Evaluation of the Metals Industry's Position on Recycling and its Implications for Environmental Emissions

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Supporting information is available on the *JIE* Web site

Summary

A healthy debate on the treatment of metals recycling in the life cycle assessment (LCA) community has persisted for more than a decade. While no clear consensus across stakeholder groups has emerged, the metals industry has endorsed a set of recycling "facts" that support a single approach, end-of-life recycling, for evaluating the environmental benefits of metals recycling. In this article we draw from research conducted in several disciplines and find that three key tenets of the metals industry capture the theoretical potential of metals recycling from a metallurgical standpoint rather than reflecting observed behavior. We then discuss the implications of these conclusions on environmental emissions from metals production and recycling. Evidence is provided that, contrary to the position of the metals industry, metals are not necessarily recycled at high rates, are recycled only a small number of times before final disposal, and are sometimes limited in recycling potential by the economics of contaminant removal. The analysis concludes that metal recycled from old scrap largely serves as an imperfect substitute for primary metal. As a result, large-scale displacement of primary production and its associated environmental emissions is currently limited to a few specific instances.

Introduction

Recycling has evolved from what was first a solely economic response to material availability to become synonymous with environmental considerations. Although metals have long been a significant component of recycling, a debate surrounding the appropriate method to account for the environmental benefits in life cycle assessment (LCA) has emerged only relatively recently. The metals industry has formalized its position on the nature and evaluation of recycling in Atherton (2007), entitled "Declaration by the Metals Industry on Recycling Principles." The publication identifies how the characteristics of metals and their recycling practices lead to a single appropriate method for calculating the emissions credits that should be associated with recycling in LCA studies. According to this method—the end-of-life recycling approach—the environmental performance of metals is to be analyzed based on how much metal is recovered at the end of a product's useful life; that is, the fraction that is not recycled must be replaced by primary production. This is in contrast to materials such as paper, plastics, and glass, which may be characterized by their recycled content as materials "that would otherwise be incinerated or landfilled as waste" (Atherton 2007, 59). In the end-of-life recycling allocation method, any metal that is not recycled at the end of life is made up for by consuming primary metal (i.e., metal produced from its mineral form). Ultimately the industry position is that "*metal recycling offsets*

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primary production processes – and their associated environmental impacts and energy consumption" [original emphasis] (Atherton 2007, 59).

In our view the end-of-life recycling allocation method neglects to acknowledge the body of work that directly contradicts its assumptions. Some of this work explicitly describes the frequency and extent of recycling, while other work provides information on the characteristics of metals that determine why and how they are recycled. For instance, Peck (2003) provides a critical discussion of conventional recycling assumptions in an analysis of material cycle closures. The author discusses aluminum recycling in Western Europe and finds that many system complexities lead to significant "myths, simplifications, and complications" (Peck 2003, 3–48) in the commonly held views of recycling.

This article considers the three most widely consumed metals/alloys, that is, iron and steel, aluminum, and copper. By synthesizing existing information on the characteristics of these metals and their recycling systems, the validity of the end-of-life recycling approach advocated by the metals industry is called into question. The analysis is specifically organized around three major assumptions of the metals industry as identified by Atherton (2007). These three assumptions provide a foundation for the end-of-life recycling allocation approach, where the function of primary production is to replace metal that is unrecovered from end-of-life products or is lost during remelting. We address the following points as they apply to iron and steel, aluminum, and copper:

1. Metals from end-of-life products are widely recycled at high rates.
2. Metals can be, and are, recycled over and over again.
3. The constraint to metals recycling is the availability of feedstock material (Atherton 2007, 59).

These three assumptions support the concept that a pool of material exists for each metal, which is manifest in the end-of-life recycling allocation approach. As long as material is present in the pool, it will be recycled; high end-of-life recycling rates (i.e., collection of metal from scrap generators) ensure that material is not lost from the pool; and the ability of metals to be recycled over and over again keep the material pool from degrading. The final section of our analysis addresses the assertion that metals recycling universally offsets (or displaces) primary production. Although the question of offsetting is a complicated issue, sufficient data are available for the U.S. aluminum market to evaluate how well the assertion might hold in a specific circumstance. We analyze the increase in U.S. secondary aluminum production that began in the late 1980s and conclude that in this circumstance increased consumption of secondary aluminum (i.e., aluminum produced from scrap) was associated with demand from an expanding market for automotive components and had little impact on the production of primary aluminum. This observation supports our position that old scrap recycling does not necessarily displace primary metal production.

