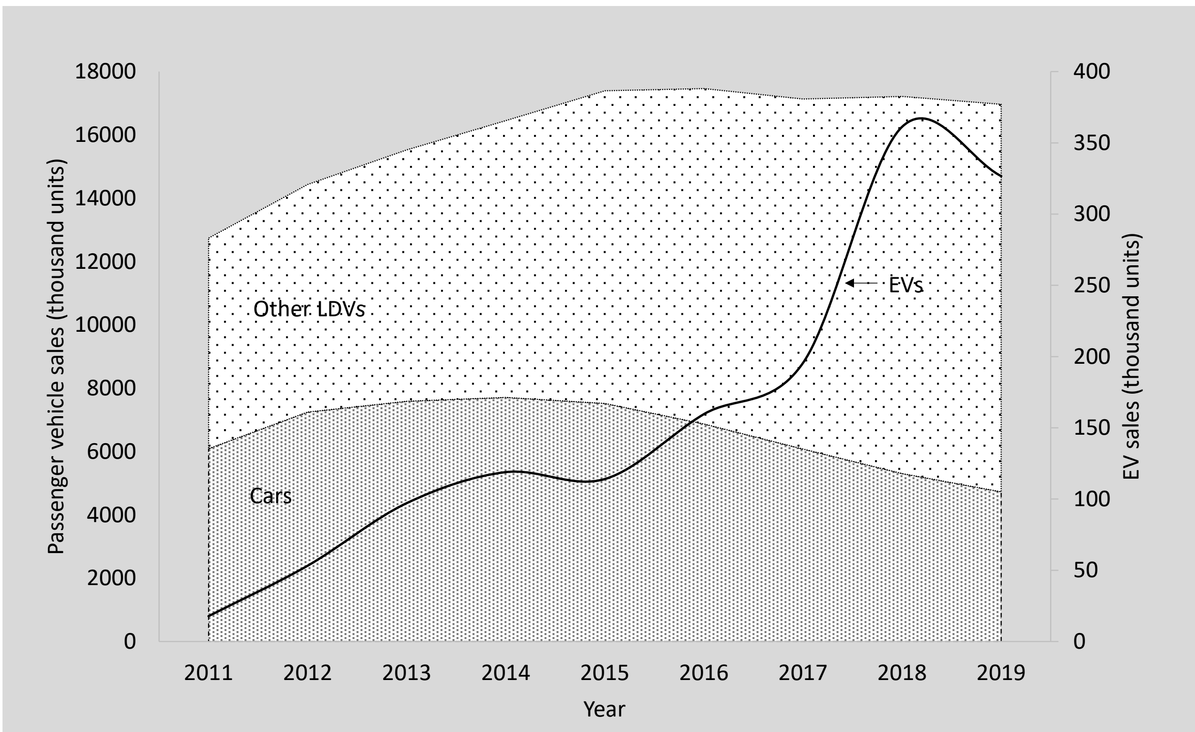


Figure. 3.1: U.S. passenger vehicle sales in recent years; Vehicle sales on left axis, EV sales on right axis (Alternative Fuels Data Center, January 2020; Statista, 2021)

Preceding the push for zero emission vehicles was a push towards better fuel economy, which has created rapid change in the automotive industry. Automotive manufacturers and original equipment manufacturers (OEMs) have responded to this initiative by replacing traditional vehicle materials with lightweight materials that are as functional. Figure 3.2 indicates some effective result in lightweighting where the curb weight of the typical U.S. passenger vehicle is immediately seen to have a 18% reduction in curb weight (3,761kg in 1976 to 3,102 kg in 1982), however, the rate of reduction slows down in the 1980's. Parallel to this is the significant reduction in gasoline prices from 1981 to 1986 (Office of Energy Efficiency & Renewable Energy, 2016) leading to less emphasis in vehicle design for fuel economy. Subsequent years welcomed competition in vehicle upgrades, resulting in new feature additions that added on to vehicle weights. We also saw the popularity of larger LDVs like pickup trucks and SUVs (United States Environmental Protection Agency, 2021), thus increasing the overall fleet average vehicle weight. The figure also shows the transition of material composition by weight in passenger vehicles – steel, iron, aluminum, copper, rubber, glass, plastics/composites, and other materials – in varying amounts. Distinct reductions of about 50% and 30% are seen in

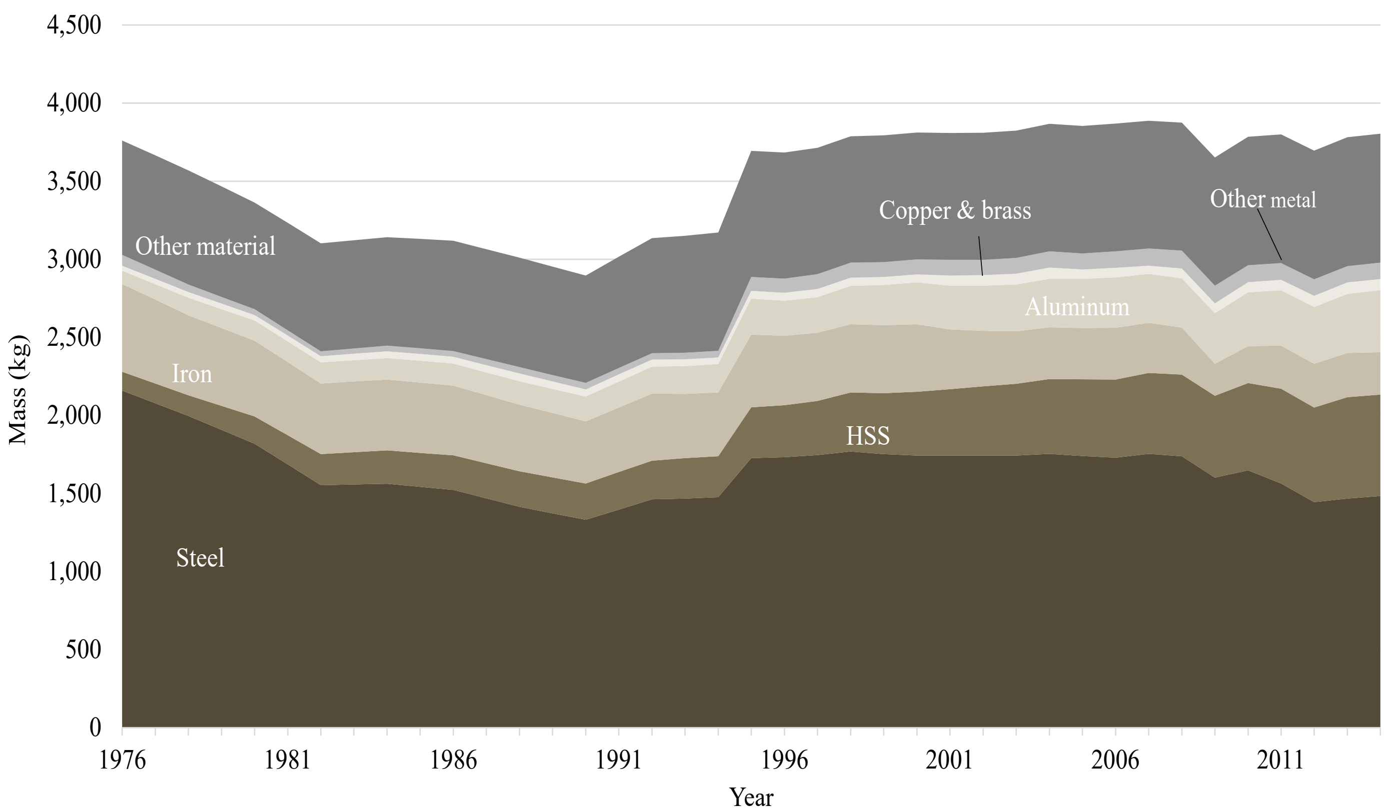


Figure 3.2: Trend in material composition of U.S. vehicles (Dai et al., 2016; Wards Intelligence, 2005)

the iron and steel content, respectively. The other components – high strength steel (HSS), aluminum, copper, brass, other metals and non-metallic materials – in the vehicle showed varying degrees of increases. HSS and aluminum show the largest increases in content of about 440% and 370%, respectively. Previous studies (Arowosola & Gaustad, 2019; Ducker Worldwide, 2017), have also reported that the use of aluminum for light-weighting is increasing in the automotive industry. Copper & brass have increased by 120%, other metals like magnesium and zinc by 50% and other non-metallic materials like plastics and composites show about a 13% increase over this period.

The major difference between an internal combustion engine (ICE) vehicle and an electric vehicle (EV) is the powertrain, which consists of an electric motor and a battery. These parts are made up of different critical and strategic materials like copper (Cu), aluminum (Al), rare earth elements (REEs), lithium (Li), cobalt (Co), etc. (Arowosola & Gaustad, 2019; Fu et al., 2020; Gruber et al., 2011; Widmer, Martin, & Kimiabeigi, 2015). Considering the trend as shown in figure 3.2 and incorporating the EV material make up of critical and strategic materials, coupled with the global target of 130 – 250 million EVs on the road by 2030, there is a need for the automotive industry to understand the probable challenges to the supply of these critical and strategic materials in order to adequately meet the inevitable surge in demand for these materials (Fu et al., 2020; Gruber et al., 2011).

Additionally, the impacts of materials used in the manufacturing of vehicles do not stop after assembly is complete, there are downstream impacts that need to be considered as well. Automotive vehicles are regarded as the topmost recycled consumer product (American Iron and Steel Institute, 2020; Kelly & Apelian, 2016). Approximately 27 million automobiles are recycled annually worldwide making dismantling, parts recovery, and automotive shredding a demonstrably significant industry (Kukreja, 2018). Market conditions typically dictate how vehicles are dismantled; in one market it will make sense to pull components out of the car and only send the shell through the shredder (also referred to as hulks) where otherwise whole cars can be pulverized. For instance, a decade ago, harness wires, a type of insulated copper wire (ICW), were pulled out of vehicles to be resold, reused, or recycled. Other vehicle parts that undergo similar process include engine blocks, transmissions, alternators, starters, and radiators. More recently, the power and capabilities of automotive shredders make it possible to shred the entire car (minus fluids and batteries). This possibility can make the process more efficient, and coupled with commodity pricing, more economical as well. These shredders, growing more popular and sophisticated, have created new commodities that the Institute for Scrap Recycling Industries (ISRI) added and defined in the Scrap Specification Circular in the late 90s (Tauben,

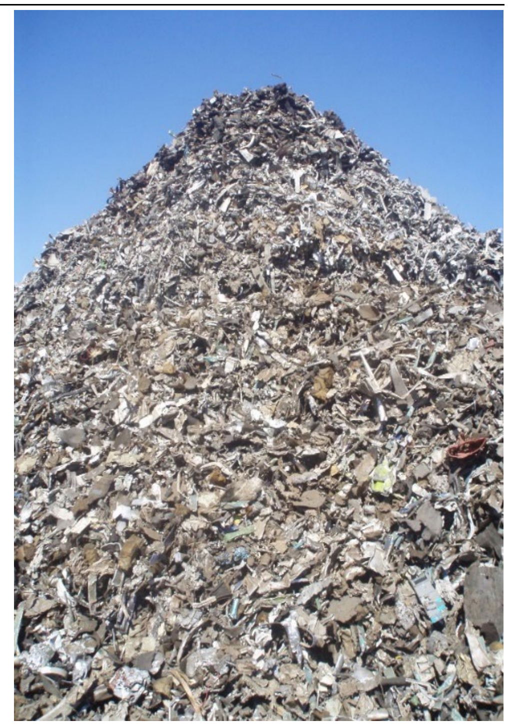
Definition	
SHREDDED NONFERROUS SCRAP (predominantly aluminum) Shall be made up of a combination of the nonferrous metals: aluminum, copper, lead, magnesium, stainless steel, nickel, tin, and zinc, in elemental or alloyed (solid) form. The percentage of each metal within the nonferrous concentrate shall be subject to agreement between buyer and seller. Material generated by eddy current, air separation, flotation, screening, other segregation technique(s), or a combination thereof. Shall have passed one or more magnets to reduce or eliminate free iron and/or large iron attachments. Shall be free of radioactive material, dross, or ash. Material to be bought/sold under this guideline shall be identified as "Zorba" with a number to follow indicating the estimated percentage nonferrous metal content of the material (e.g., "Zorba 90" means the material contains approximately 90% nonferrous metal content). May also be screened to permit description by specific size ranges.	

Figure 3.3: ISRI's definition of Zorba (Institute of Scrap Recycling Industries, 2020)

2011). Detailing all the shredded scrap commodities that have been sustained as a result is outside the scope of this paper, but one such scrap commodity, "Zorba" is highlighted here for context (cf fig 3.3). The composition of Zorba depends on the shredding and sorting technology applied and often the size of the material, also known as "fractions" (characterized as either fines, mids, or heavies). Typically, it is expected that the metallic content of Zorba be between 85%-95% aluminum (Tauben, 2011), with 1%-3% red metal (Cu, brass) although today it is more common to see around 95% Al and 2%-3% red metal. Changing the feed input, in this case going from an ICE vehicle to an EV will ultimately impact the ratios of this commodity in the future.

A UBS analysis (UBS Limited, 2017) studied how a global market with EVs having 100% market share would affect the demands of these strategic materials. Compared to 2017 global production, the demand for aluminum, manganese and copper will increase by 13%, 14% and 22% respectively. Also, the International Energy Agency's (IEA) 2019 global EV outlook (IEA, 2019) has particularly identified copper amongst others (cobalt, lithium, manganese, nickel, aluminum and graphite) as a strategic material whose supply is affected the most as a result of increasing adoption of EVs. While traditional ICE vehicles still make up a large portion of the automotive market share, we see an increasing trend in the EV market share (figure 3.1). This is not surprising, especially with the "2015 Paris declaration on electro-mobility and climate change"(UNFCCC, 2015). The declaration has seen many automotive industry partners, including manufacturers, as responders to the global call-to-action towards sustainable transport electrification. With the eventuality of EV market share increasing in the near future, the increase in the demand of these strategic materials is inevitable (Henckens & Worrell, 2020). The question then becomes how to sustain such a surge in the demands for the strategic materials required in an EV. For this study, we have chosen to focus on copper. Copper consumption has significantly increased in the past years resulting in more copper scrap generation, but without the commensurate secondary copper production, and consumption (Gómez, Guzmán, & Tilton, 2007). We will be examining the projected increase in the adoption of EVs, its effect on the demand for copper, as well as the resulting impacts, particularly on the recycling sector, at a systems level by addressing these questions:

1. How much copper will be required in the short term (2030) and long term (2060)?
2. How will increased adoption of EVs affect other related industries?

Methodology

To forecast how much copper will be required in the long term, we first estimate the amount of copper per vehicle using the U.S. Geological Survey and Oak Ridge National lab databases. Results from here are compared with those already published in literature. Secondly, we use the IPAT equation to forecast the copper demand from 2020 to 2060 and then compare results with the estimated copper supply.

Next, we analyze the implications of the forecasted demand, its effect on different industrial sectors, particularly the recycling industry and other copper end use industries.

Finally, we discuss the possibilities of minimizing the negative externalities to optimize the benefits of adopting clean mobility using EVs.

Estimating copper per vehicle

A material flow analysis (MFA) of copper was carried out using a top-down method to determine the amount of copper per vehicle. Data on copper consumption by industry for the U.S. was obtained from the U.S. Geological Survey (USGS) minerals information center from

2008 to 2019. Here, consumption by transportation equipment includes consumption by automobiles, trucks and busses, railroad, marine, aircraft and aerospace. For lack of finer resolution of copper consumption by type, we assumed that all copper consumed by this category is used for automobiles, trucks and buses.

Next, we obtained the amount of vehicles produced per annum in the U.S. from the Oak Ridge National Laboratory (ORNL) for both passenger cars and commercial cars. (Davis & Boundy, 2020; Wagner, 2020). With results from both databases, we were able to estimate the amount of copper per vehicle from 2008 to 2019 using the equation below.

$$\rho_i = \frac{Cu_i}{T_{car\ i}} \qquad \text{…eq 1}$$

Where ρ is copper per vehicle;

Cu is the amount of copper produced;

T_{car} is the total amount of vehicles produced;

i is the data year being observed.

We combined this top-down result with a bottom-up approach for comparison. For our bottom-up approach, we comprehensively gathered published values of copper content in a variety of vehicles from multiple literature. These values span from MY1975 to MY2014.

Forecasting vehicle copper demand

The vehicle copper demand is a function of some key parameters – car ownership demographics, the affinity for vehicles, and the copper content per vehicle. Two sets of parameters have been used, one for ICEs and one for EVs, because:

i. Copper content differs from ICEs to EVs.

ii. The affinity for ICEs also differs from EVs as evidenced in their different market ratios

Historic copper demand (2010 to 2019) was also calculated using the IPAT equation (eq 2) to create a comparable basis for our forecast. From 2010 to 2019, population data was obtained from the U.S. Census Bureau dataset (U.S. Census Bureau, 2019). The affinity parameter, A, is defined as the resource (which, in our analysis, is represented by the number of vehicles sold) per person. The number of vehicles sold was obtained from government database (U.S. EIA, 2021) for both ICEs and EVs. Finally, the technology parameter, T, is defined as the impact per resource. In this case, it is represented as the copper content per vehicle and obtained from the analysis described in the prior section.

$$I = P \text{ x } A \text{ x } T \quad \text{…eq 2}$$

Where I = EV copper demand

P = Population

A = Resource/person i.e., EVs sold/person

T = Impact/resource: Cu/vehicle

We also used the IPAT equation to forecast EV copper demand from 2020 to 2060. Multiple scenarios were analyzed – low, mid and high – based on the uncertainties surrounding the variables i.e., population, EV sales and copper content per vehicle.

Population (P)

Population projections are based on multiple variables – birth rate, mortality rate, and migration rates. Though these rates are nearly impossible to ascertain, the U.S. Census Bureau projects the national population based on historical trends. Its 2017 national population projections alternative scenarios (Johnson, 2020) estimates the effects of different immigration rates only on the population projections, while assuming constant birth, mortality and emigration rates across all 3 scenarios. For our analysis, we have used the main series population projections based on historical trends to narrow the uncertainties.

Affinity (A)

The affinity factor, also known as resource/person, was defined in our model as the number of vehicles sold per person. There has been a reducing trend in ICE sales since 2016, but for EVs year 2018 was a banner year for sales in the US; the following year, 2019, though, showed a decrease in sales, mainly due to the federal tax credit program cap surpassed by two (2) major EV auto manufacturers (IEA, 2020). The program provides credit to taxpayers for the purchase of eligible electric vehicles. The credit is gradually phased out after 200,000 units of qualified sales is reported by the auto manufacturer. The IRS in its notice 2019-22 (Stehn, 2019) reports the credit-phase out schedule for one of the manufacturers beginning in April 2019 after they sold more than 200,000 units of EVs eligible for the tax credit. In addition to this, the 2019/2020 global pandemic, COVID-19, continued the decreasing trend, where a further decrease is observed in the sales of EV in the first half of 2020. Projections for both ICEs and EVs are obtained from the EIA's annual energy outlook (U.S. EIA, 2021) and are used to carry out the analyses.

Technology (T)

Technology defined as the impact per resource was represented in this model as the amount of copper per vehicle. 3 scenarios were computed using low, average and high values of copper content per vehicle. For the ICE, the low, average and high values were obtained from results from the prior section (estimating copper per vehicle) over a 20-year period (2000 – 2019). The estimation represents the average copper content per vehicle produced in the U.S. "Vehicle" in this estimation mostly includes ICE vehicles and a minor portion of EVs. For the EV, the low, average and high values of T correspond to the average copper content in a hybrid electric vehicle (HEV), plugged-in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV) (International Copper Study Group, 2019) respectively. Table 3.1 shows scenarios described above and the values for both ICEs and EVs.

Table 3.1: Scenario analysis based on technology parameter for ICEs and EVs.

