Ferrous Scrap's Role in Decarbonizing Steel:

Assessing Steel Product Lifespans

Prepared for:
Steel Manufacturers Association

Prepared by:
Thomas Brady
Roderick Eggert

May 3, 2023

Dr. Thomas Brady is Executive Director of the J.P. Morgan Center for Commodities & Energy Management at the University of Colorado, Denver.

Dr. Roderick Eggert is Professor of Economics and Business at Colorado School of Mines and holds the Viola Vestal Coulter Foundation Chair in Mineral Economics.

This analysis represents their personal views. It was prepared outside of their university duties and does not reflect a viewpoint of their institutions.

TABLE OF CONTENTS

Introduction and Summary

Decarbonizing steel production is a critically important priority given that greenhouse gas emissions from iron and steel production represent approximately eight percent of global emissions.[1] Decarbonizing the global steel industry will require several significant and interrelated developments. These include greening electric grids through the greater use of solar, wind, and other renewable energies as well as developing and adopting other new technologies, such as direct reduced iron using green hydrogen power and carbon capture, utilization and storage.

Ferrous (*i.e.*, iron and steel) scrap will also play a key role in the decarbonization of the global steel industry, which has an important opportunity to make greater use of ferrous scrap in steel production. Compared to traditional ore-based manufacturing processes, steel production based on recycled scrap emits far lower greenhouse gas emissions.[2] In the United States, scrap-based electric arc furnace production, which accounts for 70 percent of domestic production, emits 78 percent less emissions per ton of steel produced than ore-based blast furnaces.[3]

Some analysts have argued that the global availability of ferrous scrap limits the role it can play in decarbonizing steel production.[4] While we agree that post-consumer scrap may not be able to supply *all* ferrous input material, we believe it is better to focus on what percentage of steel production could be scrap-based. This percentage depends importantly on three fundamental considerations: the rate of steel-demand growth, the average lifespan of steel products, and recycling rates. There is considerable uncertainty about all three considerations and, in turn, any estimate of future global scrap availability. Thus, it is imperative that better scenarios of global scrap supply be developed, based on deeper understanding of these fundamental considerations, as well as how economic considerations and public policy influence scrap availability and use. Better scenarios are essential to informing sound decision making by companies and governments.

As noted above, a key element of assessing ferrous scrap availability is the lifespan of steel products. Many estimates of global scrap availability assume that the average lifetime of a steel-

---

[1] Christian Hoffman, Michel Van Hoey, & Benedikt Zeumer, *Decarbonization challenge for steel*, McKinsey & Company (June 3, 2020), available at https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel#/.

[2] *See* Ali Hasanbeigi, *Steel Climate Impact - An International Benchmarking of Energy and CO_2 Intensities*, Global Efficiency Intelligence (Apr. 2022) at 16, 19, available at https://www.globalefficiencyintel.com/steel-climate-impact-international-benchmarking-energy-co2-intensities.

[3] CRU, *Emissions Analysis Executive Summary* (June 14, 2022) at 6-7, available at https://steelnet.org/steelmaking-emissions-report-2022/.

[4] *See, e.g.*, ResponsibleSteel, *The 'Sliding Scale': Setting Equitable Thresholds to Drive Global Steel Decarbonisation* (Dec. 9, 2022), available at https://www.responsiblesteel.org/news/the-sliding-scale-setting-equitable-thresholds-to-drive-global-steel-decarbonisation/; International Energy Agency, *Achieving Net Zero Heavy Industry Sectors in G7 Members* (May 2022) at 72, available at https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members; World Economic Forum, *What is steel scrap and how can it help us reach net zero?* (Jan. 17, 2023), available at https://www.weforum.org/agenda/2023/01/davos23-steel-scrap-decarbonization/; ArcelorMittal, *By-products, scrap and the circular economy* (accessed Mar. 23, 2023), available at https://corporate.arcelormittal.com/sustainability/by-products-scrap-and-the-circular-economy.

containing product is approximately 40 years.[5] Such estimates appear to be based on (a) industry and academic judgments on average lifespans in major end-use categories (such as vehicles, infrastructure and appliances) and (b) estimates of the allocation of overall steel use among end-use categories, historically and in the future. Many of the reviewed studies are also dated and may not fully account for modern scrap collection and recycling systems.

As described below, our original calculations of product lifespans in key scrap-producing countries suggest that lifespans may be lower, in the range between 25 and 35 years, with an estimated average of approximately 30 years.