While the focus of this work is to provide a critique of the metals industry's position as presented by Atherton (2007), it is equally important to reinforce the *theoretical potential* of metals to be recycled in the manner stated by the industry. There is a sound *metallurgical* argument in Atherton (2007) that supports the position that metals recycling could offset primary production in many instances. The inherent properties of metals in general support indefinite recycling, and contaminants can be removed from scrap to yield high-purity metal. However, the realization of this potential has been hindered by the *economic* limitations of current recycling systems.

This work identifies the differences that can exist between the metallurgical, theoretical view of metals recycling and the observed, economics-driven practice. Ultimately metals recycling is framed by metallurgy and determined by economics. Quantitative economic analysis must be called upon to provide a more robust answer to the question of the extent to which recycling offsets primary production.

"Metals from End-of-Life Products are Widely Recycled at High Rates"

In general terms, secondary metals are produced from new and old metal scrap and primary metals are produced from mined mineral ore. New scrap is generated during the production of semifabricated (i.e., metals that are in an intermediate, not fully finished, form) and finished products, and its supply is therefore a function of the overall demand for metal, the product mix, and production technology. New scrap is generally of a known origin, a uniform consistency, and relatively free of contaminants. Due to its relatively homogeneous nature and high quality, nearly all new scrap is understood to be collected for recycling nearly immediately after generation. Old scrap is generated once a product reaches the end of its useful lifetime. Product lifetimes range from less than a year for aluminum beverage cans to decades for building and construction products. Old scrap generally has a more mixed composition and contains more contaminants than new scrap. The economics of old scrap recycling, unlike the majority of new scrap grades, is tied more closely to the ability to remove these contaminants and to recover metal of a suitable quality.

One of the defining characteristics of metals according to Atherton is the maturity of their old scrap recycling markets. In the view of the metals industry, materials other than metals, such as paper products and plastics, lack economically justified postconsumer recycling markets and would otherwise be landfilled or incinerated after their useful lifetime. Conversely, the strong economic incentive to recycle metals has created mature recycling markets and conditions where "metals from end-of-life products are widely recycled at high rates" (Atherton 2007, 59).

Our first question to investigate therefore is how do the old scrap recycling rates of iron and steel, aluminum, and copper compare with a material said to have less economical recycling markets such as paper? We define the old scrap recycling rate as the fraction of metal collected from products that are retired and disposed in a given year, *t*:

$$\textit{Old scrap recycling rate} = \frac{\textit{Metal collected}}{\textit{Old scrap metal retired and disposed}}. \tag{1}$$

While the average recycling rate of municipal paper and paperboard for the United States in 2000–2007 was 48% (U.S. EPA 2008), aluminum and copper are recycled at rates between 30% and approximately 40% (McMillan et al. 2010; Sibley and Butterman 1995; Spatari et al. 2005; Zeltner et al. 1999). Iron and steel recycling rates range from 50% to 73% (Fenton 2004; Müller et al. 2006), which is only slightly higher than municipal paper and paperboard. The rate of copper recycling has been found to be moderately higher in Europe than in the United States. Estimates for Europe range widely from 48% (Bertram et al. 2002) to 67% (Ruhrberg 2006).

The caveat to the recycling statistics referenced above is that they are highly sensitive to the assumed average lifetime for each average product category. For instance, Zeltner and colleagues (1999) utilize scenarios of product mean residence times to estimate that the United States recovered between 31% and 74% of copper from retired and disposed products in 1990; the most realistic scenario yields a rate of 42%. Nonetheless, these studies represent an established methodology for estimating the mass of a specified material that is retired and disposed in a given year. By and large the statistics indicate that metals are not always recycled at high rates. The implication for environmental emissions is that without recycling there is no secondary metal production and no associated environmental benefit, no matter the method of treating recycling in LCA.

"Metals can be, and are, Recycled Over and Over Again"

In principle, metal atoms can stay in use indefinitely, passing from one product to another, and another, and so on, due to their infinite recyclability. However, Atherton's position that metals *are* recycled over and over again is not consistent with analyses of recycling practices. For instance, Markov chain analyses have estimated that copper is used 1.9 times on a global scale (Eckelman and Daigo 2008) and steel is used 2.67 times within the Japanese economy (Matsuno et al. 2007) before ultimate disposal in a landfill or loss to the environment. Wood pulp is estimated to be recycled 2.2 to 3.0 times in the Japanese economy (Hiroyuki et al. 2006)

Although a Markov chain analysis for aluminum has yet to be published, it is likely that the estimated number of uses would be similar to that of steel and copper. The key parameters in the analysis (i.e., new and old scrap recovery rates, product lifetimes, and fraction of consumption by the end-use market) are similar in certain circumstances for the three metals. A sampling of these parameters is included in the supporting information available on the Journal's Web site.