	Technology	
	(kg Cu/vehicle)	
Scenarios	*ICE*	*EV*
Min	19	40
Avg	26	60
Max	37	83

Results and Discussion

Estimating copper per vehicle

Using equation 1 for our estimation, we observe in figure 4 that copper content per vehicle is increasing with time. Amount of copper used per vehicle was calculated for each year from 2008 – 2019 and the results, together with those from existing literature (1976 to 2014), are shown in figure 3.4. The observed general trend here is an increase in the copper content of vehicles from year to year, much more so within the last 5 years where the copper per vehicle increased from 28 kg/vehicle to 34kg/vehicle. The EV portion in the estimate increases from yearly and is projected to continue to increase. While this trend might be a result of multiple dynamics, we highlight two main contributors to this trend. First, a UBS teardown analysis (table 3.2) comparing the Chevrolet Bolt (EV) and the Volkswagen Golf (ICE) (UBS Limited, 2017) showed key weight differences in material content. Compared to the Golf, the Bolt had about 7%

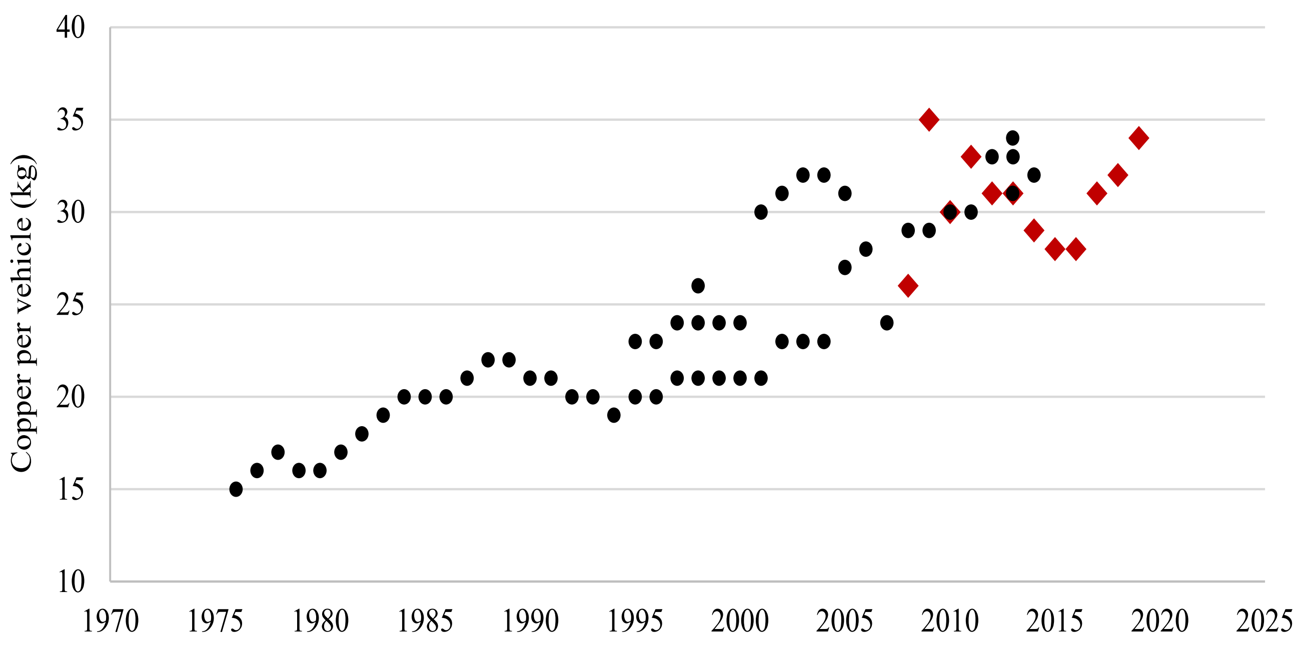


Figure 3.4: Trend in copper content per vehicle in kg; (Brahmst, 2006; Bushi, Skszek, & Wagner, 2015; Dai, Kelly, & Elgowainy, 2016; Field, Wallington, Everson, & Kirchain, 2017; Wards Intelligence, 2005)

less steel, 70% more aluminum, 80% more copper and 90% more “other materials”. The result of this teardown analysis establishes the fact that there is more copper (among other materials) in an EV than there is in a comparable ICE vehicle.

Table 3.2: UBS teardown analysis comparison (values in kg)

Material	**Chevrolet Bolt (EV)**	**Volkswagen Golf (ICE)**
Steel	650	700
Aluminum	170	100
Copper	90	50
Iron	30	100
Rubber	20	20
Other	620	325

Secondly, while there is an increasing diversity in the kinds of metals used in the automotive industry for vehicle electrification (Boulanger, Chu, Maxx, & Waltz, 2011; Fu et al., 2020), previous work by investigators (Arowosola & Gaustad, 2019) also show diversity in the kinds of alloying elements used in lightweighting ICEs. Subsequent analysis show copper as contributing a very large portion – more than half – to the total amount of strategic metals used in alloying aluminum as seen in figure 3.5. With these observations and analyses signaling the trend in copper content in both EVs and ICEs, we can project that the average copper per vehicle (ICEs and EVs) increases with time, and even much more so at a faster rate, as the EV market share increases (cf. figure 3.1).

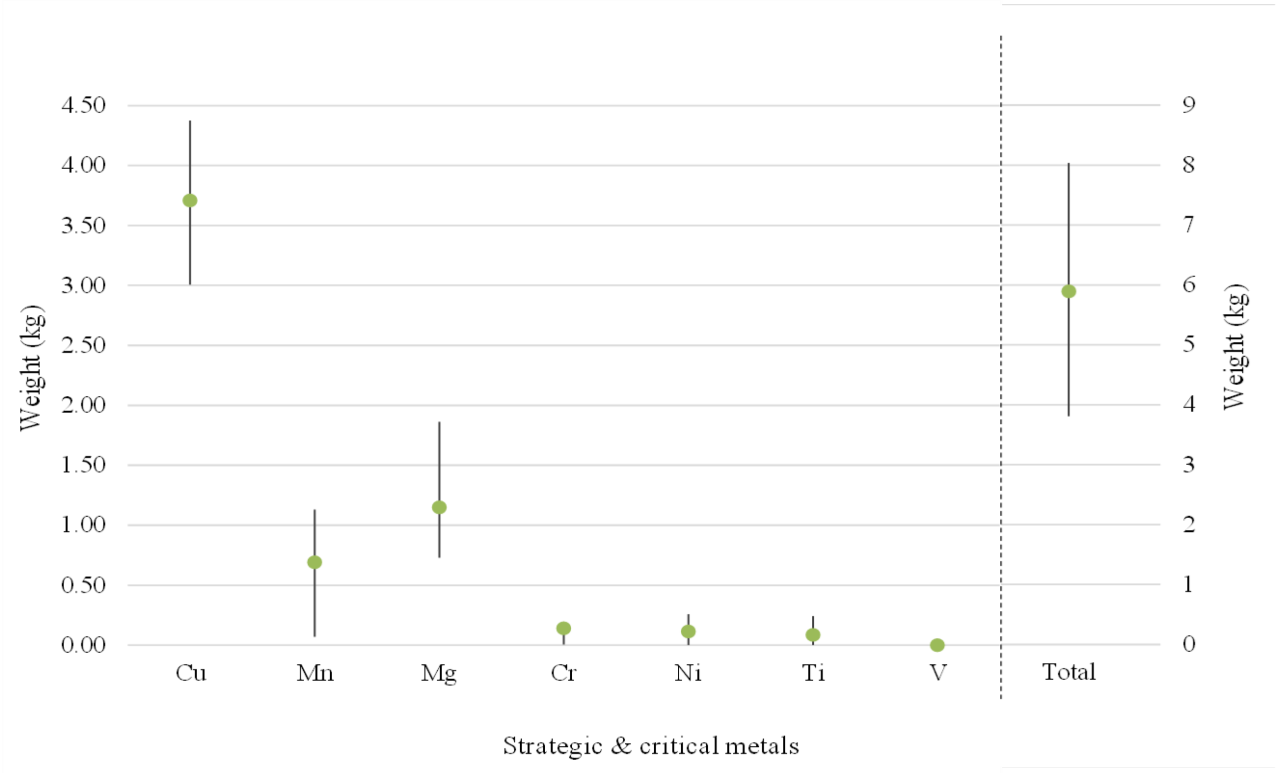


Figure 3.5: Strategic and critical metal content in lightweight vehicle aluminum alloys; Individual metal weights on left axis, total metals weight on right axis

Forecasting copper demand

Equation 2 was used to forecast the copper demand from 2020 to 2060. Total copper demand was obtained by summing up results from the ICE model and the EV model. The result (figure 3.6) shows the historic copper demand by the automotive industry (ICEs and EVs) from 2000 to 2020). It should be noted that the effect of the 2019 pandemic caused by the SARS COV2 virus, COVID-19, was accounted for in the sales of automobiles. Its effect is seen in the result as the steep drop in copper demand (and supply) in 2020. In the short term (2030), demand for copper from the transportation sector (specifically ICES and EVs) will be in the range of 308kt – 615kt, where our analysis show that about 18% of that is EV copper demand and in the

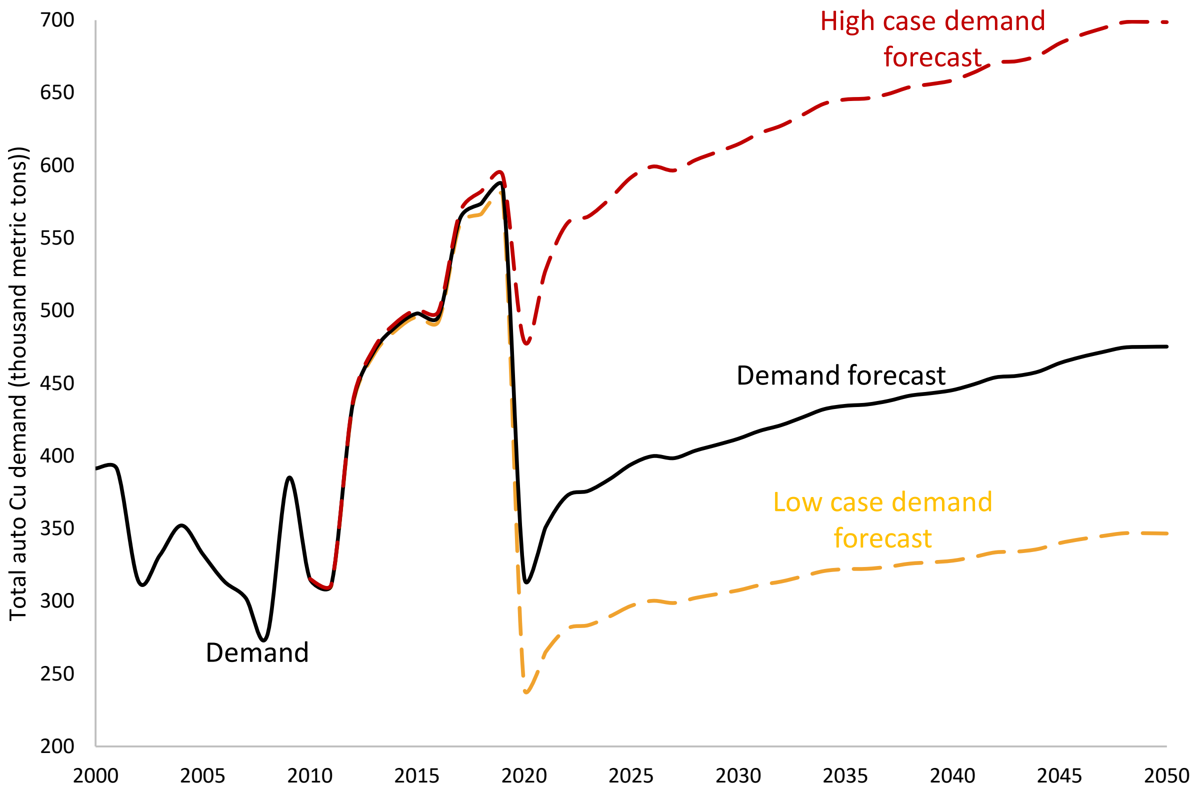


Figure 3.6: Total copper demand (ICE + EV) projection

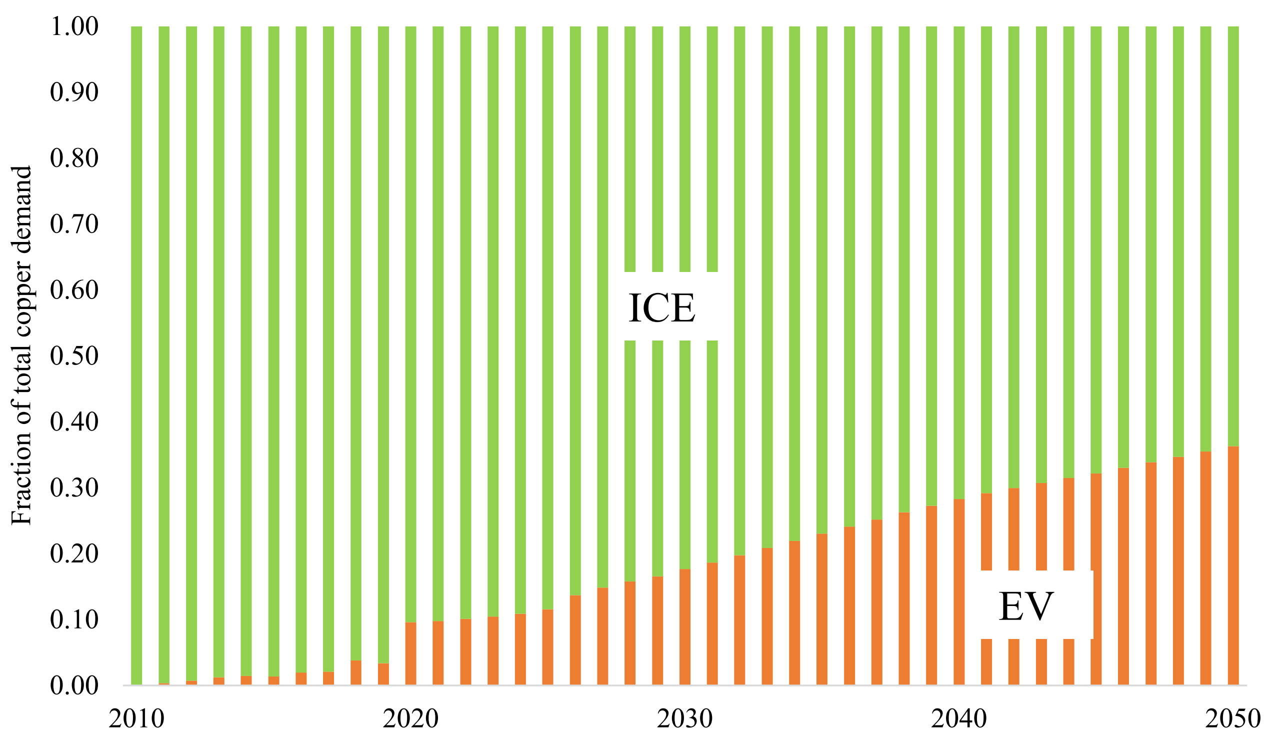


Figure 3.7: Total copper demand by vehicle type

long run (2050), demand for copper from the transportation sector will be in the range of 347kt – 699kt, where about 36% of that is EV copper demand. This analysis of future copper demand poses to be a very conservative one. The 2020 vehicle sales projection, considering the global pandemic, was estimated to be about 11.5 million units (U.S. EIA, 2021) (also see table A4 and A7 in the appendix) from a 2019 sales volume of approximately 17 million units. Subsequent year projections follow a steady recovery from the 2020 level. However, at the end of 2020, total light vehicle units sold in the U.S. were about 14.5 million units (Statista, 2021), approximately 26% more than the projected sales. This trend is seen to continue in 2021, thus making the copper demand forecast a very conservative one and now evidently picking up faster than projections. Figure 3.7 depicts the contribution to total copper demand by vehicle type. While EVs fraction of total copper demand is increasing, doubling by 2050 from a 2030 value, a larger portion of the demand is still as a result of ICEs, as well as in the long term.

Demand vs Supply: Estimating supply gap

To estimate the copper demand-supply gap, the projected copper demand was compared with copper supply. Future copper supply was modelled after GDP projections announced by the federal reserve board members. GDP model was used because of its closely related historic trend with copper supply as shown in figure 3.8.

Based on this, copper supply, modelled after GDP projections, was used to estimate the onset of copper supply constraint/gap when compared with the previously projected total copper demand. From the result in figure 3.9, it can be inferred that copper supply running on deficit is not a new occurrence as evidenced in 2009. This deficit was presumably covered by a portion of accumulated stock (2000 – 2008). However, continuous supply deficit over time will lead to a supply constraint, thus marking the onset of a copper supply gap. If future copper demand follows the high case copper demand projection, then this onset could be as early as this year (2021).

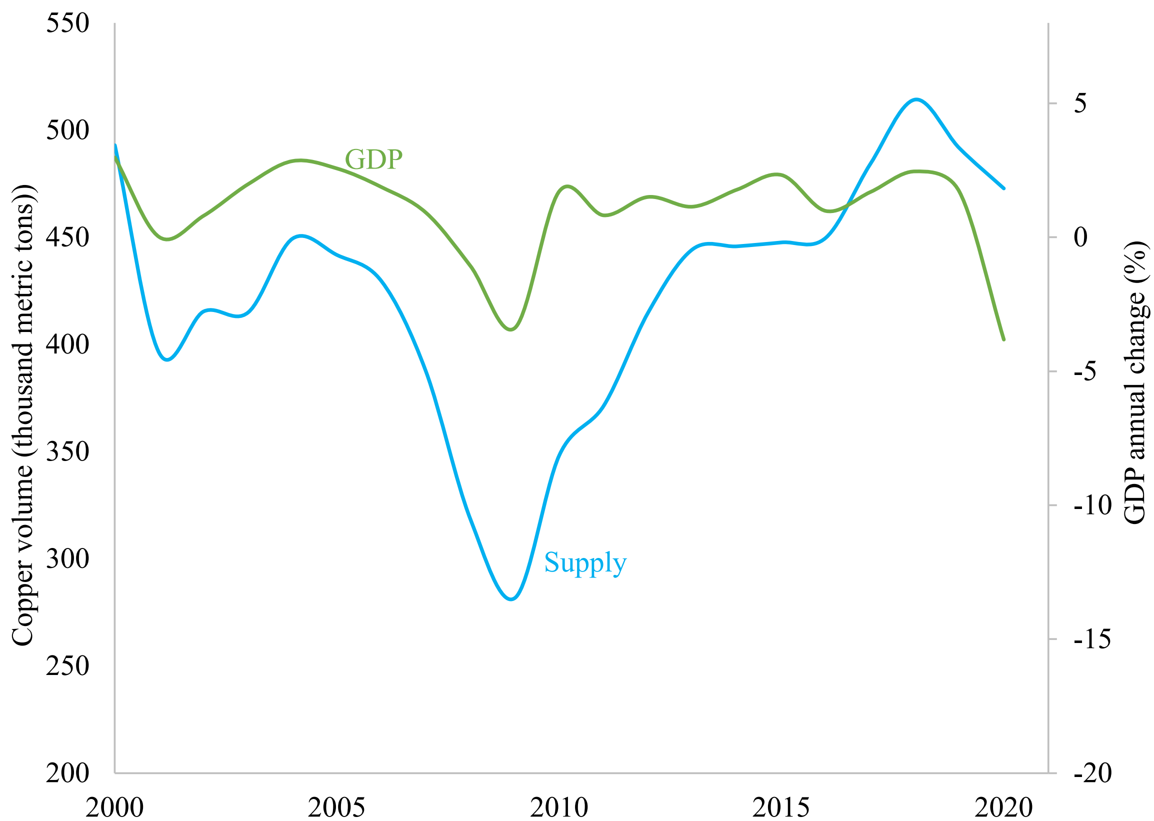


Figure 3.8: Comparing trends: Historic copper supply (left axis) and GDP change (right axis)