The rest of this section reviews the three primary types of ferrous scrap, which is important to understanding the data and analyses in the rest of the document. It then summarizes the key findings of this study. The remainder of the paper then proceeds in three parts. First, it presents an illustrative model, demonstrating that steel product lifetimes play a key role in determining the degree to which scrap and scrap-based production processes can meet global steel demand (Section 1). Second, it reviews the academic literature on the lifespans of steel-containing products (Section 2), as well as its limitations. Third, it presents original estimates of product lifetimes for important steel-producing nations derived from historical data on ferrous scrap use and apparent steel consumption (Section 3).

Types of Ferrous Scrap

Ferrous scrap comes in three basic forms. First, *home* scrap is created during iron and steel production and is most typically re-used within the plant that created it. Essentially all home scrap is recycled soon after it is created, and thus there is little room to increase use of home scrap.

Second, *prompt* scrap is production and manufacturing scrap that enters the market and is sold back to iron and steel mills for use as ferrous inputs to production. There are several subcategories of prompt scrap, including prompt industrial scrap—created as raw steel is transformed into intermediate and final products—and prompt construction scrap—which is created as steel products are trimmed and fitted at construction sites.

The ability to increase the use of prompt scrap depends heavily on the market. In mature steel production and consumption markets, with robust scrap collection and recycling systems in place, there is relatively little room to increase the utilization of prompt scrap – as most of this scrap already is recycled soon after it is created. However, especially in developing countries that continue to grow their industrial base, the infrastructure and economic incentives to collect and process prompt scrap efficiently will grow, which will likely increase the recycling of this type of scrap. This is especially so because the pursuit of decarbonization will more strongly incentivize scrap-based production.

Third, *obsolete* scrap is contained in end-of-life products. There is considerable room to increase utilization of obsolete scrap in iron and steel production, as not all obsolete scrap is actually recycled. The remainder of this study focuses primarily on obsolete scrap because, over the long-term, the increased availability of obsolete scrap has the potential to significantly

---

[5] *See, e.g.*, Simon Nicholas and Soroush Basirat, *New from Old: The Global Potential for More Scrap Steel Recycling*, Instituted for Energy Economics and Financial Analysis (Dec. 2021) at 9; World Steel Association, *Scrap use in the steel industry* (May 2021) at 2.

contribute to ferrous scrap being able to meet global steel production demand. In this respect, an analysis based on obsolete scrap is a conservative approximation of global scrap availability, and the key findings of this study will only be strengthened as global prompt scrap collection systems are bolstered.

Key Findings

First, our illustrative model demonstrates that average steel product lifetime is a key determinant of the extent to which obsolete scrap can satisfy the demand for global steel production (Section 1). As shown below, obsolete scrap satisfies between 26 and 78 percent of 2050 global steel production demand for ferrous inputs, depending on the average lifetime of a steel-containing product (between 25 and 40 years), as well as the average annual growth rate in world steel production and consumption (between 0.6 and 1.2 percent) and scrap recycling rates (between 50 and 90 percent). Shorter average product lifetimes, coupled with lower rates of steel demand growth and higher recycling rates, implies a higher percentage of overall steel production demand that may be satisfied with obsolete or post-consumer scrap (and vice versa).

Second, our review of the academic literature finds existing estimates of steel product lifespans ranging from approximately 25 years to 60 years (Section 2). The crude average of these estimates is approximately 40 years. However, much of this literature fails to provide adequate supporting details on steel product lifetimes, and further study is required. Crude average estimates also obscure differences among countries, changes over time, and distributions of product lifespan around an average (some products become obsolete sooner and others later than the average). In this context, relying on a crude estimate of average lifespans in assessing scrap supply is not only likely to be inaccurate, but it will also result in significant variation in estimates of scrap availability for steelmaking.

Third, our original estimates in nine of the largest steel-producing countries indicate that average lifespans in all countries may be less than 40 years and as low as 25 years (Section 3). A simple average, weighted by raw steel production of these countries, results in a global product lifespan of about 30 years.[6] Of course, these estimates are subject to uncertainty and debate.[7] However, the significant difference between these estimates and the 40-year lifespan frequently cited calls into question the prior estimates of product lifetimes. Moreover, as detailed below, further research on global ferrous scrap availability and steel product lifetimes will be especially vital as the Chinese steel market matures and global scrap availability increases, driven by the aging of Chinese steel products. In particular, there will be significant and unprecedented flows of scrap from China entering global supply well before 2050 that must be properly considered.

In short, we should question modelling that downplays scrap availability and minimizes the role of scrap as a reason to support the continuation of high-emitting ore-based steelmaking. While scrap may not be able to supply all of the ferrous input required for steel production, more relevant for informed decision making in the private and public sectors is developing better estimates of how large scrap's role could be in the future. Steel product lifetimes, in turn, are a

---

[6] To approximate global lifespans of steel products, we calculated a weighted average lifespan where China's lifespan comprises 50 percent and the remaining 50 percent is based on a weighted average of 2022 raw steel production volume of the other eight countries in the analysis.