These examples of the Markov chain approach do provide informative characterizations of metals use. However, the examples are subject to certain limitations, most notably their lack of accounting for changes in consumption by the end-use market. For instance, Eckelman and Daigo (2008) rely on consumption characteristics from the year 2000, which have likely evolved to some extent as the end uses of copper have changed. The number of times a given unit of copper is recycled could increase if there were increases in the recycling rate and demand for secondary copper products, but evidence presented in the following section indicates that this has not yet been the case. Taken as a whole, these results provide evidence that current recycling systems fall far short of exploiting the infinite recyclability of metal atoms.

The ramification of this gap is clear for allocating production emissions offsets to primary material production. If metals are recycled only a small number of times before being disposed and ultimately leaving the economy, there remains a need for primary material if market demand for the metal is constant or increasing. This requirement for replacement material limits the degree to which metal recycling displaces the environmental emissions of primary production. As described in the subsequent section, if separate markets exist for products whose material property requirements will allow the use of old scrap (e.g., cast aluminum) and those that will not (e.g., sheet aluminum), the number of times a metal is recycled will have little bearing on whether primary production is displaced or not.

"The Constraint to Metals Recycling is the Availability of Feedstock Material"

Atherton (2007) identifies material availability as the constraint to recycling. While it is also mentioned that material may not be economically recovered at the end of life, the discussion of metals recycling would benefit greatly from a more detailed review of other considerations, particularly the contaminants found in old scrap, that play a critical role in determining if and how metals are recycled. In the following sections we further explore how scrap quality constrains the recycling of aluminum, copper, and iron and steel.

Quality Considerations in the Use of Secondary Aluminum

There are two general forms of finished aluminum products: wrought (i.e., rolled, extruded, or forged) and cast. The requirements of the product system impose constraints on the physical properties of the alloy and, as a consequence, on their chemical composition (metal grade). This can limit the type and amount of scrap that can be utilized for each alloy. However, there is no physical constraint to alloying primary aluminum for both wrought and cast alloys.

Casting alloys generally contain mostly secondary aluminum, though they require some addition of primary aluminum to dilute contaminants to an acceptable level

(Das et al. 2007). Conversely, wrought applications require a different alloy that is designed for higher strength and ductility. Because cast aluminum alloys tend to have 3% or more silicon, they are unsuitable for use in wrought alloys after recycling. Even old scrap that is clean and sorted serves only as a minor input for the production of wrought alloys due to the sensitivity of wrought alloys to impurities (Kevorkijan 2002). The exception to this is the recycling infrastructure that has evolved for the aluminum used beverage can (UBC). Here, UBCs are collected and remelted in a closed-loop system, which directly returns UBCs to make new aluminum cans. The keys to this system are that the UBCs are segregated from contaminating metals and that the wrought alloys used in cans are designed to accommodate direct use of the remelted UBCs.

The divison between the markets for wrought products (made mostly of primary aluminum) and cast products (made mostly of secondary aluminum) is also mentioned in a number of economic analyses of the aluminum industry. In one of the few econometric studies of secondary aluminum, Deadman and Grace (1979) note the separation of the wrought and cast markets and describe the contaminants encountered during recycling as the reason why primary aluminum and secondary alloys are not substitutes. Thirty years later, Blomberg and Söderholm (2009) state that secondary alloys are used mainly for cast products in the Western European market. In the analysis of primary and scrap price ratios, Xiarchos (2006) found that neither new nor old aluminum scrap prices share a long-term relationship with primary aluminum prices over the period 1985–2000. This finding lends support to the view that separate markets exist for products made of mostly primary aluminum and those that are made with mostly scrap.

Quality Considerations in the Use of Secondary Copper

In addition to the categories of "primary" and "secondary," other basic forms of copper can be distinguished. These include unrefined copper, refined copper, and coppery alloys. Unrefined copper refers to intermediate forms that have not undergone electrolytic refining, such as black copper and blister copper; refined copper contains at least either 99.85% copper by weight or 97.5% copper by weight (ICSG 2010); and copper alloys include brass, which is copper alloyed with up to 45% zinc, and bronze, which is copper alloyed with 12% to 16% tin.