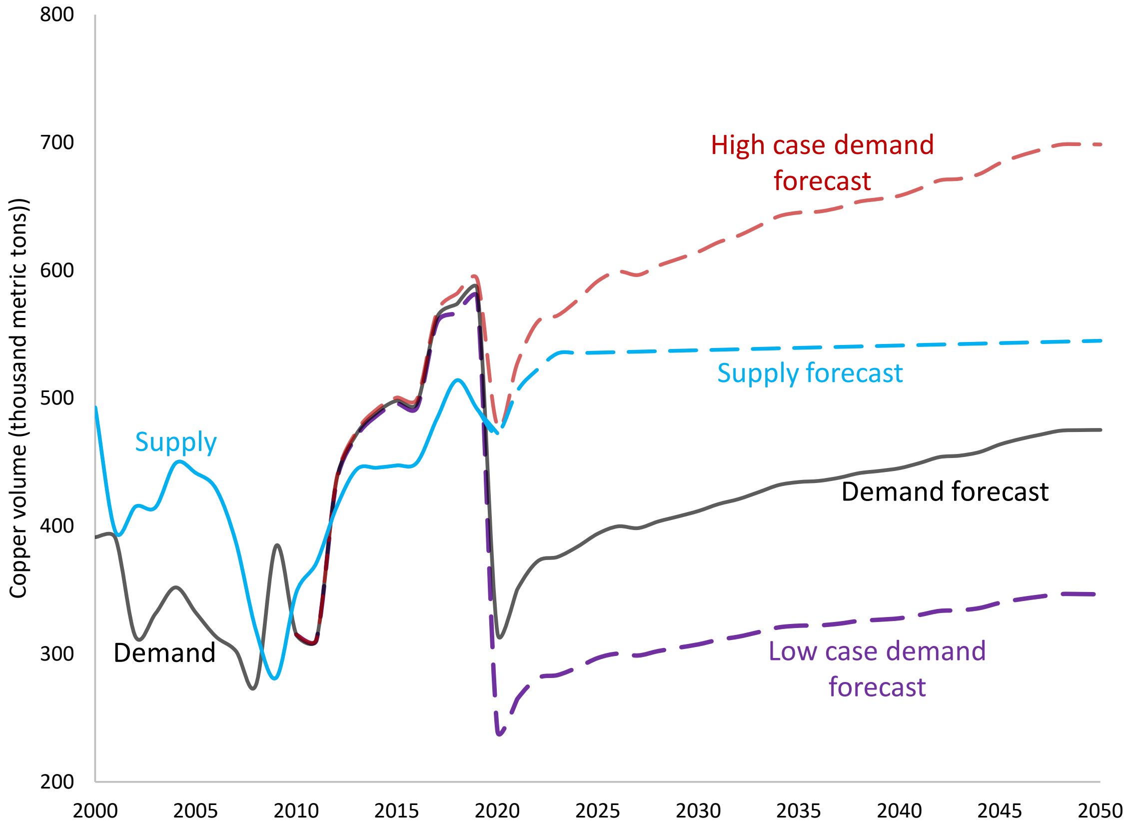


Figure 3.9: Comparing Copper Supply and Demand

System-level effects of increasing EV copper demand

On other Cu end use sectors (competing demand)

Copper is a multi-versatile material and as such, finds use in different industries. The building and construction industry is the largest market for copper, found in both modern buildings and historical structures as window frames, plumbing, structural reinforcements, roofing, wiring, etc. The industrial equipment industry finds use for copper in manufacturing plants, industrial transformers and motors, valves, fittings and so on. Electrical and electronic industrial copper uses include electrical power transformers, distribution, telecommunication networks, industrial and commercial electronics, etc. For general consumer products, copper uses include appliances, instruments, consumer goods, etc. (Copper Alliance, 2020). Copper use in the top five industrial consumers of copper is tracked and estimated over a ten-year historic period, and 15 futuristic years, respectively.

From 2009 to 2019, it is observed that there is about 2%, and 13% reduction in the amount of copper use in the building construction (809 kt to 796 kt) and industrial machinery (149 kt to 130 kt) industries, respectively. The largest increase of 87% is observed in transportation equipment (198 kt to 370 kt), followed by increases of 12% each in the electrical and electronics industry (330 kt to 370 kt) and in the consumer products industry (165 kt to 185 kt). It is estimated that by 2035, if this 10-year trend continues, the distribution of copper use will be 29%, 42%, 15%,

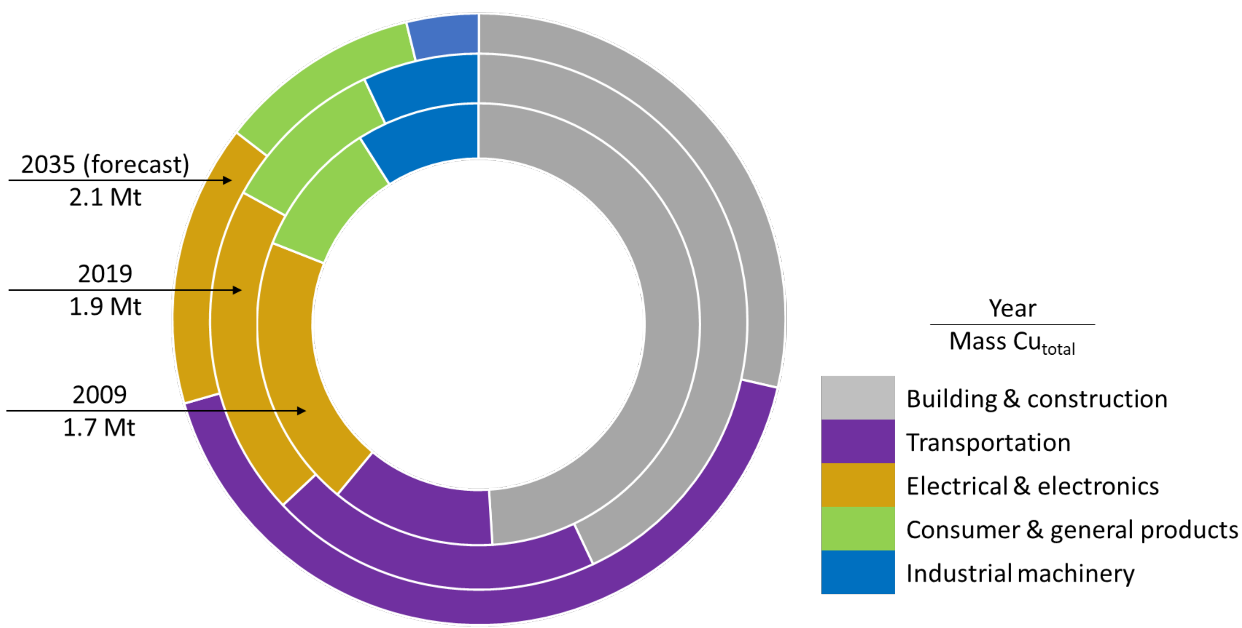


Figure 3.10: Copper use trend across its 5 major industrial sectors

11%, 4% across the building & construction, transportation, electrical & electronics, consumer & general products and industrial machineries industries. Figure 3.10 compares these estimated distributions with those from previous years.

On the recycling industry

The recycling industry is a well-established industry that has been active for over 150 years. Scrap yards play a significant role in the automotive industry supply chain – by processing end of life vehicles (ELVs). Figure 3.11 shows the general flow in the recycling operation of ELVs, a large source of both ferrous and non-ferrous scrap. Depending on how the vehicle is processed – dismantling and shredding hulks or pulverizing whole cars – the product can be "smelter ready" material for secondary processors, shipped domestically or exported for use or further processing. Regardless, most of this material ends up at secondary processors that produce the metals used by the automotive industry. Figure 3.12 briefly details and defines the downstream separation processes. Here we see the various steps necessary to methodologically separate the shredder residue into metallic-based products (Zorba, Twitch, etc.) in accordance with the ISRI standards and specifications. These products are useful in different industries, one of which is the automotive industry and thus presents the opportunity for a closed loop system. One key challenge preventing more closed loop recycling is contamination and accumulation of unwanted materials in the scrap stream (Gaustad et al., 2010; Naohiko. & Hideki., 2006). For ferrous recyclers, the most challenging of these contaminants is copper and nickel because it is difficult to remove from the molten steel and also has a high accumulation rate (Hatayama, Daigo, & Tahara, 2014). ELVs, being the largest source of steel scrap, are also the major source of copper contamination (Daehn, Cabrera Serrenho, & Allwood, 2017). Shredders are becoming more and more advanced with improvements in the eddy current conveyer systems, and additional sensors and magnets, that not only can produce multiple size fractions of the finished materials but better sort out metals according to their base metal. Additionally, the conveyers have sections for human inspection where laborers pull out materials like shredded electric motors, also known as copper "meatballs," (cf figure 3.13) to prevent contamination in the end product, which are then sold as a separate commodity. While separation and sorting techniques are relatively efficient at liberating copper from the ferrous stream, the end products still have crossover contamination from other metals, whether it is a ferrous stream with varying percentages of unliberated copper or on the other side, a copper stream that contains steel and other trace impurities. In both cases, the contamination limits utilization in producing certain products depending on their compositional specification windows. For the ferrous stream, the use of secondary steel that is contaminated with copper, is constrained to mainly the production of rebar (building and construction sector), as rebar has a comparatively higher tolerance for impurities (Daehn et al., 2017).

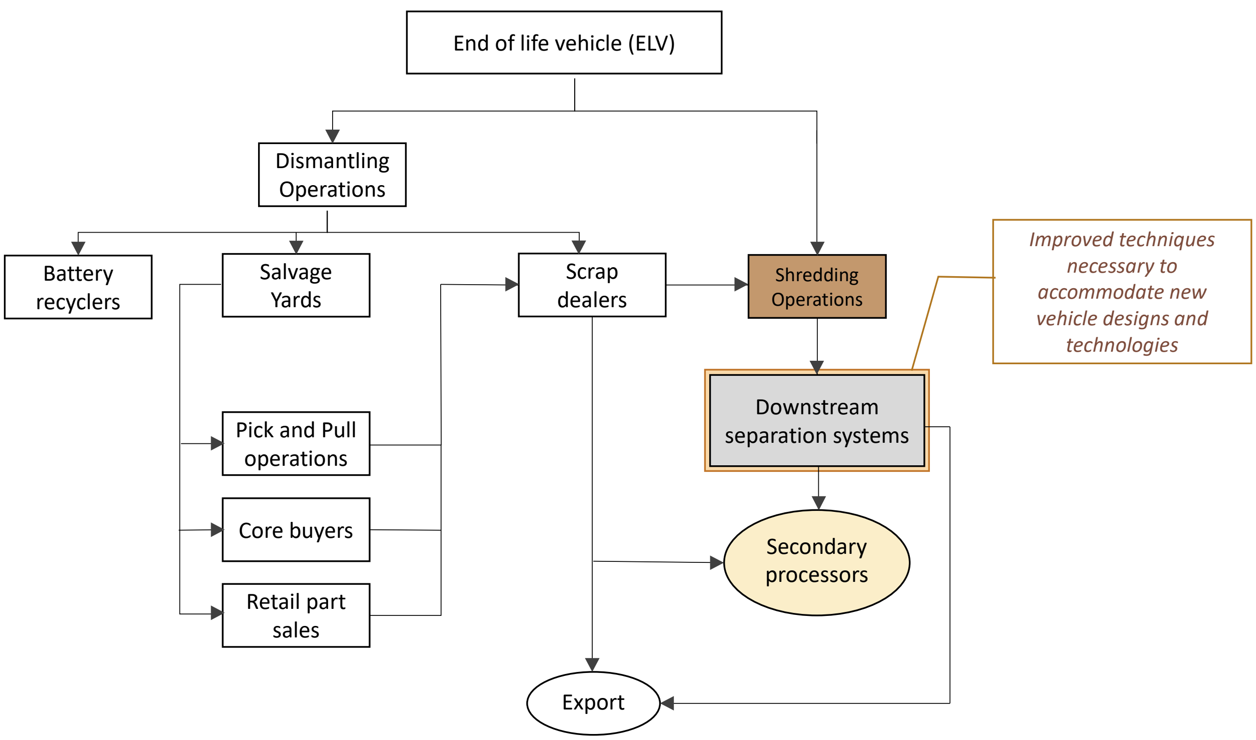


Figure 3.11: End of life vehicle process flow (Brooks, Gaustad, Gesing, Mortvedt, & Freire, 2019; Gaustad, Olivetti, & Kirchain, 2012; Kelly & Apelian, 2016)

Ironically, as opposed to ELVs being the largest contributors to secondary steel contamination, the automotive sector has stringent compositional requirements for metals used to

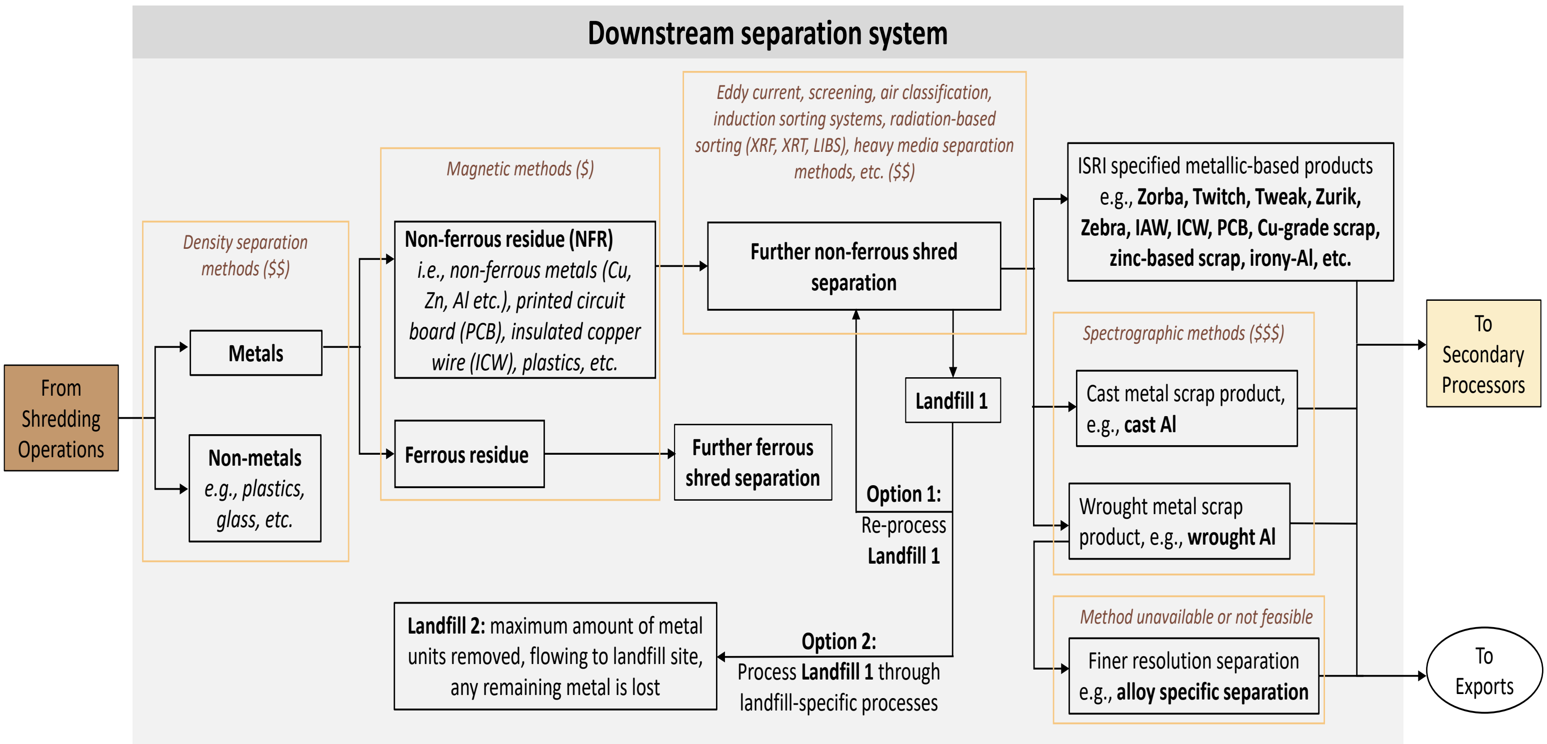


Figure 3.12: Downstream separation system processes, tracking non-ferrous scrap, current separation methods and relative costs (Brooks et al., 2019; Gaustad et al., 2012; Javaid & Essadiqi, 2013; Kelly & Apelian, 2016)

make autobody alloys. From a ferrous recycling point of view, this already poses a major challenge for the recycling industry to completely achieve circularity via a closed loop, leading to the dilution of copper-contaminated secondary steel with primary steel (Brooks et al., 2019). Furthermore, the reduction in the demand for building and infrastructure, as analyzed in the previous section, will lead to a shortage of sinks for secondary steel (Daehn et al., 2017), resulting in more dilution with primary and/or a higher rate of downcycling. From a non-ferrous recycling point of view, the use of more copper in vehicles leads to a higher volume of contaminated copper, thus further reducing the copper recovery rate from ELVs. This, similar to the shortage of sinks for secondary aluminum (Arowosola, Gaustad, & Brooks, 2019), caused by the use of more wrought aluminum and less castings in vehicle design for lightweighting, results in the limited utilization of secondary copper for certain products. The expected presence of more copper in automotive steel scrap, will thus require shredders to have more advanced copper segregation capability. This does not only lead to less contamination of steel, but also leads to an economic profit for the recyclers, as the liberated copper results in a profitable copper scrap stream and cost savings for the copper end users, as secondary produced copper costs less than its primary equivalent (Agrawal & Sahu, 2010).

Implications

This work aimed to understand the effect of EV adoption on the demands for copper, one of the strategic materials required in an EV. Our results show a cascading effect – starting with the increasing trend in copper content in a typical vehicle – cutting across other industries.

Figure 3.13: Electric motors, after the shredding process, also known as copper 'meatballs'

Our results show that among the copper end-use industries, the transportation sector is driving the overall increase in copper demand. Ironically, it is likely to be one of the most negatively impacted sectors if prices were to go up as a result of a short-term copper supply constraint. Unlike the building and construction industry, the automotive sector, has stringent compositional requirements for metals used in vehicle production. With the current recycling technology, the sector cannot take maximum advantage of secondary metal production and thus depend, to a large ratio, on primary produced metals. Also, the automotive sector is one of the lower profit margin industries; manufacturers find it difficult to pass on increases in prices of raw materials to consumers due to the characteristic intense market competition of the industry (Kallstrom, 2019).

Considering the recycling industry, the effect of increasing copper use in vehicles tentatively results in a higher copper contamination for recyclers. Tentative because vehicle design may be upgraded to allow for easy removal of copper products in vehicles, thus allowing for a relatively low copper contamination of shredded material. Barring this, advancements in technology will be required for a more effective and precise sorting of the shredded material.

CHAPTER 4

COPPER AT END-OF-LIFE

Introduction

Copper is categorized as a base metal. Its demand is usually an indicator of the economic growth of a region presumably because its demand signifies advancement in and adoption of technology. Among other base metals, copper has the highest production volume as seen in figure 4.1 and likewise is the case for global production (Mudd & Weng, 2012).