It is important to note that refined copper can contain both primary and secondary metal that has been rerefined. Evidence of a long-run relationship between the prices of primary copper and unalloyed old copper scrap is found by Xiarchos (2006). Xiarchos, however, did not examine the relationship between prices of primary copper and alloyed grades of old scrap, which contain a smaller fraction of copper and require complete smelting and converting (Richardson 2000). Ayres and colleagues (2002, 35) state that the castings market is driven by "the supply of secondary copper that cannot be purified sufficiently for use as wire." This separation is born out in data on reported scrap consumption by end user type (e.g., ingot makers, refineries, and brass and wire-rod mills). In 2006 and 2007, U.S. brass and wire-rod mills were responsible for 90% of the new scrap consumption and less than 10% of old scrap consumption, while ingot makers consumed nearly 60% of all old scrap (USGS 2010).

Electrical and electronic applications, which require pure refined copper, have grown to become the predominant end-use market and are responsible for more than 70% of global copper consumption (Henstock 1996). Although old scrap can theoretically be rerefined to meet the requirements of electrical applications, the fraction of total world consumption that is secondary production has fallen from 18% in 1966 to 13% in 2005 (Gómez et al. 2007). These results support the observations of old scrap recycling rates, which indicate that the copper industry recovers barely half of all old scrap that is generated.

Similar to the global industry, the U.S. secondary copper industry has also experienced a decrease in reliance on old scrap: the annual mass of copper in old scrap consumed decreased by 71% between 1990 and 2008 (USGS 2010). While the mass of old scrap consumed has fallen, the mass of new scrap consumed has remained relatively stable. The two trends result in the ratio of old scrap to new scrap consumption plummeting from 80% in 1990–1991 to 45% in 1998 and 22% in 2008 (USGS 2010). Jolly (2000) indicates that this trend is related to increased new scrap collection from increased manufacturing, shuttered old scrap processing capacity, increased old scrap exports, and decreased collection of old scrap. Indeed, the export of old copper scrap increased nearly three-fold between 1990 and 2008 (U.S. ITC 2009).

Although it is possible for old copper scrap to be rerefined for use in high-purity applications, contaminants can still render scrap economically suitable only for copper alloys like brass for valves and bronze for statuary. The large gap between total world stocks and consumption of old copper scrap indicates that recycling this material may be cost prohibitive at current copper prices (Gómez et al. 2007). This economic barrier is likely due to a combination of factors, such as products containing low concentrations of copper, or a recycling infrastructure that is insufficiently developed to recover high-quality copper. Unlike aluminum, where old scrap recycling is largely constrained by the differences between wrought and cast alloys, the limits to old copper recycling appear to be the difficulties of economically recovering copper from existing stocks.

Quality Considerations in the Use of Secondary Iron and Steel

The use of secondary metal in the production of steel is also subject to quality considerations, although it is less of a constraint than in the case of copper and much less of a constraint in the case of aluminum. The current basic oxygen furnace (BOF) process produces primary steel and is limited to a scrap input of 30% because of the need to maintain thermal balance in the process. On the other hand, steel produced by the electric arc furnace (EAF) route can be sourced from 100% scrap (Fenton 2004), as well as direct reduced iron and pig iron. EAF steel can be tailored to many applications, but BOF steel is mostly used for rolled products. The use of scrap iron and steel will not be universal as long as high scrap content EAF steel is unable to meet material property requirements for certain products, such as automotive body panels and packaging.

Due to the different scrap tolerances in BOF and EAF steel, it is not appropriate to follow Atherton (2007) and assume that, by default, the recycling of any given mass of steel offsets emissions from the BOF process. A more appropriate approach would be to first note what type of steel is used in a product (e.g., BOF cold rolled sheet) and use an emissions intensity that is calculated based on measured life cycle emissions for that type of steel. This would avoid assumptions of how iron and steel scrap is recovered and utilized decades into the future when the product is eventually retired and disposed.

"Metal Recycling Offsets Primary Production Processes"

Here we evaluate the ability of secondary aluminum to offset primary production. Since it was first commercially produced, aluminum has experienced its greatest increases in consumption when new product applications have emerged. McMillan and colleagues (2010) identify a distinct period from 1986 to 2006 where aluminum consumption rapidly increased. Their article also estimates in-use stocks of aluminum following a logistic growth trend. During this period, non-UBC old scrap consumption also experienced significant growth. UBC scrap is not included because beverage cans largely constitute a closed-loop system. Figure 1 depicts this growth in old scrap consumption relative to the growth in U.S. aluminum producer net shipments less shipments of aluminum for cans. Producer net shipments data provide a measure of industry output to markets and are calculated as the U.S. gross shipments minus intra-industry shipments between producers (Aluminum Association 2008).

We contend that increased non-UBC old scrap and secondary aluminum consumption experienced during the period from 1986 to 2006 was associated with large-scale adoption of cast aluminum components in cars and light trucks and had little association with the production of primary aluminum. Additionally the decrease in old scrap consumption experienced after 1993 was compensated by increased new scrap recovery and increased imports of alloyed aluminum, not additional production of primary aluminum. These observations and conclusions are consistent with the limited substitutability of aluminum produced for castings, which contain mostly secondary aluminum, and aluminum produced for wrought products.

Analyzing the trends of the U.S. aluminum market provides the foundation for a quantitative economic analysis of the interactions between the primary and secondary aluminum markets. This is the type of analysis that is necessary to quantify the extent to which aluminum recycling displaces primary production. Even though the examination of market trends presented here is qualitative in nature, it nonetheless draws important conclusions about how the economics of aluminum recycling determine how secondary material is supplied and consumed. The market trends illustrate how non-UBC old scrap supply and demand bear little association to the consumption of primary aluminum. This adds support to the argument that metals recycling does not displace primary production except in some circumstances. The recommendation that a quantitative economic analysis be developed in the future is discussed in the conclusion.

Our evaluation encompasses the U.S. market system, including international trade flows. The inclusion of international trade data captures some of the influence of aluminum markets in countries other than the United States and is a sufficient addition for the purpose of the analysis presented in this article, given its largely qualitative nature. Extending the system boundaries of the analysis to include the fate of

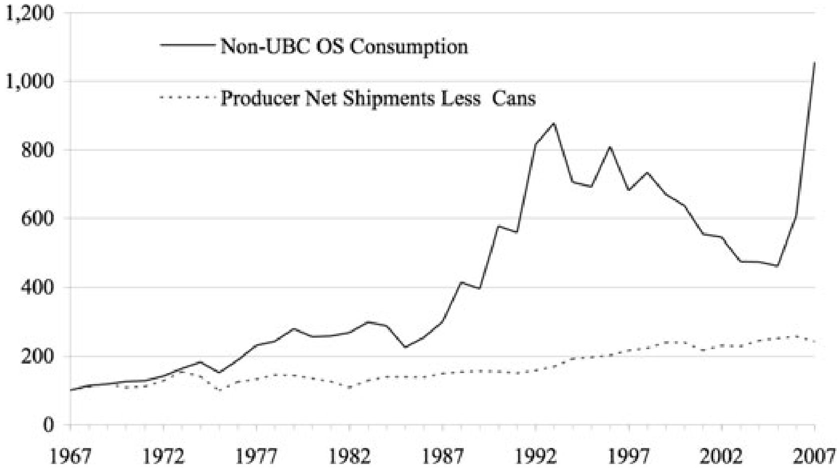

Figure 1 Growth of aluminum old scrap (OS) consumption excluding used beverage containers (UBC; USGS 2009) and producer net shipments less cans (Aluminum Association 2008), rebased (1967 = 100).

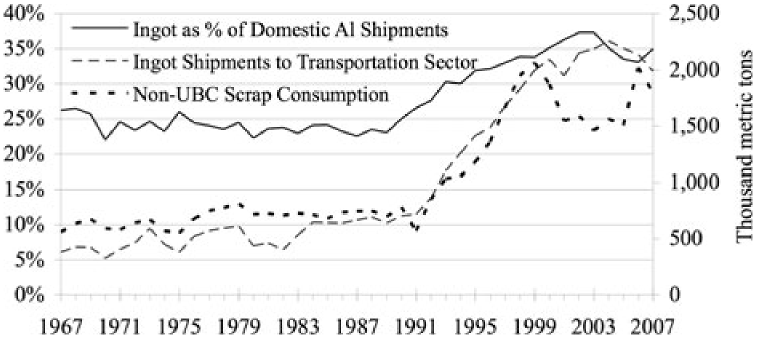

Figure 2 Ingot producer net shipments to the transportation sector, producer net shipments of ingot as a percentage of producer net shipments (excluding exports and shipments to cans; Aluminum Association 2008), and total scrap consumption (less UBCs) by secondary smelters (USGS 2009). Al = aluminum. One metric ton (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons.

aluminum after it is exported to a foreign country is greatly constrained by the availability of detailed, public aluminum production and consumption data.