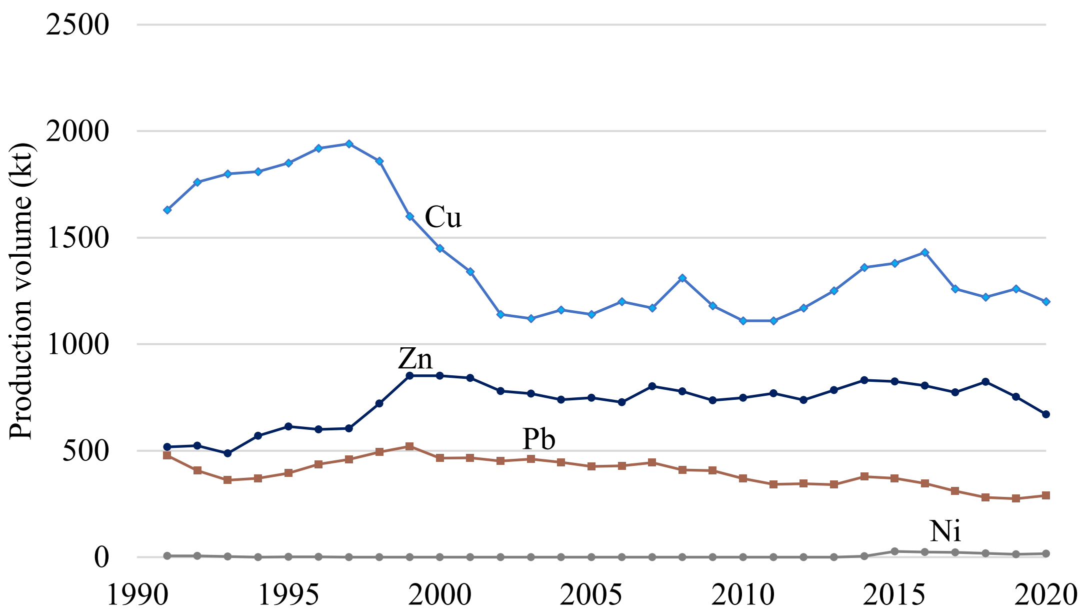


Figure 4.1: Domestic production volume of copper and other select base metals in the U.S. (U.S. Geological Survey, Several years-a)

Copper has been used, reused and recycled as itself or as its alloys for centuries. In the U.S., the major sectors that use copper are the building and construction, transportation, electrical and electronics, consumer & general products and industrial machinery sectors. These sectors boast of a wide range of copper and copper bearing products that have diverse uses e.g., copper is used in building and construction as pipes and tubing for water, gas, cables, etc.; in transportation for aircraft, automobiles, etc.; in electrical and electronics for printed circuit boards, electrical connectors, power cables, etc.; in consumer and general products for jewelry, coins, musical instruments, etc.; and in industrial machinery for light and heavy appliances and equipment. All these products remain in use for different lengths of time, (e.g., vehicles are in use for an average of 20 years and buildings are in use for an average of 50 years). At their end of life (EOL), these products become post-consumer scrap and come into the waste management system via different pathways.

Previously, it was found that vehicle lightweighting results in the introduction of foreign materials as they are being purposefully incorporated into the streams of base metals as alloying elements to modify and enhance the properties of the metal to achieve different functionalities across multiple vehicle parts. The previous analysis focused on the use of aluminum as a choice lightweighting material in the automotive industry and results show the presence of new alloying materials like vanadium (Arowosola & Gaustad, 2019) that need to be managed at the vehicle's end of life. Asides these foreign materials causing new challenges in the recycling stream – as some of these materials are deemed critical and may end up as tramp elements, accumulating in the aluminum stream with continuous recycling – copper, a prominent alloying material that has proven to be challenging to recyclers at end of life, makes up a considerable portion of the alloying element content of aluminum alloys. Like many clean energy technologies, copper plays a very important role in vehicle electrification. Analysis done in previous sections of this work shows that an increase in copper demand for electric vehicles will be in tandem with the anticipated adoption of electric vehicles. This EV demand for copper, as previously discussed, can easily cause a domino effect across multiple industrial sectors, as well as create a strain in copper supply. In the world today, it is not a case of scarce copper – in fact, copper is in abundance in the earth crust, so much so that the concern for the availability of copper as a raw material is not in the horizon. The concern is the cost of obtaining and liberating said copper from the earth as the ore grade of copper continuously depletes.

Given the continuous depletion of ore grades, coupled with the increased economic and environmental impacts of producing copper from lower ore grades, it is imperative to actively consider alternative sources of copper supply to minimize both economic and environmental impacts. Copper recycling presents as a very viable option for alternatively sourcing copper given its many advantages like 100% recyclability and no loss of properties upon continuous recycling. However, various analyses from literature (Gómez et al., 2007) suggest that the rate of recycling old copper scrap is depleting over time and available old scrap is increasing. Old

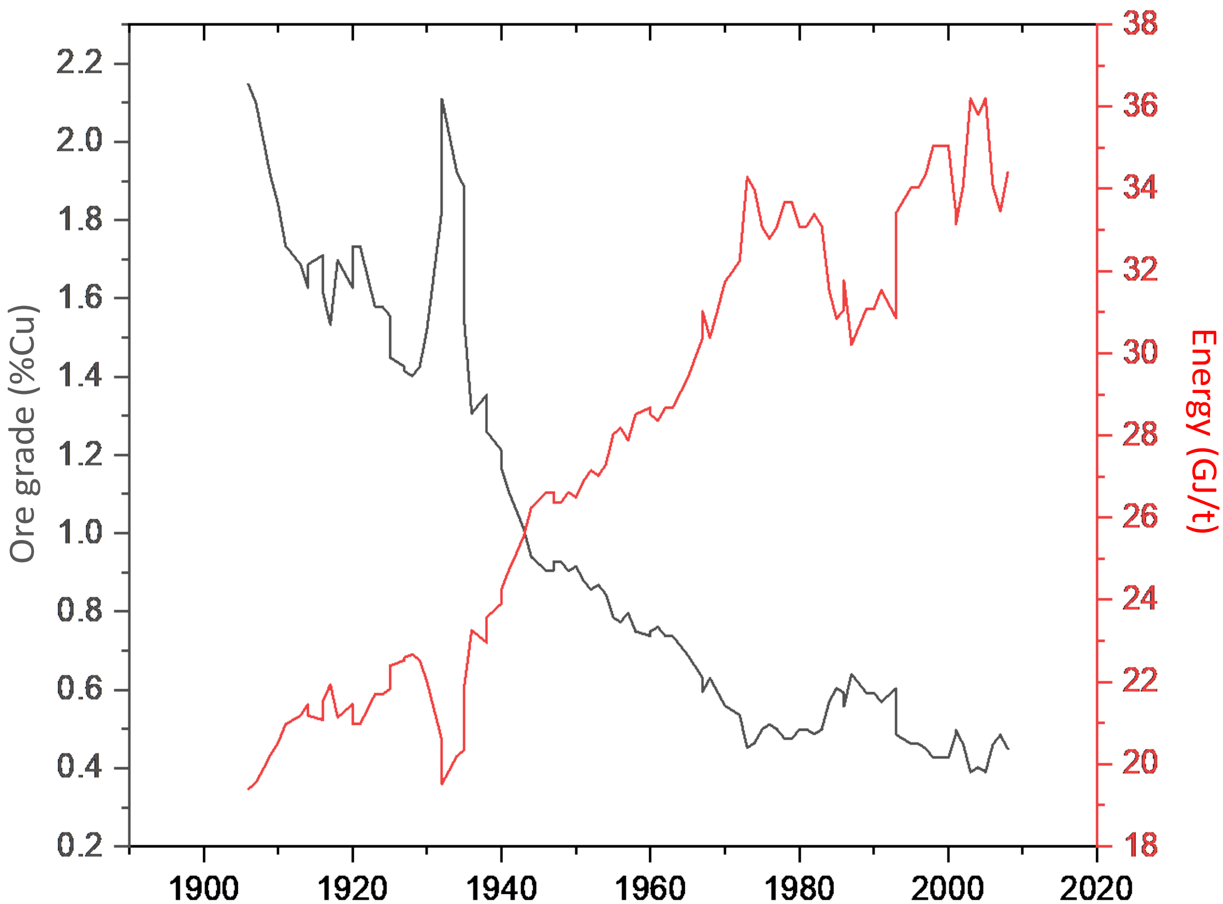


Figure 4.2: Trend in U.S. copper ore grade versus energy consumed per ton of copper mined. (Calvo, Mudd, Valero, & Valero, 2016; Crowson, 2012; Mudd & Weng, 2012)

copper scrap in this context is defined as copper bearing products that have been used and have reached their end of life. Another type of copper scrap is the new copper scrap also called ‘prompt’ copper scrap and is the copper scrap that is obtained from fabrication processes of copper bearing products and are collected for recycling and reuse. They are clean copper scrap that have not gone into the use phase and thus are easily recycled with little to no material handling or scrap processing. More so, with previous analysis showing an increase in the demand for copper, there is need to make use of the presumably abundant copper scrap to supplement primary copper supply with secondary copper. Thus, for an understanding of the ensuing disconnect between abundant copper scrap and a relatively low secondary copper production volume, this work aims to study the flow of copper at its end-of-life (EOL) using material flow analysis (MFA). MFA is not a new method of analysis in literature; it has been around for decades. It has found use across diverse fields and topics, across industries, government organizations and corporations. As the name implies, it is the study of materials – their stocks and flows – through a defined system. Often, some studies are focused on a single substance in the system, as is the case with this study, and they are aptly called substance flow analysis (SFA). There have been studies on copper stocks and flows globally (Glöser, Soulier, & Tercero Espinoza, 2013) (Tong & Lifset, 2007) and in different regions and countries (Bonnin, Azzaro-Pantel, Pibouleau, Domenech, & Villeneuve, 2013; Daigo, Hashimoto, Matsuno, & Adachi, 2009; Guo & Song, 2008; Soulier, Glöser-Chahoud, Goldmann, & Tercero Espinoza, 2018; Wang, Chen, & Li, 2015). Many of these studies (Bonnin et al., 2013; Guo & Song, 2008; Spatari, Bertram, Fuse, Graedel, & Rechberger, 2002) cover the entire copper cycle; production, fabrication, use and waste management, while some focus on select stages in the life cycle. Wang et al(Wang et al., 2015) analyzed the flow of copper in the production stage with the U.S.

as the spatial boundary and a temporal boundary of 1974 to 2012. Based on the conservation of mass, a foundation for both the MFA and SFA, and complemented by the stock and flow (STAF) method for where there is insufficient data, their analysis emphasizes the processing of copper within the production stage. Wang et al (Wang, Chen, Zhou, & Li, 2017) studied the generation of China's potential copper scrap based on consumption in previous years using a dynamic SFA to highlight the transformation flows of copper through the system. Like many MFAs and SFAs, a top-down approach is used; in this case, they used the top-down approach to estimate the end-of-life scrap quantity that may be available for recycling and re-introduction into the copper cycle. Despite the inherent uncertainties in the approach, results from many analyses using the top-down approach have been able to inform areas where strategies, new methods and techniques, regulations and even policies, might be beneficial to the sustainability of copper. A couple of studies (Glöser et al., 2013; T. E. Graedel et al., 2004) have developed dynamic models for stocks and flows using this method. These models are able to highlight the transformation and estimate the amount of copper as it moves from one stage to the other in the copper cycle. These models have been used across industries and organizations towards their various sustainability practices.

One of these organizations is the International Copper Association (ICA) where copper stocks and flows are reported for different regions (ICA, 2020). Table 1 shows a summary of results from some of the copper flow analyses in literature. The studies focus on select regions and countries and results from the EOL stage have been highlighted in the table. First, it can be concluded that the discard flow – the rate at which copper and copper products reach the end of their useful life and come out of use into the waste stream – increased with time for all regions shown. This can be attributed to a mix of circumstances ranging from economic developments to

Table 4.1: Comparing copper flow data across multiple spatial and temporal boundaries.

Boundary		Recycling	Flows (thousand tons)								Reference
Spatial	Temporal	rate	Discard	Recycled	Separation loss	Net export	Landfilled	Other losses			
									Dissipative	*Others*	
Asia	1994	64%	1080	690		-690	440	640		***640***	(Graedel et al., 2004)
China	1994	187%	150	280		-490	87[a]	270		***270***	(Graedel et al., 2004) in (Guo and Song, 2008)
	2004	247%	703	1736		-1187	154				(Guo and Song, 2008)
	2018	53%	1780	920	550	-880		300	*60*	***240***	(ICA, 2020)
Japan	2000					150	114	70	*30*	***40***[b]	(Daigo et al., 2009)
	2005	69%	805	510		132	99	64	*29*	***35***[b]	(Daigo et al., 2009)
	2018	34%	990	320	50	-20		620	*40*	***580***	(ICA, 2020)
Europe	1994	80%	920	740		-300	480				(Spatari et al., 2002)
	1994	80%	930	740		-300	490[a]				(Graedel et al., 2004)
EU 28	1994	49%	1570	775							(Soulier et al., 2018)
	1999	44%	1805	800							(Soulier et al., 2018)
	2014	65%	2620	1610	430	570		580	*130*	***450***	(Soulier et al., 2018)
	2018	49%	2850	1320	350	350		1180	*140*	***1040***	(ICA, 2020)
NA	1994	36%	1410	510		190	710[a]				(Graedel et al., 2004)
	2018	17%	3210	540	180	490		2490	*120*	***2370***	(ICA, 2020)

[a]Loss reported to include dissipative loss [b]Loss categorized as flow into other material stream

social behaviors. Secondly, is copper loss that cannot be accounted for, i.e., other losses. Initially, the analyses attributed, flows that could not be categorized as either exports or landfilled to other losses, and rightly so.

Currently, as depicted by the ICA (2020), other losses are now further categorized as separation losses (losses during scrap handling like sorting), dissipative and others. These finer resolved categories inform target areas for copper recovery. Alarming though, is the magnitude of the unaccounted-for losses. *Where is the copper?*

In their study, Daigo et al (2009) analyzed the stocks and flows of copper in Japan and accounted for not just copper, but also copper-based alloys. In doing so, they include a higher resolution in terms of the pathways of copper flow at its EOL, accounting for the flow of copper into other material streams like steel and aluminum. So, their *"others"* values shown in table 4.1

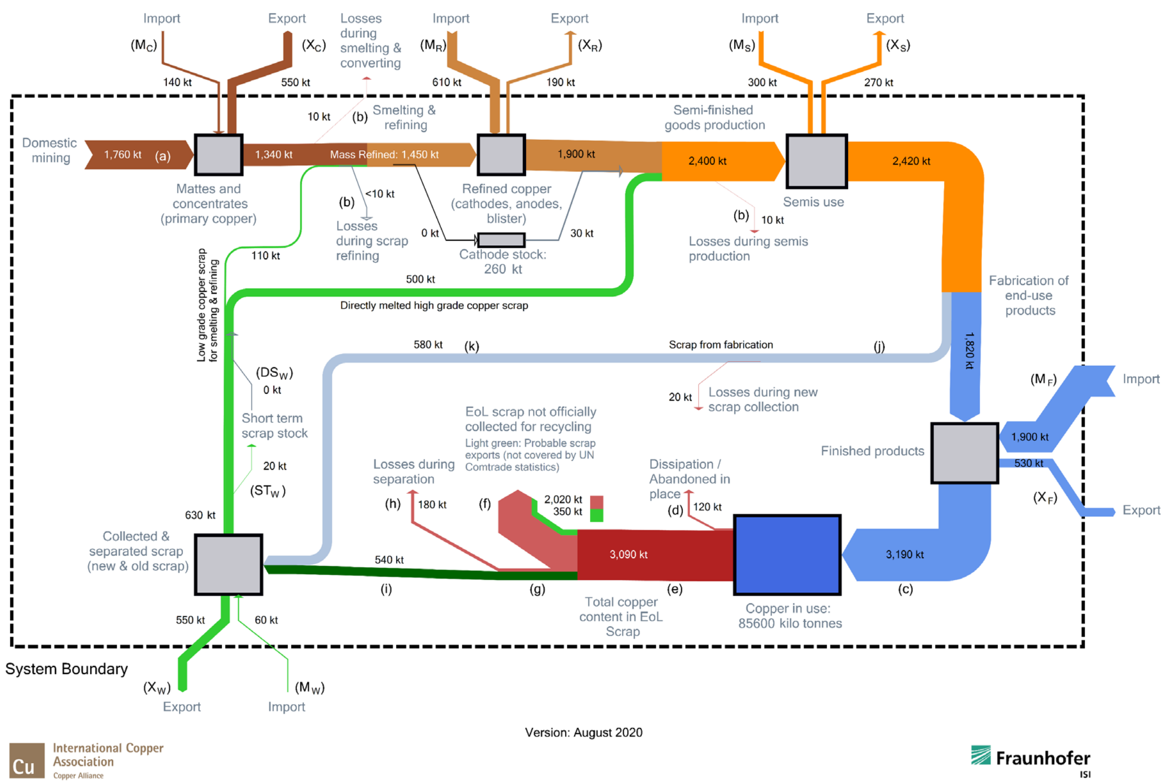


Figure 4.3: North America copper stocks and flows 2018 (ICA, 2020)

are categorized in their study as flows into other material streams, thus, depicting a higher resolution for copper flow in Japan at its EOL. Figure 4.3 shows the 2018 North America copper stocks and flows. The end-of-life estimates from the result above adds to our motivation on refining the end-of-life flows to a higher resolution. The *unaccounted-for* loss, i.e., "EoL scrap not officially collected for recycling" as identified above, is a worrisome sink for copper accounting for both resource and revenue loss, especially for copper stakeholders given the trend in copper price as shown in figure 4.4. A current analysis of the flow of copper through the recycling industry is necessary to adequately analyze where (i.e., which EOL Cu bearing product) the copper to be recycled comes from, how much of it comes into the recycling process, where it goes and how much of it goes out of the recycling process. Therefore, like Wang et al (2015) focusing on the production stage in the copper cycle, this study solely focuses on the EOL

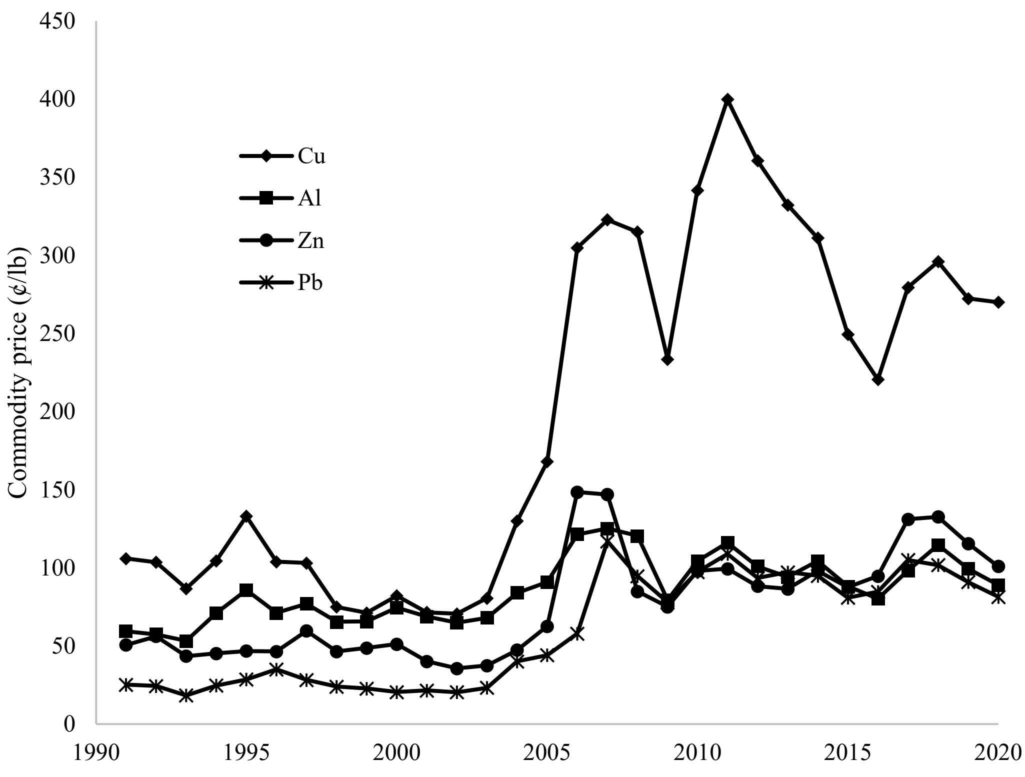


Figure 4.4: 30-year LME commodity price; U.S. producer spot price for Al (U.S. Geological Survey, Several years-b)

stage with the aim being to resolve the EOL flows to a higher level of granularity for a deeper understanding of the gap previously discussed, i.e., the disconnect between the abundant copper scrap and the relatively low secondary copper production volume. In reality, the question "Where is the copper?" is a valid question that presents more of a knowledge gap than a mere process gap. Presently, there is no knowledge of where this huge amount of copper is sinking to and copper stake holders, particularly the International Copper Association (ICA), have vested interests in answering the question. Because this gap transcends into being more of a knowledge gap, this study attempts a bottom-up approach to resolve the end-of-life flow of copper so as to offer the ICA a higher resolution of copper flow at its EOL.