UBC scrap (approximately 60% of total old scrap consumption during the same period [USGS 2009]) is excluded from the analysis due to the closed-loop recycling system of aluminum beverage cans and the separate market for UBCs. This closed-loop system represents an instance where economics, infrastructure, and technology have evolved to enable metal recycling to offset primary production.

Old Scrap Demand Derived from Secondary Ingot Consumption

Because old scrap is an input for the production of secondary alloys, old scrap demand is derived from the consumption of aluminum products manufactured from secondary alloys, namely cast products such as automotive engine blocks and transmission housings. An indication of this association is the short-run elasticity for secondary alloy demand with respect to automotive production, which was calculated as 0.52 by Blomberg and Hellmer (2000). This indicates that a 0.52% increase in secondary alloy demand is associated with a 1% increase in auto production.

Cast aluminum was first widely used in the transportation sector in the years leading up to the Great Depression, and in the 1920s the U.S. automotive industry consumed more than half of primary and secondary production (Wallace 1937). This trend was short-lived and use in automobiles plummeted during the 1930s. Renewed interest in automotive applications did not reemerge until the oil shocks of the 1970s (Schatzberg 2003), and it took another decade before significant and widespread use of aluminum components began.

Collection and consumption of old scrap stagnates without demand from markets that can cost-effectively utilize old scrap to meet product material property requirements. It is difficult to imagine with today's sophisticated automobile recycling infrastructure that not long ago the United States suffered from what was called the "junk automobile problem" (Adams 1973). In the mid-1960s automotive hulks began accumulating in auto wreckers' yards due to the contemporaneous factors of surging vehicle sales and retirement, and the transition from open-hearth to BOF steelmaking (Adams 1973). The BOF process utilizes less scrap than the open-hearth process and, as an additional impediment to recycling, no. 2 bundles of ferrous metals formed from vehicles were low-quality scrap due to contamination by nonmetallic materials and nonferrous metals. Recycling the large stock of vehicle hulks did not occur until later in the decade with widespread use of the hammermill auto shredder, which enabled separation of metallic and nonmetallic fractions, and the emergence of EAF steelmaking, which can utilize 100% scrap (Adams 1973).

Returning to the U.S. aluminum market, figure 2 depicts the growth of producer shipments of aluminum ingot (i.e., a standard, cast form that is later processed) for transportation and of total scrap consumption (less UBCs) by secondary smelters. The association between these two data sets supports our points that scrap consumption is economically driven and it is derived from demand for products that utilize scrap as an input, such as aluminum ingot for castings in the transportation sector. For the period 1970–1990, ingot shipments maintained a stable fraction of domestic aluminum shipments at 25%. As the design of cars and light trucks once again incorporated cast aluminum components, the demand for secondary aluminum increased markedly.

The typical view of scrap consumers is that secondary smelters (also known as "refiners") consume mostly old scrap to produce castings and integrated producers, refiners, and fabricators consume new scrap to produce wrought products (Blomberg and Hellmer 2000). What is readily apparent from the figure is that the ingot net shipments for cars and light trucks are closely correlated to scrap consumption by secondary smelters. Quantifying the Pearson correlations (ρ) for the period shows a value of 0.81 (95% confidence interval [CI] $0.67 \leq \rho \leq 0.89$) for car and light truck net shipments of ingot and scrap consumption by secondary smelters.

Increased Recovery and Consumption of New Aluminum Scrap

In the mid-1990s, secondary smelters were faced with a shrinking consumption of non-UBC old scrap even as production of ingot for transportation markets increased. Evaluating data on new scrap generation and consumption reveals that these consumers turned to new scrap as an alternate source of material. The consumption of new scrap and non-UBC old scrap by secondary smelters is shown in figure 3, which indicates that new scrap grew to become an important source of input material during the time that ingot shipments for transportation were rapidly increasing. Secondary smelters' share of total new scrap consumption was in a general decline from 1960 to 1991, falling from 76% to 25%. However, the share increased to 59% by 1999 and remained around 55% through 2007. The reversal of this trend corresponds to the same period when ingot net shipments to the transportation sector rapidly increased.

The large increase in new scrap consumption by secondary smelters that began in 1992 was accompanied by an increase in the total amount of new scrap consumed in the United States. The general assumption regarding the generation and consumption of new scrap is that it closely follows the total amount of aluminum used in an economy. Until the early 1990s, secondary recovery from new scrap was associated with apparent consumption (i.e., the sum of production, net imports, and stock changes). From 1946 to 1993 the Pearson correlation coefficient of the two series is 0.99 (95% CI $0.98 \leq \rho \leq 0.99$). In the mid-1990s this relationship changed and growth in new scrap consumption vastly outpaced that of net shipments and apparent consumption. From 1994 to 2007 the correlation coefficient was –0.19 (95% CI $-0.65 \leq \rho \leq 0.38$).

Much of the increase in new scrap is the result of improved recovery from dross and skimmings. In 1990 approximately 6% of total aluminum new scrap consumed was recovered from dross and skimmings; by 1995 recovery had increased to 12% of total new scrap consumed (USGS 2009). Based on their increasing share of new scrap consumption, it appears that secondary smelters were largely the recipients of the increased new scrap supply.

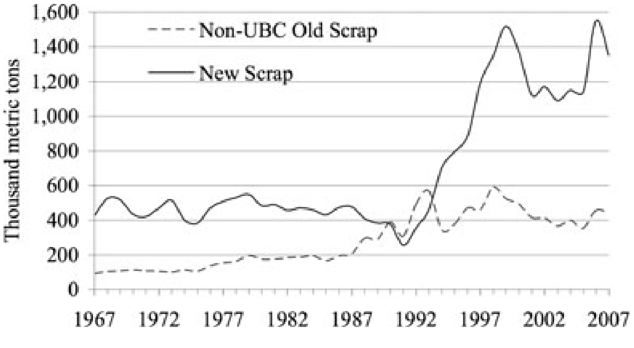

Figure 3 Secondary smelter consumption of aluminum new scrap and non-UBC aluminum old scrap (USGS 2009).

Evaluating the Offset of Primary Aluminum

Estimates of the total primary and secondary aluminum consumed in the United States can be generated by incorporating trade data on unwrought alloyed and unalloyed aluminum with existing data on scrap consumption and primary production. This section essentially takes a mass balance approach in its estimation of total consumption; however, the goal is not to develop a detailed accounting of all aluminum mass flows. Instead, the goal is to provide a foundation for future quantitative economic analysis by exploring the underlying trends of secondary and primary consumption in light of the contemporaneous trends for old scrap consumption and new scrap consumption examined in the previous two sections.

The analysis of these data shows that even with the increased recovery of new scrap, U.S. consumption of new scrap and non-UBC old scrap decreased from 1999 to 2003. However, producer net shipments of aluminum to the automotive market continued to increase. These producer net shipments likely came from imports of alloyed ingot from abroad, although it is not possible to disaggregate trade data in a way to quantify or classify these imports. This analysis supports the position that the demand for products that predominantly utilize secondary aluminum has little effect on the production and consumption of primary aluminum.

Although it is not possible to know the fraction of primary and secondary alloys in the net trade of unwrought aluminum alloys, we assume that 100% of these unwrought alloys are consumed for castings. This assumption is made to evaluate whether or not a large increase in consumption of aluminum for castings is associated with any change in the consumption of primary material for wrought products. Estimates of total primary consumption are then obtained as the sum of domestic primary production, net imports of unalloyed aluminum, and imports of semi-fabricated products. Total secondary consumption is estimated by the sum of the net trade of unwrought alloys and total old scrap consumption.

Even using the upper bound estimate that 100% of the net trade of unwrought alloyed ingots is consumed for castings, the estimated total consumption of primary and secondary aluminum follows the general movement of producer net shipments of mill products and ingots, respectively. Figure 4 does not reveal an association of primary consumption with the large increase in secondary consumption in the early 1990s. Estimated production of secondary aluminum more than tripled between 1991 and 1999, yet there is little evidence from a graphical analysis that this rapid increase had much, if any, association with primary consumption. More likely both primary and secondary consumption were responding to demand in their respective markets and little, if any, displacement of primary production occurred.

Conclusion

The purpose of this analysis is to establish that the basic tenets articulated by Atherton (2007) reflect the metallurgical

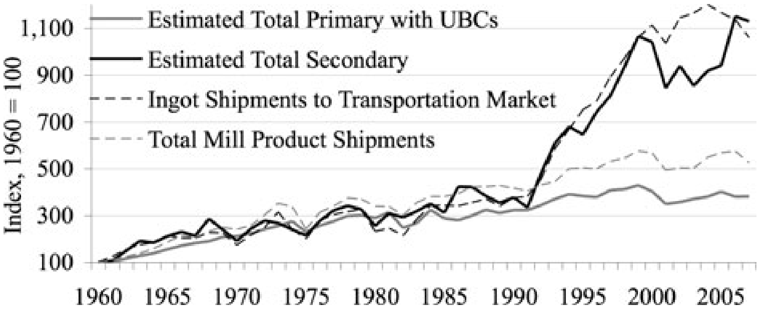

Figure 4 Index of estimated consumption of primary and secondary aluminum, rebased (1960 = 100).