Acknowledging the complexity in obtaining raw data for a bottom-up-approach, this analysis supplements with estimates based on available raw data and given the inherent non-homogeneity in such raw-data, data curation is used to homogenize and standardize the raw data.

Methodology

This analysis follows the material flow analysis (MFA) attributes listed in Graedel's perspective (Thomas E. Graedel, 2019). This work gives a higher resolution of the stocks and flows of copper through the recycling system. Various works have depicted the copper stocks and flows of various regions to different resolutions. Shown below (figure 4.5) is a generic copper cycle adapted from Rechberger and Graedel (2002), highlighting this study's system boundary to encompass the recycling system. Looking into the EOL processes of copper scrap, this work focuses on the copper scrap pathways though the recycling industry with the goals and scope of the analysis defined below.

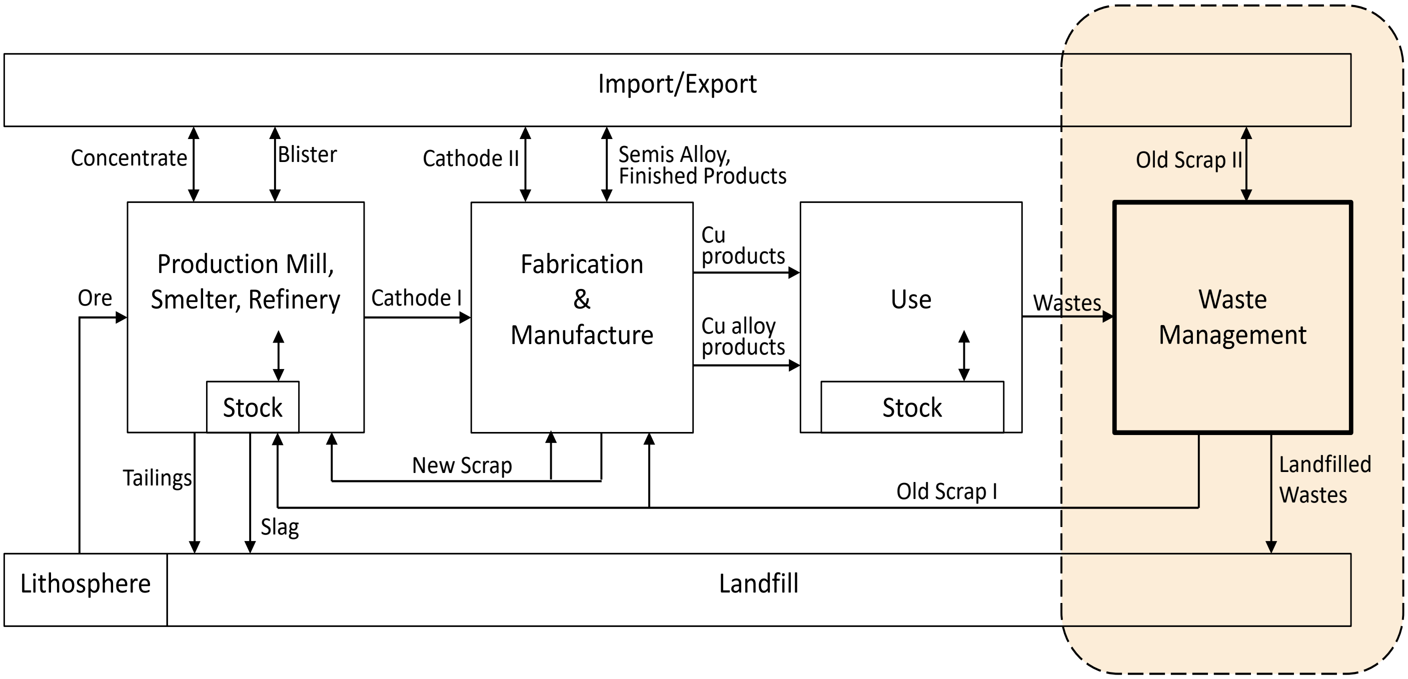


Figure 4.5: Generic copper cycle (adapted from (Rechberger & Graedel, 2002), highlighting system boundary for this study

Goal and Scope

The goal is to present a material flow analysis (MFA) of copper scrap sources and sinks at EOL with the intention of identifying where losses exist and plausibility of redirecting them for better circularity.

At the first stage, this work surveys and analyzes scrap yard operations:

- the kind of scrap and volume that comes into the yard,
- the processes these scraps undergo and
- where they go to after processing.

A follow-up stage would be to survey and analyze secondary processors in relation to:

- what kind of scrap categories are utilized,
- the volume processed,
- the end products and their distribution.

Results and Discussions

A survey of literature and scrap yard operations enlightens on the different pathways of scrap flow into the recycling system: construction and demolition (C&D), municipal solid waste (MSW), waste electrical and electronic equipment (WEEE), end of life vehicle (ELV), Industrial electronic waste (IEW), Industrial non-electronic waste (INEW). These make up the scrap collection pathways that will be further analyzed. Also, this work was able to gather the kinds of copper scrap commodities that are purchased and processed by scrap yards and then sold to secondary processors for use in fabricating different copper end-use products. With these findings, figure 4.6 shows a higher resolution of our highlighted system boundary from figure 4.5.

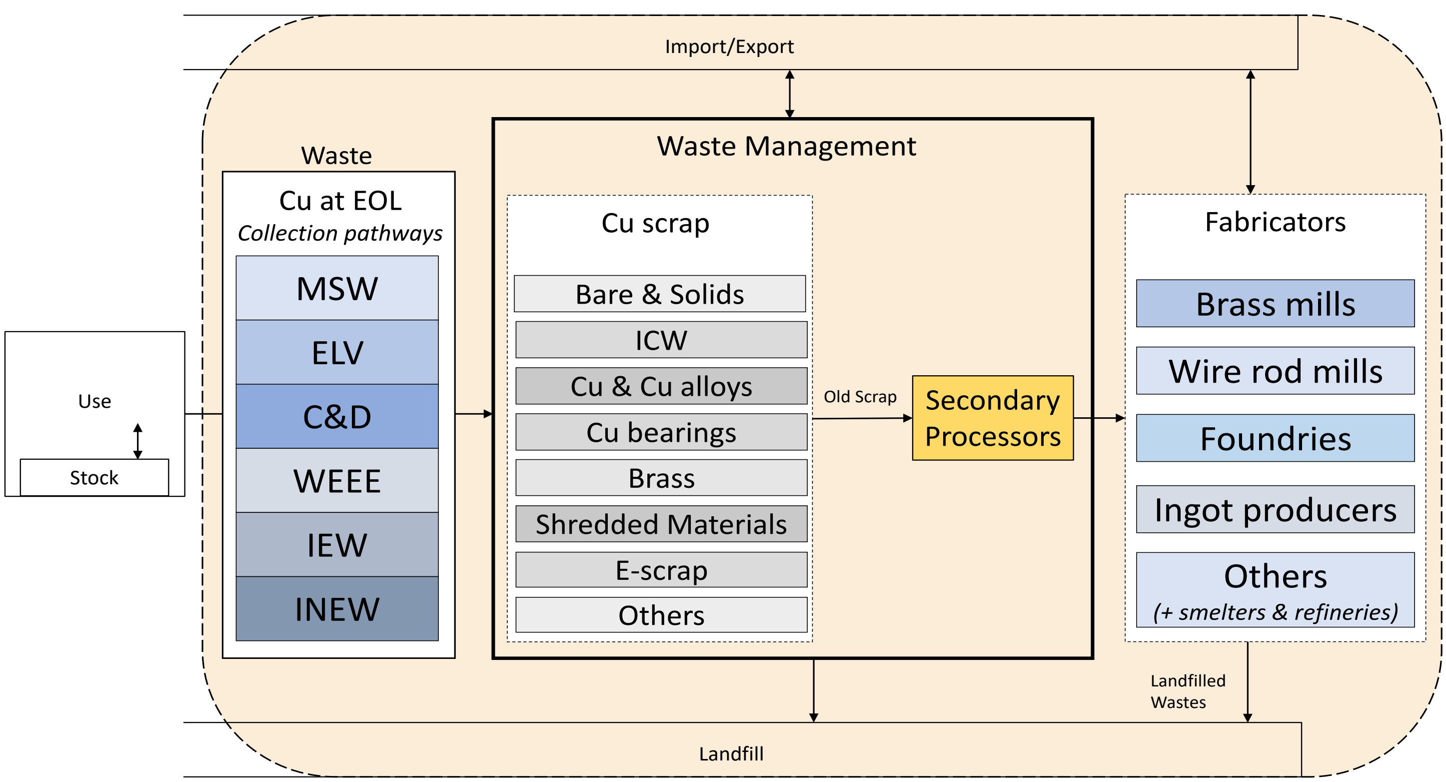


Figure 4.6: Copper flow cycle showing higher resolution at end of life.

The various flows and stocks depicted in the system above are described below.

Collection pathways

Construction and demolition (C&D): Waste flow via C&D comprises of waste and debris generated from the construction, repair, renovation as well as demolition of built structures like houses, roads, bridges, dams, etc. Examples of materials that could be found in a C&D waste flow are wood, asphalt, metal, concrete, etc. Steel made up less than 1% of the total C&D debris generation pre-processing (US EPA, 2020a). In 2018, approximately 76% of C&D waste was recycled and the remainder was landfilled (US EPA, 2021a).

Municipal Solid Waste (MSW): MSW is the waste generated from daily residential, institutional, and commercial consumption. It includes food, paper, glass, metal, plastics, and other material wastes. The 2018 MSW generated had 8.7% metal content, about 23 million metric tons, where steel and aluminum account for over 90% of the MSW metal content. 34% of total metal generated in this flow is recycled and about 55% is landfilled.(US EPA, 2020a).

End of Life Vehicle (ELV): As the name implies, ELV is the vehicle that has been discarded and no longer intended to be used as a means of transportation. In other words, the vehicle has reached the end of its useful life and thus, discarded as waste. Processing ELV is a cumbersome operation as it comprises of a wide variety of material composition mix, coupled with its complex structure. A typical U.S. vehicle contains approximately 75% metal (ferrous and non-ferrous) and 25% of non-metals (plastic, glass, polymers, etc.) (US EPA, 2017). The average yearly recycling rate of ELVs is 95% (LeBlanc, 2019), a similar rate to France (94.2%) and U.K 92.8% (VRW, 2020).

Waste from Electronic and Electrical Equipment (WEEE): When the various electronic devices and gadgets that are used are no longer useful or wanted, they are discarded and become WEEE (also called e-waste). Examples go far beyond our phones, they include televisions, computers, game consoles, fax machines, tablets, headphones, DVD players, and the list goes on. Basically, any electronic device, gadget and equipment that we may find in homes and commercial facilities. In 2019, the U.S. generated about 6.9 million tons (2.4 million tons in 2009) of e-waste and only 15% (25% in 2009) of this was recycled (Earth911, 2021; US EPA, 2021b).

Industrial Waste: This is waste from industrial operations and can be categorized as industrial electric waste (IEW) and industrial non-electric waste (INEW).

Scrap commodities

The kinds of scrap commodities available and traded as copper scrap in the recycling industry are also tracked and are defined here:

Bare and solids: These scrap commodities are made up of clean, uncoated and unalloyed copper wires, solids, clippings, bus bars, punching and tubing. The copper wires in this category are free of insulation (also called bare bright). These scrap category is further divided into No.1 and No. 2 to signify the level of purity, where No.1 is 99% copper while No. 2 has a 96% nominal copper content with a 94% minimum copper content (Institute of Scrap Recycling Industries, 2020).

Insulated copper wire (ICW): This scrap category is made up of insulated copper wires and cables like electric power cables, connecting wires, household appliances, harness wires, etc.

Like the *bare and solids*, this category is divided into different specifications – No. 1 ICW, No. 2 ICW, No. 3 ICW – per size of wire, ergo copper content.

Copper and copper alloys: This category consist of light copper like sheet copper, boilers, and similar scraps with at least 88% copper content (average of 92% copper) and copper alloys like brass and bronze solids and turnings with a minimum of 61.3% and maximum 5% iron (Institute of Scrap Recycling Industries, 2020). In this category, further identification would include red brass, yellow brass and specialty products.

Copper bearings: This category is made up of end-of-life products that are made of copper and other materials. Examples of commonly traded copper bearing scrap include electric motors, automotive radiators, copper transformers, alternators, starters, compressors (sealed units).

E-Scrap: Electronic and electrical scrap commodities make up this category of traded copper scrap. Usually consist of end-of-life products from *WEEE* and *IEW.*

Secondary Processors

Secondary processors collect scrap commodities and process them for use. Usually collected in a scrap yard, various processes and material handling operations specific to the scrap commodity are performed. Some of these processes are sorting, wire chopping, shredding operations, eddy current separations, etc.

Fabricators

Finally, processed scrap commodities move to the fabricators where they are used for the fabrication of copper end products, usually semi-finished goods. Conversations with scrap specialists enlightened on the different kinds of copper scrap that are being processed. Below shows a list of the different types of fabricators that use copper scrap in their product fabrication.

Brass mills: Feedstock comprising of over 50% scrap (and the remainder refined copper) is melted and alloyed in brass mills to make intermediate cast products like copper sheets, plates, strips, tubes, etc. Further processes are later employed to transform the cast feedstock into mill products like plumbing lines and connectors, busbars, air conditioning tubes, etc.

Wire rod mills: Products from the wire rod mills end up as one form of electrical conductor or the other in differing sizes. Depending on size and function, the electrical wire could be stranded, insulated and/or formed into cables.

Foundries: Shaped castings, usually fabricated with the aid of a mold, are produced in the foundry. The feedstock in the foundry usually consists of virgin metal, scrap and pre-alloyed ingots. Products from the foundry find use in a variety of industries.

Ingot makers: Different ingots – relatively pure metal that is cast into different shapes – of different alloys are the finished products of ingot makers. The shapes of the ingots are standardized and are sent on for further processing.

Others (including smelters and refineries): Other fabricators include powder plants (producing copper powder and copper flakes for powder metallurgy products), chemical industries, and other material industries like aluminum industry. Smelters and refineries also consume copper scrap as their feed alongside primary copper.

Flow Analysis

Multiple secondary processors were surveyed for the daily operations involving copper and its flow. Data gathered include the source of copper scrap and percentage contribution of each source to the total in-coming copper scrap. The copper scrap sources identified are general public, peddlers, dealers, industrial scrap, auto wreckers, demo (demolition scrap), disposal, municipalities, small businesses, imports, and others. The survey was also able to identify that of the copper scrap processed in the yard, export accounts for about 51% and the remaining 49% is consumed domestically, where it is distributed amongst secondary producers like brass and wire mills, foundries and ingot producers. It is also noted that a portion of this domestically consumed copper scrap goes into the alloying of non-copper-based materials like aluminum, zinc and nickel. Figure 4.7 is a Sankey depicting the flows of copper scrap at its EOL from source to sink where the band widths are proportional to the flow volumes.

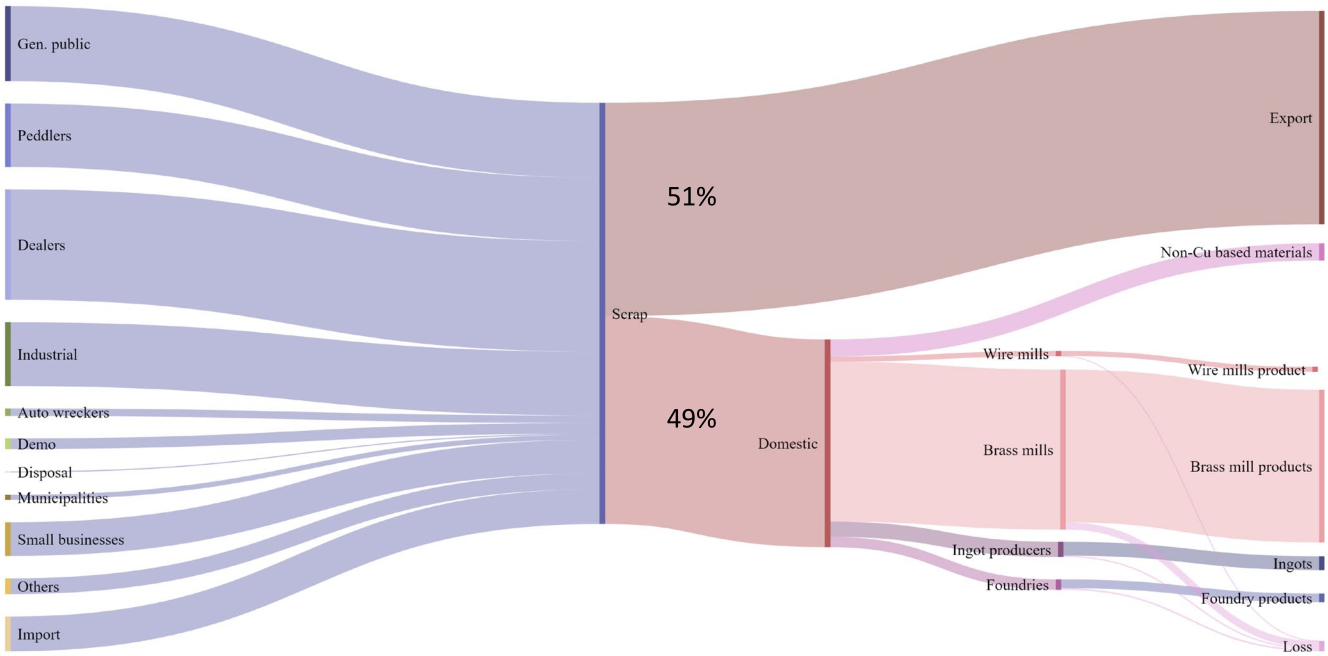


Figure 4.7: Sankey diagram showing copper scrap flow at EOL

Implications

So far, the survey carried out and conversations with scrap handlers, suggest the following as possible causes for a recorded high volume of copper loss.

Copper loss as a result of recent policy changes

Some recent changes in copper losses can be easily attributed to the recent enforcement of the Chinese green fence. China is the largest importer of non-hazardous waste for recycling and/or resource recovery. (Balkevicius, Sanctuary, & Zvirblyte, 2020). Regarding the import of copper scrap, data shows China as one of the largest importers of U.S. copper scrap – alloyed, unalloyed, segregated and unsegregated (USGS, Several years). A downside to this was the problem associated with low grade and contaminated scrap, and the environmental footprints associated with processing these scraps to a higher quality required for reuse, recovery and/or recycling. In 2013, the Chinese government enacted operation green fence to control the quality of scrap (initial target was plastic scrap) and combat illegal waste imports into the country. From then till now, the green fence ban has been expanded to encompass all waste imports, enforcing a not more than 0.5% contaminant, and thus in the case of copper scrap, only No. 1 Cu from the *bare and solids* Cu scrap category can readily be exported to China as is.

This ban has clearly impacted the volume of scrap exported by the U.S. as shown in figure 4.8 as China shows a huge volume across years and a steep plunge in volume as the operation green fence is expanded to encompass more than plastic waste. A comparison of the total volume of

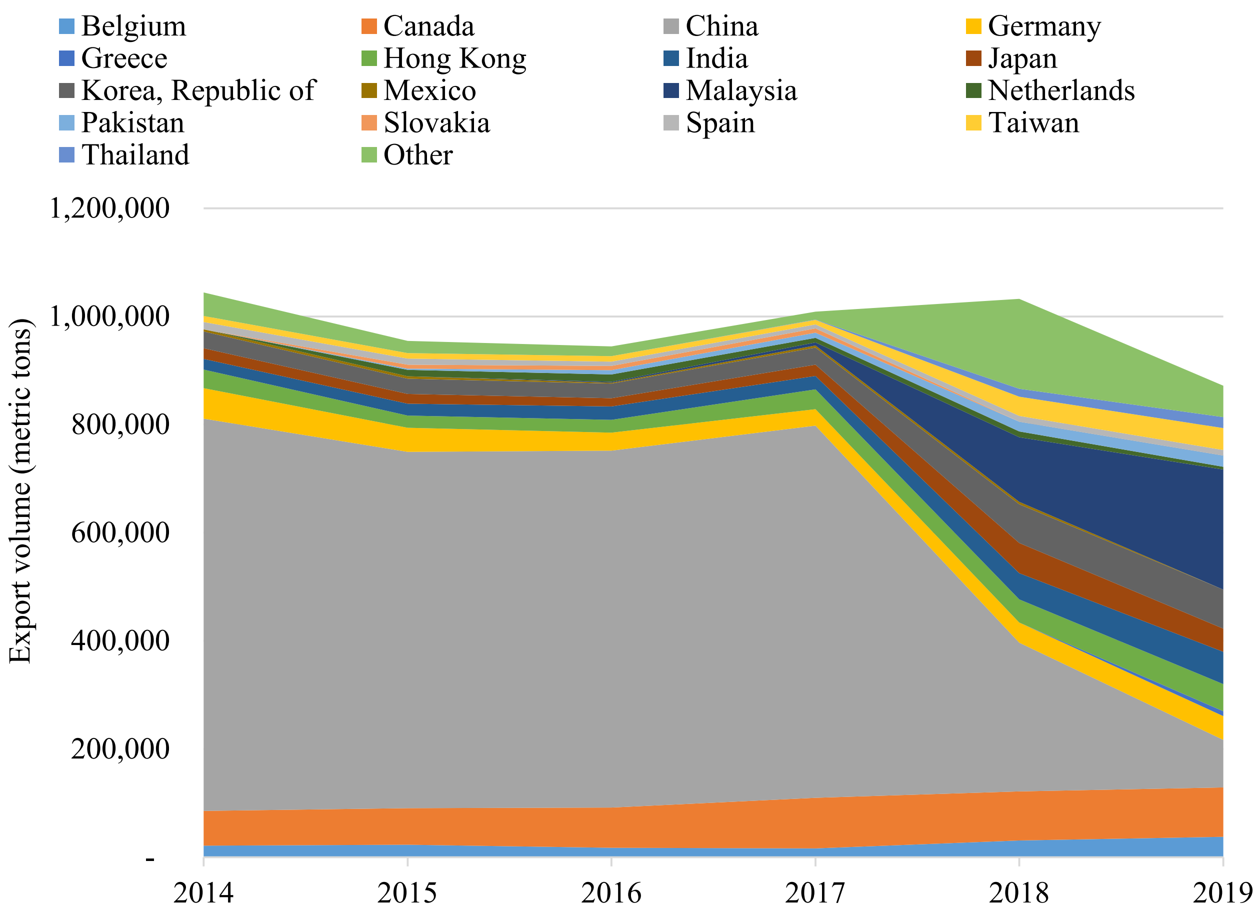


Figure 4.8: Recent trend in export volume by country

copper scrap exported to China (figure 4.9) shows about 70% reduction from 2018 to 2019: about 62% in unalloyed scrap and over 80% in alloyed scrap.

Conversations with scrap yard experts reveals that on one hand, scrap suppliers still have the burden of these "usually exported" copper scrap and are looking for secondary processors to purchase it off them. On the other hand, secondary processors are not readily buying these scrap categories as current copper recycling technologies and processes in the U.S. are not equipped to process copper scrap from these categories. Thus, scrap from here ends up in an unaccounted-for stock, that either gets abandoned or eventually landfilled.

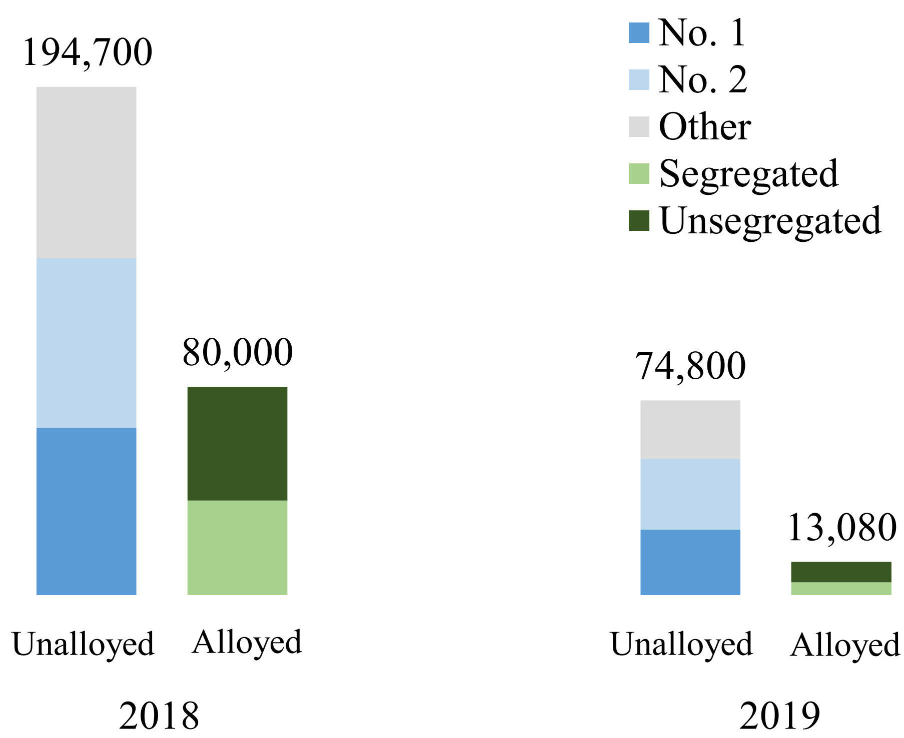


Figure 4.9: Comparison of scrap export to China by type; 2018 vs 2019

Copper loss into other material streams

Copper as a versatile metal finds use (major or minor) in almost every industry – from air conditioning, plumbing and heating in the building industry, to general consumer products like bells, electronics, etc. It could be used purely as copper or as an alloy of copper, e.g., brass. Beyond this, copper is used as an alloying metal in other material streams like aluminum, nickel, tin and, at a minimal extent, in steel, to form alloys of these materials.

Figure 4.10 shows results from a previous analysis of aluminum alloys where copper makes up about 15% by weight of the total alloying elements used in the aluminum alloys in a typical vehicle, making it the 3rd largest alloying metal by weight after silicon and magnesium. Copper as an element easily alloys with other materials; this property of copper also makes it

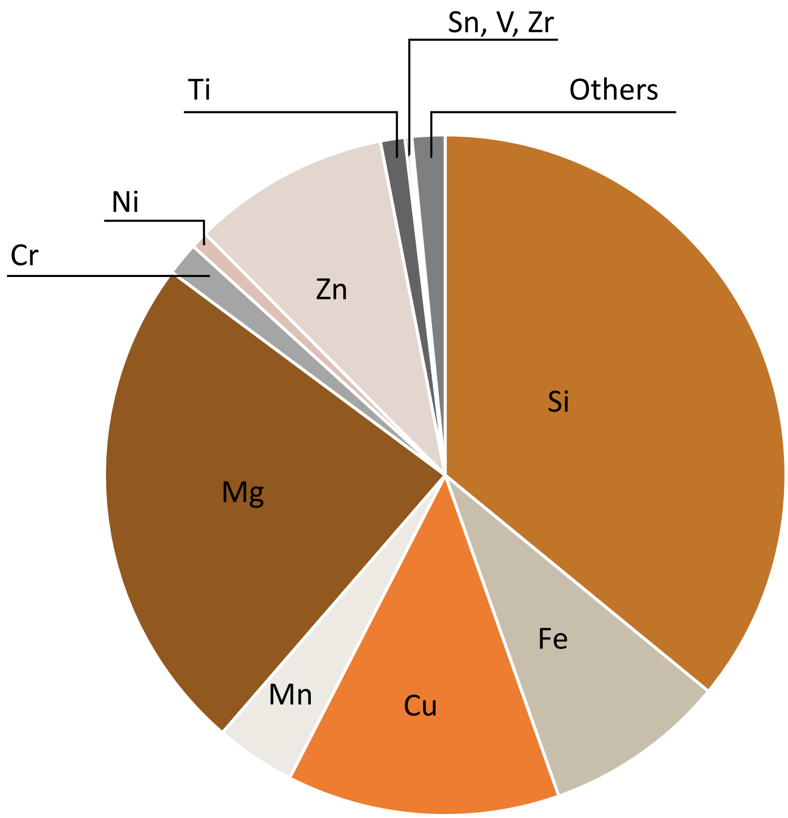


Figure 4.10: Alloying element distribution in aluminum alloys found in a typical lightweight vehicle

difficult to remove from the base metal upon recycling. As such, many recyclers find ways to make use of the difficult-to-remove copper in their recycling processes, such that copper remains and accumulates in the base metal cycle upon continuous recycling.

While the accumulation of copper in these other material streams is usually captured and reported as lost, the report above suggests that a significant portion of copper reported as lost should more appropriately be characterized as "lost to the copper stream" or "unusable in the copper stream" as it is technically not lost but trapped in the streams of other materials. Thus, while non-circularity might linearly exist for copper, an elevated point of view might show an interconnected circularity with other material stream that is acceptable from a sustainability standpoint.

CHAPTER 5

Conclusions and recommendations

Efforts to attain clean mobility have ongoing challenges. To put these into context, this work attempts to inform how the transition to clean mobility impacts the use of materials and its sustainability. On one hand, both material and economic losses attributed to the dissipation of critical metals in the aluminum stream of the automotive industry are quantified and analyzed. On the other hand, a model to forecast the demand for copper is designed, given the push for the adoption of electric vehicles and its relatively high copper intensity. Results show that the amount of critical and strategic materials going into the automotive industry via the aluminum stream is not insignificant. Though a fraction of this is lost via in-use dissipation and losses to the environment, a significant portion accumulates in the aluminum stream. Also, based on historic data, an increasing trend is observed in copper content in a typical vehicle – EVs and ICEs inclusive. While this trend is a result of various dynamics, two major contributors are highlighted. On one hand, ICEs contribute to this observed trend because of the increasing amount and diversity in the kinds of alloying elements used to achieve lightweighting (Arowosola & Gaustad, 2019) where copper is observed as contributing a large portion. On the other hand, EVs play a part in this as there is more copper in an EV than there is in a comparable ICE vehicle (80% more copper in a Chevrolet Bolt than in a Volkswagen Golf for example).

Going off these two contributors, the demand for copper is projected to increase and have a cascading effect on other industries, first of which is the competing demand for copper amongst other copper-end use industries, wherein the transportation sector is the driving force. On its effect on the recycling industry, the expected presence of more copper in automotive steel scrap, will require shredders to have more advanced copper segregation capability. This does not only lead to less copper contamination of steel, but also leads to an economic profit for the recyclers, as the liberated copper results in a profitable copper scrap stream. From an environmental perspective, this also allows for a closed copper cycle loop.

While the above are recommendations for future projections, there is currently a disconnect in the copper cycle. The reported volume of available copper scrap and volume of recycled copper indicates a huge loss in copper. According to the ICA, over 70% of the copper discard flow is reported as lost and unaccounted for. Thus, a substance flow analysis of copper at EOL was carried out to resolve the EOL flows to a higher level of granularity for a deeper understanding of the disconnect between the abundant copper scrap and the relatively low recycled copper volume. Results show that while an alarming volume of copper may be recorded as "loss", a significant portion is lost to another primary material stream because of its accumulation in the parent stream. For example, copper (primary material) used as an alloying metal in aluminum (parent) alloy is lost to the copper cycle but confined to the aluminum cycle and thus not achieving a closed copper cycle loop. This portion of loss should more appropriately be characterized as "unusable in the copper stream" as it is technically not lost but trapped in other material stream. Therefore, while non-circularity might linearly exist for copper, an elevated point of view might show an interconnected circularity with other material stream that is acceptable from a sustainability standpoint.

Secondly, the trade ban on scrap export to China – the largest importer of U.S. copper scrap – has presumably impacted the usual modus operandi in scrap processing, causing a disruption in the flow of copper and a local accumulation of copper scrap that is normally not domestically processed for recycling. This, as a result, has led to an increase in the recent volumes that are recorded as "lost" in the copper cycle.

Generally, to achieve a more linear circular economy, enhanced recovery techniques will be required (Ciacci et al., 2015; Laner and Rechberger, 2016). Technological strategies like improved inbound inspection in yards, positive material identification tools, and spectrographic-based robotic sorting may provide improvements, although the economic feasibility of these approaches will require capturing the value of the contained metals more efficiently than current trend (Moss et al., 2013; Wagstaff, 2018).

In the case of primary materials lost in parent streams, rather than strive for a linear circularity, an interconnected circularity may be achieved through operational strategies like blending models that can make better use of the contained alloying elements. This minimizes dilution with parent metal, or downcycling into castings (Staley et al., 2018). However, to effectively carry out such operational strategy, technological solutions to ensure positive material identification with alloying element resolution would be required.

Finally, it is acknowledged that governmental interventions to a large extent, impact circular economy. However, policy mandates can play a huge role in the effectiveness of these strategies. Like the operation green fence is supposed to improve China's waste management, it is important to enact policies that are designed to make the attainment of both linear and interconnected circular economies more feasible than they are at present, thus ensuring a robust secondary supply of resources.

Future work

As with the case with the automotive industry, evaluating the sustainability impacts of material use in and across industries provides a solid foundation to ensure a viable material supply into the future. These evaluations should cut across different operational levels – from sustaining and optimizing material consumption to investigating the impacts of technological changes. With this at the fore front, together with recent environmental and economic situations, future studies can broadly be centered around the question **"How can the present terms of sustainability intentions be optimized while ensuring the future goals**?". With such thought-provoking research question posed, several dimensions should be considered, navigating a systems-thinking approach rather than a linear approach. These studies should generally focus on the 3 cores of sustainability in order to present a holistic view on sustainability concerns, environmentally, economically and socially, with an understanding of the importance, trade-offs, benefits, and effects of sustainability practices.

Some future studies that may spin off from this work can generally be classified under these umbrella topics:

Circular economy

Here, the focus will be aimed at eliminating waste whilst encouraging the continual use of resources. As mentioned previously in this dissertation, recent clean energy policies have signaled the drive towards clean mobility which require various technological changes that depend on the use of **critical and strategic materials**. Because of this dependence, a future project under this theme targeted at the automotive industry could investigate ***Mass decompounding and secondary savings of electric vehicles***, where analysis will investigate the different avenues (vehicle components) where vehicle mass could be saved to mitigate the currently observed increasing trend in electric vehicle curb weight.

Based on the results from this dissertation intersecting the automotive industry and the recycling industry, further surveys could be carried out focusing on secondary producers, e.g., the brass and wire mills, foundries, etc. for a better understanding of the volumes and **consumption of both primary and secondary materials.**

Another future project targeted at the recycling industry could ***Investigate recycling strategies for non-ferrous industries*** – as an extension of the latter part of this dissertation to other non-ferrous commodity metals.

Industrial ecology

Here the focus will be aimed at studying and tracking materials and energy flows through systems. An example project is investigating **producer responsibility** and the **ecoefficiency of manufacturing**. An example targeted at the automotive industry is analyzing ***the journey to clean mobility; is it an "acquittal" or a "delayed judgement?"***

Consumer behavior

Here the focus will be on **consumerism**, the use and disposal of goods and services by consumers. One example of a project here is **"*Impacts of consumer behavior on consumed product*"**, a project based on the understanding that achieving sustainability targets are largely dependent on human behavior and idiosyncrasies.

The above topics will, to a large extent, involve methodologies and techniques like data mining and harnessing, material flow analysis, dynamic modeling and forecasting, industrial and consumer surveys, multicriteria decision analysis, geospatial analysis, among others. These research topics have high national and global impacts and are of vested interests to the National Science Foundation (NSF), United States Environmental Protection Agency (USEPA), International Copper Association (ICA), United Nations (UN), Institute of Scrap Recycling Industries (ISRI), The Aluminum Association, U.S. Department of Energy (DOE), REMADE Institute, amongst many others.

REFERENCES

Agrawal, A., & Sahu, K. K. (2010). Problems, prospects and current trends of copper recycling in India: An overview. *Resources, Conservation and Recycling, 54*(7), 401-416. doi:https://doi.org/10.1016/j.resconrec.2009.09.005

Alonso, E., Field, F. R., & Kirchain, R. E. (2012). Platinum Availability for Future Automotive Technologies. *Environmental Science & Technology, 46*(23), 12986-12993. doi:10.1021/es301110e

Alternative Fuels Data Center. (January 2020). U.S. Plug-in Electric Vehicles Sales by Model. In: U.S. Department of Energy.

American Iron and Steel Institute. (2020). Steel Sustainability in the Auto Market.

Arowosola, A., & Gaustad, G. (2019). Estimating increasing diversity and dissipative loss of critical metals in the aluminum automotive sector. *Resources, Conservation and Recycling, 150*, 104382. doi:https://doi.org/10.1016/j.resconrec.2019.06.016

Arowosola, A., Gaustad, G., & Brooks, L. (2019). Aluminum Alloys in Autobodies: Sources and Sinks. In *Light Metals 2019* (pp. 1381-1383): Springer.

Balkevicius, A., Sanctuary, M., & Zvirblyte, S. (2020). Fending off waste from the west: The impact of China's Operation Green Fence on the international waste trade. *World economy, 43*(10), 2742-2761. doi:10.1111/twec.12949

Ballinger, B., Stringer, M., Schmeda-Lopez, D. R., Kefford, B., Parkinson, B., Greig, C., & Smart, S. (2019). The vulnerability of electric vehicle deployment to critical mineral supply. *Applied Energy, 255*, 113844. doi:https://doi.org/10.1016/j.apenergy.2019.113844

Barnhart, J. (1997). Occurrences, Uses, and Properties of Chromium. *Regulatory Toxicology and Pharmacology, 26*(1), S3-S7. doi:https://doi.org/10.1006/rtph.1997.1132

Bayliss, C. (2019). *Presentation at the 2019 TMS Annual Meeting*. Retrieved from

Bonnin, M., Azzaro-Pantel, C., Pibouleau, L., Domenech, S., & Villeneuve, J. (2013). Development and validation of a dynamic material flow analysis model for French copper cycle. *Chemical engineering research & design, 91*(8), 1390-1402. doi:10.1016/j.cherd.2013.03.016

Boon, J. E., Isaacs, J. A., & Gupta, S. M. (2000). Economic Impact of Aluminum-Intensive Vehicles on the U.S. Automotive Recycling Infrastructure. *Journal of Industrial Ecology, 4*(2), 117-134. doi:10.1162/108819800569717

Boulanger, A. G., Chu, A. C., Maxx, S., & Waltz, D. L. (2011). Vehicle Electrification: Status and Issues. *Proceedings of the IEEE, 99*(6), 1116-1138. doi:10.1109/JPROC.2011.2112750

Brahmst, E. (2006). Copper in end-of-life vehicle recycling. *The Center for Automotive Research, Ann Arbor, Michigan*.