potential of metals recycling and not the economic realities of current practice. The claims that (1) metals are widely recycled at high rates, (2) metals are recycled over again, and (3) the constraint to metals recycling is strictly the availability of feedstock material serve as the foundation for the metal industry's position that recycling displaces primary production, and therefore reduces the net effect of environmental emissions from metals production processes. The complex and dynamic behavior of metals recycling precludes its distillation to a set of universal "facts," and the blanket statement that recycling displaces primary production ignores the effects of the economics of removing contamination accumulated during recycling and the different tolerances for contamination across alloys. Rather than generalizing the behavior of metals, we recommend that the metals industry revise its stance to acknowledge the complexities of recycling and take a more nuanced view of the unique characteristics of individual metals and their recycling systems, such as discussed by Dubreuil and colleagues (2010).

This article has identified evidence that iron and steel, aluminum, and copper are not necessarily recycled at high rates and that significant constraints on use of scrap exist. The article has also provided evidence that the consumption of secondary aluminum, while beneficial in terms of nonrenewable resource conservation and reduced emissions, is currently limited in its ability to offset primary production and its environmental emissions outside of the aluminum beverage can system. The combination of modest recycling rates (similar to municipal paper and paperboard products), the sustained demand for metal-containing products, and the likelihood that metals are recycled only a small number of times before ultimate disposal indicate the inevitability of primary metal production and associated emissions. Old scrap recycling has a particularly limited ability to offset emissions from primary aluminum due to the contamination limits of wrought products.

The graphical analysis of aluminum market trends was performed only for the United States, although interactions with foreign markets were captured to some extent by the inclusion of international trade data. Performing the same analysis for other markets may reveal different trends in aluminum production and consumption, but similar conclusions are likely to be reached regarding primary production displacement as long as the economics governing old scrap consumption are comparable. Discussion by Blomberg and Hellmer (2000), Blomberg and Söderholm (2009), and Peck (2003) indicates that Western Europe shares similarities with the U.S. market.

The question of to what extent metals recycling displaces primary production is best answered by quantitative economic analysis. In economic terms, this question becomes an exercise in quantifying the substitution between old scrap and primary metal. This type of analysis is beyond the scope of this article, but it would involve first determining the appropriate production function for each type of metal/alloy (e.g., cast aluminum, wrought aluminum, refined copper, copper alloy, BOF steel, and EAF steel) and then econometrically estimating the associated substitution between old scrap and primary metal. An alternate approach would be to develop an econometric model of the market for each type of metal/alloy and estimate cross-price elasticity of demand (i.e., the percentage change in demand of good *x* associated with a 1% change in the price of good *y*).

While we find it necessary to identify the disparities between the views of the metals industry and the current economic realities of recycling systems, we fully recognize the theoretical potential of metals recycling from a metallurgical standpoint. Indefinite recycling of secondary metal could occur if detrimental contaminants were not accumulated through successive recycling or could be cost-effectively removed or diluted, or if alloys were without tolerances for contaminants. Scrap contamination and variation in alloy tolerances have implications for the economics of scrap recycling. No matter the metallurgical possibilities of metals recycling, there will be little, if any, demand for scrap sources that are uneconomic to recycle.

Many opportunities have already been identified for increasing metals recycling. The ability to minimize contamination is especially important for aluminum, but less so for copper. For aluminum, studies have identified means of negating the impact of scrap contaminants and increasing the use of secondary aluminum, such as the development of recycling-friendly alloys (Das 2006; Das et al. 2007; Gaustad et al. 2010; Gesing and Wolanski 2001; Li et al. 2011) and improved scrap-sorting technology (Gesing 2004; Gesing and Wolanski 2001). For copper, large technological improvements are possible over existing methods of recycling electronic waste that increase metal recovery as well as reduce process emissions (Hagelüken 2006). Ilgin and Gupta (2010) have provided a review of many product design and manufacturing strategies for increasing and improving recycling. Improvements in infrastructure systems for segregation of metals and greater participation rates in recycling programs would certainly move the current state of recycling much closer to what the metals industry has envisaged in the work of Atherton (2007).

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Supporting Information

Additional supporting information may be found in the online version of this article.

Supporting Information S1: This supporting information contains comparisons of factors relating to Markov chain analysis (appendix S1) and backing data for figures and analyses from the main text (appendix S2).