Brooker, A. D., Ward, J., & Wang, L. (2013). *Lightweighting Impacts on Fuel Economy, Cost, and Component Losses*. Paper presented at the SAE 2013 World Congress and Exhibition. https://doi.org/10.4271/2013-01-0381

Brooks, L., Gaustad, G., Gesing, A., Mortvedt, T., & Freire, F. (2019). Ferrous and non-ferrous recycling: Challenges and potential technology solutions. *Waste Management, 85*, 519-528. doi:https://doi.org/10.1016/j.wasman.2018.12.043

Bushi, L., Skszek, T., & Wagner, D. (2015). Comparative LCA Study of Lightweight Auto Parts of MMLV Mach-I Vehicle as per ISO 14040/44 LCA Standards and CSA Group 2014

LCA Guidance Document for Auto Parts | SpringerLink. *Engineering Solutions for Sustainability*. doi:10.1007/978-3-319-48138-8_19
Calvo, G., Mudd, G., Valero, A., & Valero, A. (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? *Resources, 5*(4). doi:10.3390/resources5040036
Chappuis, L. B. (2019). *Material Specification and Recycling for the 2015 Ford F-150*. Retrieved from https://www.lbcg.com/media/downloads/events/411/day-2-laurent-b-chappuis-technical-expert-lightweight-stampings-vehicle-program-engineering-sbu-ford.6735.pdf
Cheah, L., & Heywood, J. (2011). Meeting U.S. passenger vehicle fuel economy standards in 2016 and beyond. *Energy Policy, 39*(1), 454-466. doi:https://doi.org/10.1016/j.enpol.2010.10.027
Cheah, L. W. (2010). Cars on a diet: the material and energy impacts of passenger vehicle weight reduction in the US.
Ciacci, L., Reck, B. K., Nassar, N. T., & Graedel, T. E. (2015). Lost by Design. *ENVIRONMENTAL SCIENCE & TECHNOLOGY, 49*(16), 9443-9451. doi:10.1021/es505515z
Copper Alliance. (2020). Global 2020 Semis End Use Data Set. In.
Crowson, P. (2012). Some observations on copper yields and ore grades. *Resources Policy, 37*(1), 59-72. doi:https://doi.org/10.1016/j.resourpol.2011.12.004
Cui, J., & Roven, H. J. (2010). Recycling of automotive aluminum. *Transactions of Nonferrous Metals Society of China, 20*(11), 2057-2063. doi:https://doi.org/10.1016/S1003-6326(09)60417-9
Daehn, K. E., Cabrera Serrenho, A., & Allwood, J. M. (2017). How Will Copper Contamination Constrain Future Global Steel Recycling? *Environmental Science & Technology, 51*(11), 6599-6606. doi:10.1021/acs.est.7b00997
Dai, Q., Kelly, J., & Elgowainy, A. (2016). Vehicle Materials; Material Composition of U.S. Light Duty Vehicles. In: Argonne National Laboratory.
Daigo, I., Hashimoto, S., Matsuno, Y., & Adachi, Y. (2009). Material stocks and flows accounting for copper and copper-based alloys in Japan. *Resources, conservation and recycling, 53*(4), 208-217. doi:10.1016/j.resconrec.2008.11.010
Davis, S. C., & Boundy, R. G. (2020). Transportation Energy Databook. In (38.1 ed.): Oak Ridge National Laboratory.
Department of the Interior. (2018). Final List of Critical Minerals 2018. *Federal Register, 83*, 23295.
Ducker Worldwide. (2017). *Aluminum Content in North American Light Vehicles 2016 to 2028*. Retrieved from
Duclos, S. J., Otto, J. P., & Konitzer, D. G. (2010). Design in an era of Constrained Resources. *Mechanical Engineering Magazine Select Articles, 132*(09), 36-40. doi:10.1115/1.2010-Sep-3
Earth911. (2021). 20 Staggering E-Waste Facts in 2021.
Energy, U. S. D. o. (2011). Critical Materials Strategy. In.
European Aluminium. Aluminium Automotive Manual. https://www.european-aluminium.eu/resource-hub/aluminium-automotive-manual/
European Aluminium Association. (2002). Materials - Alloy constitution. In *The Aluminum Automotive Manual*.

European Commission. (2017). *2017 list of Critical Raw Materials for the EU*. Retrieved from

European Commission, & Industry, D. E. a. (2013). *Critical raw materials for the EU. Report of the Ad-hoc working group on defining critical raw materials*. Retrieved from

Field, F. R., Wallington, T. J., Everson, M., & Kirchain, R. E. (2017). Strategic Materials in the Automobile: A Comprehensive Assessment of Strategic and Minor Metals Use in Passenger Cars and Light Trucks. *Environmental Science & Technology, 51*(24), 14436-14444. doi:10.1021/acs.est.6b06063

Fridlyander, I. N., Sister, V. G., Grushko, O. E., Berstenev, V. V., Sheveleva, L. M., & Ivanova, L. A. (2002). Aluminum Alloys: Promising Materials in the Automotive Industry. *Metal Science and Heat Treatment, 44*(9), 365-370. doi:10.1023/A:1021901715578

Fu, X., Beatty, D. N., Gaustad, G. G., Ceder, G., Roth, R., Kirchain, R. E., . . . Olivetti, E. A. (2020). Perspectives on Cobalt Supply through 2030 in the Face of Changing Demand. *Environmental Science & Technology, 54*(5), 2985-2993. doi:10.1021/acs.est.9b04975

Gaustad, G. (2009). *Towards Sustainable Material Usage: Time-dependent evaluation of upgrading technologies for recycling.* Massachusetts Institute of Technology, Retrieved from http://dspace.mit.edu/handle/1721.1/53243

Gaustad, G., Li, P., & Kirchain, R. (2007). Modeling methods for managing raw material compositional uncertainty in alloy production. *Resources, Conservation and Recycling, 52*(2), 180-207. doi:https://doi.org/10.1016/j.resconrec.2007.03.005

Gaustad, G., Olivetti, E., & Kirchain, R. (2010). Design for Recycling. *Journal of Industrial Ecology, 14*(2), 286-308. doi:10.1111/j.1530-9290.2010.00229.x

Gaustad, G., Olivetti, E., & Kirchain, R. (2012). Improving aluminum recycling: A survey of sorting and impurity removal technologies. *Resources, Conservation and Recycling, 58*, 79-87. doi:https://doi.org/10.1016/j.resconrec.2011.10.010

Glöser, S., Soulier, M., & Tercero Espinoza, L. A. (2013). Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation. *Environmental Science & Technology, 47*(12), 6564-6572. doi:10.1021/es400069b

Graedel, T. E. (2019). Material Flow Analysis from Origin to Evolution. *Environmental Science & Technology, 53*(21), 12188-12196. doi:10.1021/acs.est.9b03413

Graedel, T. E., Allwood, J., Birat, J. P., Buchert, M., Hagelüken, C., Reck Barbara, K., . . . Sonnemann, G. (2011). What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology, 15*(3), 355-366. doi:10.1111/j.1530-9290.2011.00342.x

Graedel, T. E., van Beers, D., Bertram, M., Fuse, K., Gordon, R. B., Gritsinin, A., . . . Vexler, D. (2004). Multilevel Cycle of Anthropogenic Copper. *Environmental Science & Technology, 38*(4), 1242-1252. doi:10.1021/es030433c

Gruber, P. W., Medina, P. A., Keoleian, G. A., Kesler, S. E., Everson, M. P., & Wallington, T. J. (2011). Global Lithium Availability. *Journal of Industrial Ecology, 15*(5), 760-775. doi:https://doi.org/10.1111/j.1530-9290.2011.00359.x

Guo, X., & Song, Y. (2008). Substance flow analysis of copper in China. *Resources, conservation and recycling, 52*(6), 874-882. doi:10.1016/j.resconrec.2007.10.003

Gómez, F., Guzmán, J. I., & Tilton, J. E. (2007). Copper recycling and scrap availability. *Resources Policy, 32*(4), 183-190. doi:https://doi.org/10.1016/j.resourpol.2007.08.002

Hatayama, H., Daigo, I., & Tahara, K. (2014). Tracking effective measures for closed-loop recycling of automobile steel in China. *Resources, Conservation and Recycling, 87*, 65-71. doi:https://doi.org/10.1016/j.resconrec.2014.03.006

Hatayama, H., & Tahara, K. (2015). Criticality Assessment of Metals for Japan's Resource Strategy. *MATERIALS TRANSACTIONS, 56*(2), 229-235. doi:10.2320/matertrans.M2014380
Henckens, M. L. C. M., & Worrell, E. (2020). Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates. *Journal of Cleaner Production, 264*, 121460. doi:https://doi.org/10.1016/j.jclepro.2020.121460
ICA. (2020). Copper stocks and flows. Retrieved from https://copperalliance.org/about-copper/stocks-and-flows/
ICCT. (2018). China's New Energy Vehicle Mandate Policy (Final Rule). In: International Council on Clean Transportation.
IEA. (2019). Global EV Outlook 2019. In. IEA, Paris.
IEA. (2020). Global EV Outlook 2020. In. Paris: IEA.
Institute of Scrap Recycling Industries. (2020). Scrap Specifications Circular. from ISRI
International Copper Study Group. (2019). World Copper Factbook. In: ICSG.
Javaid, A., & Essadiqi, E. (2013). *Final Report on Scrap Management, Sorting and Classification of Steel*. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/mineralsmetals/pdf/mms-smm/busi-indu/rad-rad/pdf/2003-23(cf)cc-eng.pdf
Johnson, S. (2020). A Changing Nation: Population Projections Under Alternative Migration Scenarios. In (pp. 25-1146). Washington, DC: U.S. Census Bureau.
Kallstrom, H. (2019). Intense competition leads to low profit margins for automakers. *Market Realist*.
Kelly, S., & Apelian, D. (2016). *Automotive aluminum recycling at End of Life; A Grave to Gate Analysis*. Retrieved from http://1pp2jy1h0dtm6dg8i11qjfb1-wpengine.netdna-ssl.com/wp-content/uploads/2016/06/Final-Report-Automotive-Aluminum-Recycling-at-End-of-Life-A-Grave-to-Gate-Analysis.pdf
Kim, H.-J., McMillan, C., Keoleian, G. A., & Skerlos, S. J. (2010). Greenhouse Gas Emissions Payback for Lightweighted Vehicles Using Aluminum and High-Strength Steel. *Journal of Industrial Ecology, 14*(6), 929-946. doi:10.1111/j.1530-9290.2010.00283.x
Kukreja, R. (2018). 6 Positive Facts About The Global Car Recycling Industry - Conserve Energy Future. *Conserve Energy Future*.
Laner, D., & Rechberger, H. (2016). Material Flow Analysis. In M. Finkbeiner (Ed.), *Special Types of Life Cycle Assessment* (pp. 293-332). Dordrecht: Springer Netherlands.
LeBlanc, R. (2019). How are Cars Recycled? *Sustainable Businesses*.
Lewis, G. M., Buchanan, C. A., Jhaveri, K. D., Sullivan, J. L., Kelly, J. C., Das, S., . . . Keoleian, G. A. (2019). Green Principles for Vehicle Lightweighting. *Environmental Science & Technology, 53*(8), 4063-4077. doi:10.1021/acs.est.8b05897
Miller, W. S., Zhuang, L., Bottema, J., Wittebrood, A. J., De Smet, P., Haszler, A., & Vieregge, A. (2000). Recent development in aluminium alloys for the automotive industry. *Materials Science and Engineering: A, 280*(1), 37-49. doi:https://doi.org/10.1016/S0921-5093(99)00653-X
Ministry of Heavy Industries and Public Enterprises. (2019). *Faster Adoption and Manufacturing of Electric Vehicles in India*. New Delhi: Extraordinary Gazette of India Retrieved from

https://dhi.nic.in/writereaddata/UploadFile/publicationNotificationFAME%20II%208March2019.pdf
Modaresi, R., & Müller, D. B. (2012). The Role of Automobiles for the Future of Aluminum Recycling. *Environmental Science & Technology, 46*(16), 8587-8594. doi:10.1021/es300648w
Moss, R. L., Tzimas, E., Willis, P., Arendorf, J., Thompson, P., Chapman, A., . . . Peason, J. (2013). Critical metals in the path towards the decarbonisation of the EU energy sector. *Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies. JRC Report EUR, 25994*.
Mudd, G. M., & Weng, Z. (2012). Base Metals. In T. M. Letcher & J. L. Scott (Eds.), *Materials for a sustainable future* (pp. 11-59): Royal Society of Chemistry.
Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Suh, S., Shigetomi, Y., & Oshita, Y. (2014). Global Flows of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum. *Environmental Science & Technology, 48*(3), 1391-1400. doi:10.1021/es4033452
Naohiko., O., & Hideki., K. (2006). Recyclability Evaluation Method Considering Material Combination and Degradation. *JSME, 71*.
Nassar, N. T., Graedel, T. E., & Harper, E. M. (2015). By-product metals are technologically essential but have problematic supply. *Science Advances, 1*(3), e1400180. doi:10.1126/sciadv.1400180
National Research, C. (2008). *Minerals, Critical Minerals, and the U.S. Economy*. Washington, DC: The National Academies Press.
National Research Council. (2008). Critical Minerals. In *Minerals, Critical Minerals, and the U.S. Economy*. Washington, DC: The National Academies Press.
Natural Resources Canada. (2020). Zero Emission Vehicle Awareness Initiative. In: Government of Canada.
Nuss, P., Harper, E. M., Nassar, N. T., Reck, B. K., & Graedel, T. E. (2014). Criticality of Iron and Its Principal Alloying Elements. *Environmental Science & Technology, 48*(7), 4171-4177. doi:10.1021/es405044w
Office of Energy Efficiency & Renewable Energy. (2016). *Fact #915: Average Historical Annual Gasoline Pump Price, 1929-2015*. @ENERGY Retrieved from https://www.energy.gov/eere/vehicles/fact-915-march-7-2016-average-historical-annual-gasoline-pump-price-1929-2015
Olivetti, E. A., Ceder, G., Gaustad, G. G., & Fu, X. (2017). Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. *Joule, 1*(2), 229-243. doi:https://doi.org/10.1016/j.joule.2017.08.019
Peiró, L. T., Méndez, G. V., & Ayres, R. U. (2013). Material Flow Analysis of Scarce Metals: Sources, Functions, End-Uses and Aspects for Future Supply. *Environmental Science & Technology, 47*(6), 2939-2947. doi:10.1021/es301519c
Rechberger, H., & Graedel, T. E. (2002). The contemporary European copper cycle: statistical entropy analysis. *Ecological Economics, 42*(1), 59-72. doi:https://doi.org/10.1016/S0921-8009(02)00102-7
Restrepo, E., Løvik, A. N., Wäger, P., Widmer, R., Lonka, R., & Müller, D. B. (2017). Stocks, Flows, and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles. *Environmental Science & Technology, 51*(3), 1129-1139. doi:10.1021/acs.est.6b05743

Soulier, M., Glöser-Chahoud, S., Goldmann, D., & Tercero Espinoza, L. A. (2018). Dynamic analysis of European copper flows. *Resources, conservation and recycling, 129*, 143-152. doi:10.1016/j.resconrec.2017.10.013
Spatari, S., Bertram, M., Fuse, K., Graedel, T. E., & Rechberger, H. (2002). The contemporary European copper cycle: 1 year stocks and flows. *Ecological economics, 42*(1), 27-42. doi:10.1016/S0921-8009(02)00103-9
Staley, J. T., & Lege, D. J. (1993). Advances in aluminium alloy products for structural applications in transportation. *J. Phys. IV France, 03*(C7), C7-179-C177-190.
Staley, J. T., Van Horn, Kent R., & Bridenbaugh, P. R. (2018). Aluminum Processing. In *Encyclopaedia Britannica*: Encyclopaedia Britannica, inc.
Statista. (2021). Vehicle sales in the United States 1976-2020. from Mathilde Carlier https://www.statista.com/statistics/199983/us-vehicle-sales-since-1951/
Stehn, M. (2019). *Phase-out of Credit for New Qualified Plug-in Electric Drive Motor Vehicles*.
Tauben, S. (2011). The Evolution of the Copper Scrap Industry. In. Saint Louis, MO.
The European Parliament and Council of the European Union. (2009). *Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles*. Official Journal of the European Union Retrieved from http://data.europa.eu/eli/dir/2009/33/oj
The European Parliament and the Council of the European Union. (2000). *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles - Commission Statements*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2000.269.01.0034.01.ENG&toc=OJ%3AL%3A2000%3A269%3ATOC
Tong, X., & Lifset, R. (2007). International copper flow network: A blockmodel analysis. *Ecological economics, 61*(2), 345-354. doi:10.1016/j.ecolecon.2006.03.008
U.S. Census Bureau, P. D. (2019). *Table 1; Monthly Population Estimates for the United States: April 1, 2010 to December 1, 2020 (NA-EST2019-01)*.
U.S. EIA. (2021). Annual Energy Outlook; Table 38. Light-Duty Vehicle Sales by Technology Type. from U.S. Energy Information Administration https://www.eia.gov/outlooks/aeo/data/browser/#/?id=48-AEO2021&cases=ref2021&sourcekey=0
U.S. Geological Survey. (2018). *Mineral Commodity Summaries 2018*. U.S. Geological Survey Retrieved from https://doi.org/10.3133/70194932.
U.S. Geological Survey. (Several years-a). Mineral Commodity Summaries. In.
U.S. Geological Survey. (Several years-b). Statistics and Information (several commodities). In.
UBS Limited. (2017). UBS Evidence Lab Electric Car Teardown –Disruption Ahead? In (Vol. Q Series).
UNFCCC. (2015). Paris declaration on electro-mobility and climate change & call to action. In.
United States Environmental Protection Agency. (2021). *The 2020 EPA Automotive Trends Report*.
US EPA. (2017). *Processing End-of-Life Vehicle: A Guide for Environmental Protection, Safety and Profit in the United States-Mexico Border Area*. Retrieved from https://www.epa.gov/sites/production/files/2020-10/documents/eol_vehicle_guide_final_english.pdf
US EPA. (2020a). *Advancing Sustainable Materials Management: 2018 Fact Sheet*.

US EPA. (2020b). *Automotive Trends Report*. Retrieved from: https://www.epa.gov/automotive-trends/explore-automotive-trends-data
US EPA. (2021a). 1960-2018 Data on Construction and Demolition Debris by Weight (in thousands of U.S. tons). In C. a. D. D. M.-S. Data (Ed.).
US EPA. (2021b, 2021-06-10). Cleaning Up Electronic Waste (E-Waste). Retrieved from https://www.epa.gov/international-cooperation/cleaning-electronic-waste-e-waste
USEPA. (2018). Sources of Greenhouse Gas Emissions. Retrieved from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#transportation
USEPA. (2021). Trends in Greenhouse Gas Emissions. Retrieved from https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions
USGS. Commodity Statistics and Information. Retrieved from https://minerals.usgs.gov/minerals/pubs/commodity/
USGS. (Several years). *Minerals Yearbook; Copper*. Retrieved from
VRW. (2020). Eurostat Releases Figures Of Latest ELV Reuse, Recycling And Recovery Targets. *Auto Recycling World*.
Wagner, I. (2020). Motor Vehicle Production of the United States and Worldwide 1999-2019. In: Statista.
Wagstaff, S. R. (2018). The impact of recycling on the mechanical properties of 6XXX series aluminum alloys.
Wang, M., Chen, W., & Li, X. (2015). Substance flow analysis of copper in production stage in the U.S. from 1974 to 2012. *Resources, conservation and recycling, 105*, 36-48. doi:10.1016/j.resconrec.2015.10.012
Wang, M., Chen, W., Zhou, Y., & Li, X. (2017). Assessment of potential copper scrap in China and policy recommendation. *Resources policy, 52*, 235-244. doi:10.1016/j.resourpol.2016.12.009
Wards Intelligence. (2005). Wards Automotive Yearbook. In.
Widmer, J. D., Martin, R., & Kimiabeigi, M. (2015). Electric vehicle traction motors without rare earth magnets. *Sustainable Materials and Technologies, 3*, 7-13. doi:https://doi.org/10.1016/j.susmat.2015.02.001
Zimmermann, T., & Gößling-Reisemann, S. (2013). Critical materials and dissipative losses: A screening study. *Science of The Total Environment, 461*(Supplement C), 774-780. doi:https://doi.org/10.1016/j.scitotenv.2013.05.040

APPENDIX

Other results and supplementary data

Copper per vehicle

Table A1: Trend in copper Intensity per vehicle; highlighted column is result from top-down analysis for copper content

	Copper per vehicle (kg Cu/vehicle)					
Year	Top-down analysis	Existing literature				
		Wards	Dai, Kelly, and Elgowainy 2016	Brahmst 2006	Field et al. 2017	Bushi et al 2015
1976		15				
1977		16				
1978		17				
1979		16				
1980		16				
1981		17				
1982		18				
1983		19				
1984		20				
1985		20				
1986		20				
1987		21				
1988		22				
1989		22				
1990		21				
1991		21				
1992		20				
1993		20				
1994		19				
1995		20	23			
1996		20	23			
1997		21	24			
1998		21	24	26		
1999		21	24			
2000	23	21	24			
2001	23	21	30			
2002	19	23	31			
2003	20	23	32			
2004	21	23	32			
2005	20		27	31		
2006	19		28			
2007	19		24			
2008	21		29			
2009	37		29			

2010	27	30		
2011	24	30		
2012	30	33		
2013	30	33	31	34
2014	29	32		
2015	28			
2016	28			
2017	33			
2018	33			
2019	34			

Vehicle types and their copper content

The average copper content for the different commuter vehicle types is shown below.

ICEV: Internal Combustion Engine Vehicle

HEV: Hybrid Electric Vehicle

PHEV: Plugged-in Hybrid Electric Vehicle

BEV: Battery Electric Vehicle

Ebus: Electric Bus

E-Bus was not included in this research.

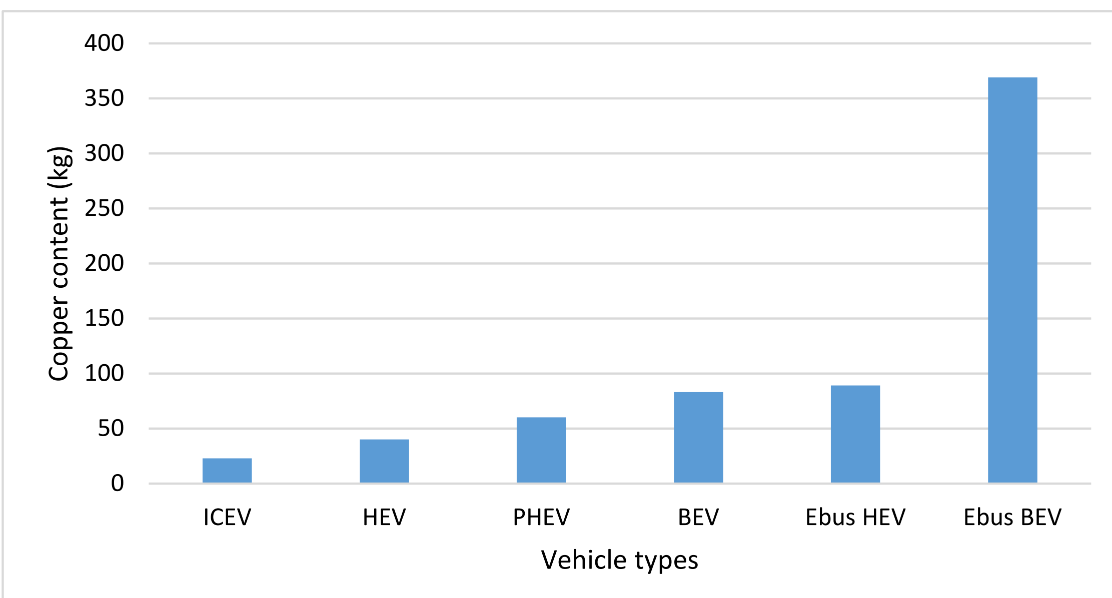


Figure A1: Vehicle types and their average copper content (ICSG, 2018)

Copper demand parameters

Table A2: Historic copper demand parameter values

<table>
<tr><th></th><th></th><th colspan="2">Sales (units)</th><th colspan="4">Technology (kg Cu/vehicle)</th></tr>
<tr><th>Year</th><th>Population</th><th>ICE</th><th>EV</th><th>ICE</th><th colspan="3">EV</th></tr>
<tr><td>2000</td><td>283,437,649</td><td>17,349,700</td><td></td><td>23</td><td></td><td></td><td></td></tr>
<tr><td>2001</td><td>286,138,973</td><td>17,122,400</td><td></td><td>23</td><td></td><td></td><td></td></tr>
<tr><td>2002</td><td>288,804,655</td><td>16,816,200</td><td></td><td>19</td><td></td><td></td><td></td></tr>
<tr><td>2003</td><td>291,364,214</td><td>16,639,100</td><td></td><td>20</td><td></td><td></td><td></td></tr>
<tr><td>2004</td><td>294,015,263</td><td>16,866,900</td><td></td><td>21</td><td></td><td></td><td></td></tr>
<tr><td>2005</td><td>296,762,293</td><td>16,948,200</td><td></td><td>20</td><td></td><td></td><td></td></tr>
<tr><td>2006</td><td>299,658,194</td><td>16,504,100</td><td></td><td>19</td><td></td><td></td><td></td></tr>
<tr><td>2007</td><td>302,533,358</td><td>16,089,000</td><td></td><td>19</td><td></td><td></td><td></td></tr>
<tr><td>2008</td><td>305,298,802</td><td>13,194,800</td><td></td><td>21</td><td></td><td></td><td></td></tr>
<tr><td>2009</td><td>307,954,399</td><td>10,402,300</td><td></td><td>37</td><td>Low</td><td>Mid</td><td>High</td></tr>
<tr><td>2010</td><td>309,321,666</td><td>11,550,409</td><td>4,391</td><td>27</td><td rowspan="10">40</td><td rowspan="10">60</td><td rowspan="10">83</td></tr>
<tr><td>2011</td><td>311,556,874</td><td>12,724,037</td><td>17,763</td><td>24</td></tr>
<tr><td>2012</td><td>313,830,990</td><td>14,380,029</td><td>53,171</td><td>30</td></tr>
<tr><td>2013</td><td>315,993,715</td><td>15,432,998</td><td>97,102</td><td>30</td></tr>
<tr><td>2014</td><td>318,301,008</td><td>16,333,318</td><td>118,882</td><td>29</td></tr>
<tr><td>2015</td><td>320,635,163</td><td>17,293,977</td><td>114,023</td><td>28</td></tr>
<tr><td>2016</td><td>322,941,311</td><td>17,317,384</td><td>159,616</td><td>28</td></tr>
<tr><td>2017</td><td>324,985,539</td><td>16,954,419</td><td>195,581</td><td>33</td></tr>
<tr><td>2018</td><td>326,687,501</td><td>16,863,685</td><td>361,315</td><td>33</td></tr>
<tr><td>2019</td><td>328,239,523</td><td>16,635,356</td><td>326,644</td><td>34</td></tr>
</table>

Copper demand forecast variables

The IPAT equation was used to forecast copper demand. The following are the variable values used for the parameters.

Population

The mid-point value (highlighted) was used in this analysis.

Table A3: U.S Population projection under multiple scenarios (Johnson, 2020)

Year	Low	Mid	High
2020	330,640,000	332,639,000	335,638,000
2021	332,477,000	334,998,000	338,781,000
2022	334,289,000	337,342,000	341,921,000
2023	336,071,000	339,665,000	345,056,000
2024	337,820,000	341,963,000	348,179,000
2025	339,532,000	344,234,000	351,287,000
2026	341,213,000	346,481,000	354,384,000
2027	342,849,000	348,695,000	357,464,000
2028	344,439,000	350,872,000	360,521,000
2029	345,979,000	353,008,000	363,552,000
2030	347,467,000	355,101,000	366,552,000
2031	348,901,000	357,147,000	369,517,000
2032	350,281,000	359,147,000	372,445,000
2033	351,607,000	361,099,000	375,335,000
2034	352,881,000	363,003,000	378,186,000
2035	354,104,000	364,862,000	380,999,000
2036	355,277,000	366,676,000	383,775,000
2037	356,404,000	368,448,000	386,514,000
2038	357,485,000	370,179,000	389,219,000
2039	358,524,000	371,871,000	391,892,000
2040	359,522,000	373,528,000	394,536,000
2041	360,484,000	375,152,000	397,154,000
2042	361,411,000	376,746,000	399,748,000
2043	362,308,000	378,314,000	402,324,000
2044	363,178,000	379,861,000	404,885,000
2045	364,026,000	381,390,000	407,437,000
2046	364,856,000	382,907,000	409,984,000
2047	365,672,000	384,415,000	412,529,000
2048	366,477,000	385,918,000	415,078,000
2049	367,274,000	387,419,000	417,635,000
2050	368,068,000	388,922,000	420,202,000

Affinity

Total ICE sales (Table A4) and Total EV sales (Table A7) were used for the copper demand from ICEs

Table A4: ICE sales projections

Year	Cars	Truck	Total ICE sales
2020	4,530,709	6,458,267	10,988,976
2021	4,867,392	7,274,765	12,142,157
2022	5,296,284	7,544,722	12,841,006
2023	5,324,176	7,581,095	12,905,271
2024	5,373,486	7,743,421	13,116,907
2025	5,477,615	7,874,311	13,351,926
2026	5,448,718	7,750,465	13,199,183
2027	5,352,035	7,612,817	12,964,852
2028	5,400,679	7,579,199	12,979,878
2029	5,432,147	7,543,908	12,976,055
2030	5,501,298	7,428,264	12,929,562
2031	5,523,609	7,406,604	12,930,213
2032	5,528,902	7,333,042	12,861,944
2033	5,533,903	7,306,438	12,840,342
2034	5,533,435	7,285,143	12,818,578
2035	5,479,234	7,218,676	12,697,910
2036	5,404,901	7,129,298	12,534,199
2037	5,350,316	7,065,132	12,415,448
2038	5,311,641	7,012,635	12,324,275
2039	5,234,393	6,963,347	12,197,740
2040	5,180,020	6,889,037	12,069,057
2041	5,155,409	6,867,499	12,022,908
2042	5,135,849	6,872,183	12,008,032
2043	5,069,843	6,822,972	11,892,815
2044	5,018,476	6,811,471	11,829,946
2045	4,991,060	6,861,549	11,852,609
2046	4,957,419	6,843,921	11,801,340
2047	4,902,429	6,829,571	11,732,000
2048	4,842,635	6,809,611	11,652,246
2049	4,746,519	6,764,523	11,511,042
2050	4,648,842	6,709,949	11,358,791

Table A5: EV cars sales projections

Year	100mile EV	200mile EV	300mile EV	Plug-in 10 Gas	Plug-in 40 Gas	Electric Gasoline Hybrid	Total EV cars

2020	2,103	46,674	66,729	21,783	5,690	124,642	267,621
2021	2,163	44,807	59,881	28,945	5,803	140,875	282,474
2022	2,206	45,592	68,174	34,308	5,297	164,036	319,613
2023	2,151	43,200	73,933	37,976	4,772	175,780	337,813
2024	2,165	42,335	81,159	43,215	4,534	189,136	362,544
2025	2,255	43,661	85,751	51,154	4,536	203,892	391,250
2026	2,338	43,893	93,682	58,625	4,640	217,139	420,317
2027	2,415	45,695	100,260	67,048	4,799	228,585	448,802
2028	2,594	50,307	112,001	80,461	5,235	249,042	499,640
2029	2,775	55,718	127,052	84,512	5,748	265,578	541,383
2030	3,014	64,079	146,093	89,913	6,553	286,566	596,218
2031	3,205	71,680	170,892	91,540	7,104	303,466	647,887
2032	3,398	80,699	194,989	94,800	7,617	319,845	701,348
2033	3,567	89,484	225,035	96,257	8,024	336,021	758,387
2034	3,721	98,524	255,861	97,580	8,400	352,073	816,160
2035	3,821	106,646	287,058	97,312	8,645	364,635	868,116
2036	3,890	114,503	317,868	96,472	8,815	375,847	917,394
2037	3,956	122,774	350,624	95,697	8,974	388,464	970,489
2038	4,023	131,644	385,449	95,193	9,137	402,728	1,028,173
2039	4,042	138,659	417,807	92,922	9,145	413,162	1,075,737
2040	4,077	147,294	449,137	92,208	9,232	426,690	1,128,639
2041	4,110	155,088	477,869	90,322	9,246	444,741	1,181,376
2042	4,146	162,885	504,420	88,353	9,239	461,139	1,230,182
2043	4,142	169,632	527,033	85,745	9,153	473,842	1,269,548
2044	4,144	176,384	550,888	83,058	9,061	487,941	1,311,477
2045	4,160	183,525	576,527	80,520	8,986	504,388	1,358,106
2046	4,180	192,515	602,107	78,945	8,967	522,378	1,409,092
2047	4,177	199,802	630,767	76,119	8,861	538,024	1,457,748
2048	4,170	207,439	656,528	73,601	8,760	553,645	1,504,143
2049	4,129	213,003	679,249	70,239	8,575	564,758	1,539,953
2050	4,088	218,845	699,941	67,173	8,400	575,786	1,574,232

Table A6: EV trucks sales projections

Year	200mile EV	300mile EV	Plug-in 10 Gas	Plug-in 40 Gas	Electric Gasoline Hybrid	**Total EV trucks**
2020	11,144	26,088	3,729	20,691	216,244	277,897
2021	12,630	31,497	4,121	24,875	256,559	329,681
2022	13,753	36,169	4,270	24,775	273,683	352,650
2023	14,602	41,027	4,382	22,785	281,266	364,062
2024	17,316	47,087	4,656	21,191	293,693	383,943
2025	19,958	51,166	4,780	38,793	307,147	421,844
2026	23,025	54,421	4,822	113,801	357,389	553,458
2027	25,795	59,169	5,346	132,550	379,950	602,810
2028	29,765	67,692	6,035	134,485	394,047	632,024
2029	34,156	77,479	6,770	134,531	405,301	658,237
2030	38,607	91,313	7,507	136,689	419,663	693,779
2031	43,773	105,544	8,310	139,987	434,449	732,063
2032	49,244	122,178	9,114	144,208	448,685	773,429
2033	55,012	139,531	9,935	148,170	463,218	815,866
2034	60,931	158,387	10,776	151,887	478,439	860,419
2035	66,334	177,171	11,545	154,255	490,154	899,458
2036	71,367	196,053	12,375	155,758	500,326	935,880
2037	76,429	215,950	13,380	157,420	511,730	974,908
2038	81,471	237,020	14,542	159,191	524,183	1,016,407
2039	86,126	256,045	15,809	159,814	534,286	1,052,080
2040	90,597	276,559	17,268	160,448	545,192	1,090,064
2041	95,248	291,863	18,959	160,774	557,541	1,124,384
2042	100,153	306,840	20,940	161,118	571,434	1,160,484
2043	104,271	320,158	23,057	160,284	581,239	1,189,009
2044	108,785	334,289	25,581	159,799	593,519	1,221,974
2045	114,176	350,454	28,748	160,214	610,525	1,264,117
2046	118,937	368,292	32,390	160,215	625,594	1,305,428
2047	123,507	384,656	36,533	159,500	638,918	1,343,113
2048	128,099	402,002	41,344	158,725	652,750	1,382,920
2049	132,088	417,066	46,652	156,915	663,158	1,415,879
2050	135,976	432,617	52,716	154,916	673,537	1,449,762

Table A7: Total EV sales projections

Year	Total EV cars	Total EV trucks	Total EV sales
2020	267,621	277,897	545,517
2021	282,474	329,681	612,156
2022	319,613	352,650	672,263
2023	337,813	364,062	701,875
2024	362,544	383,943	746,487
2025	391,250	421,844	813,093
2026	420,317	553,458	973,775
2027	448,802	602,810	1,051,612
2028	499,640	632,024	1,131,665
2029	541,383	658,237	1,199,620
2030	596,218	693,779	1,289,996
2031	647,887	732,063	1,379,951
2032	701,348	773,429	1,474,777
2033	758,387	815,866	1,574,253
2034	816,160	860,419	1,676,579
2035	868,116	899,458	1,767,575
2036	917,394	935,880	1,853,274
2037	970,489	974,908	1,945,397
2038	1,028,173	1,016,407	2,044,580
2039	1,075,737	1,052,080	2,127,816
2040	1,128,639	1,090,064	2,218,703
2041	1,181,376	1,124,384	2,305,761
2042	1,230,182	1,160,484	2,390,666
2043	1,269,548	1,189,009	2,458,557
2044	1,311,477	1,221,974	2,533,450
2045	1,358,106	1,264,117	2,622,223
2046	1,409,092	1,305,428	2,714,520
2047	1,457,748	1,343,113	2,800,861
2048	1,504,143	1,382,920	2,887,063
2049	1,539,953	1,415,879	2,955,832
2050	1,574,232	1,449,762	3,023,994

Copper supply

Table A8: Historic GDP per capita growth rate and copper supply to transportation sector

Year	GDP per capita growth (%)	Copper Supply (kt)
2000	3.56	493
2001	2.98	396
2002	0.00	415
2003	0.80	415
2004	1.98	449
2005	2.84	442
2006	2.56	429
2007	1.87	387
2008	0.91	318
2009	-1.08	282
2010	-3.39	348
2011	1.72	371
2012	0.82	415
2013	1.50	444
2014	1.14	446
2015	1.78	448
2016	2.32	450
2017	0.98	484
2018	1.69	514
2019	2.46	492
2020	1.70	473

References

AFDC; U.S. Plug-in Electric Vehicle Sales by Model: https://afdc.energy.gov/data/10567

Brahmst, E. (2006). Copper in end-of-life vehicle recycling. *The Center for Automotive Research, Ann Arbor, Michigan*.

Bushi, L., Skszek, T., & Wagner, D. (2015). Comparative LCA Study of Lightweight Auto Parts of MMLV Mach-I Vehicle as per ISO 14040/44 LCA Standards and CSA Group 2014 LCA Guidance Document for Auto Parts | SpringerLink. *Engineering Solutions for Sustainability*. doi:10.1007/978-3-319-48138-8_19

CDA; Annual data 2020 (Copper Supply and Consumption - 1999-2019); Table 4 https://www.copper.org/resources/market_data/pdfs/annual-data-book-2020_final.pdf

Dai, Q., Kelly, J., & Elgowainy, A. (2016). Vehicle Materials; Material Composition of U.S. Light Duty Vehicles. In: Argonne National Laboratory.

Gohlke, D. & Zhou, Y.; Impacts of Electrification of Light-Duty Vehicles in the United States, 2010-2017; Energy System Division; ANL, 2018

Field, F. R., Wallington, T. J., Everson, M., & Kirchain, R. E. (2017). Strategic Materials in the Automobile: A Comprehensive Assessment of Strategic and Minor Metals Use in Passenger Cars and Light Trucks. *Environmental Science & Technology, 51*(24), 14436-14444. doi:10.1021/acs.est.6b06063

International Copper Study Group. (2018). World Copper Factbook. In: ICSG.

Johnson, Sandra; A Changing Nation: Population Projections Under Alternative Immigration Scenarios. Current population reports; Feb 2020

Statista. (2021). Vehicle sales in the United States 1976-2020. from Mathilde Carlier https://www.statista.com/statistics/199983/us-vehicle-sales-since-1951/

U.S. Census Bureau. (2019). *Table 1; Monthly Population Estimates for the United States: April 1, 2010 to December 1, 2020 (NA-EST2019-01)*.

U.S. Census Bureau. (2019). Monthly Intercensal Resident Population Estimates for the United States: April 1, 2000 to July 1, 2010

U.S. EIA. (2021). Annual Energy Outlook; Table 38. Light-Duty Vehicle Sales by Technology Type. from U.S. Energy Information Administration https://www.eia.gov/outlooks/aeo/data/browser/#/?id=48AEO2021&cases=ref2021&sourcekey=0

Wards Intelligence. (2005). Wards Automotive Yearbook.

World bank; https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=US