[7] The uncertainties are greatest in the emerging steel producing and consuming countries.

fundamental element of any estimate of global scrap availability and scrap’s ability to satisfy demands for ferrous inputs to steel production.

SECTION 1: An Illustrative Model

To illustrate the role that steel product lifetimes play in determining ferrous scrap's share of global steel production, this section develops estimates of obsolete scrap's production share between 2025 and 2050. These are not projections or forecasts. Rather, they are based on a number of assumptions and show the sensitivity of scrap shares to steel product lifetimes, as well as scrap recycling rates and steel demand growth rates.

The model considers (1) the pool of available obsolete scrap multiplied by (2) the recycling rate (*i.e.*, the percent of potentially available scrap that is actually recycled) relative to (3) total production in that year. In turn, the pool of available obsolete scrap reflects the amount of steel in end-use products manufactured L years ago, where L is the average lifetime of a steel-containing product.[8]

More formally:

$$\text{Scrap Share}_t \text{ (in percent)} = [(\text{Recycling Rate}_t \times \text{Production}_{t-L})/(\text{Production}_t)] \times 100$$

Where:

Scrap Share_t = obsolete scrap's percent share of raw steel production in year t
Recycling Rate_t = the percent of available obsolete scrap that is recycled in year t
Production_t = raw steel production in year t
Production_{t-L} = the quantity of obsolete scrap that becomes available for recycling in year t, which equals production L years ago where L = the average product lifetime

This model is a simplified view of the future in that it ignores economic considerations and does not account for public policies that might encourage or discourage recycling. We note that as governments pursue policies to decarbonize and improve scrap collection systems, the economic incentives to collect and process scrap will likely increase substantially, resulting in higher obsolete scrap capture. The model also does not include differences among countries and changes over time in recycling rates and product lifetimes, which can be significant.

We estimate obsolete scrap's contribution to steel production under the following conditions:

- Average steel-product lifetimes of 25, 30, 35, and 40 years, reflecting the range in values discussed later in this report (Sections 2 and 3).
- Recycling rates of 50 percent and 90 percent. Fifty percent is an estimated baseline for developed economies today. Ninety percent is at the upper end of the aspirational target of 88-90 percent stated by the International Energy Agency (IEA) in a 2020 report.[9]

---

[8] There also is obsolete scrap that became available in the past but was not recycled. This unrecycled, obsolete scrap typically has relatively high costs of recycling and was not profitable to recycle at prices prevailing when it became available. When prices rise, some this previously unrecycled scrap is recycled. But for purposes of this simple model, we ignore pre-existing stocks of obsolete scrap and use raw-steel production in the past as a proxy for the amount of steel in products that reach the end of their useful lives in a given year. In this respect, the model conservatively estimates global scrap supply.

[9] International Energy Agency, *Iron and Steel Technology Roadmap – Towards more sustainable steelmaking* (Oct. 2020) at 12, available at https://www.iea.org/reports/iron-and-steel-technology-

- Annual growth in world steel production and consumption of 0.6 and 1.2 percent between 2020 and 2050. Based on a recent presentation at the Organisation for Economic Cooperation and Development, CRU projects 0.6 percent annual growth in global steel demand through 2050.[10] The IEA has also projected 0.6 percent and 1.2 percent annual growth in global steel demand through 2050 based on two different demand scenarios. First, under the IEA Stated Policies Scenario, which assumes current demand trajectories based on existing and announced policies, the IEA projects 2050 global steel demand of approximately 2.5 billion metric tons.[11] Second, under the IEA Sustainable Development Scenario, which assumes that policies are implemented to achieve net zero steel emissions by 2050, the IEA projects 2050 global steel demand of approximately 2.1 billion metric tons.[12] Using CRU's reported 2020 demand of 1.74 billion metric tons, we estimate an annual demand growth rate of 1.2 percent under the Stated Policies Scenario and of 0.6 percent under the Sustainable Development Scenario. In light of the fact that CRU and the IEA's Sustainable Development Scenario have nearly identical growth rates of 0.6 percent, we present this as our base case scenario but also provide the calculations using the 1.2 percent scenario.
- Historical estimates of world raw steel production for 1982 to 2021 are from the World Steel Association.[13]

Tables 1 and 2 summarize the results for 2050. They illustrate how product lifetimes, recycling rates, and demand growth rates influence ferrous scrap's share of global steel production. For example, a global scenario with annual demand growth of 0.6 percent, average product lifetime of 25 years and a recycling rate of 50 percent suggests that 43 percent of global raw steel production could be met through recycling by 2050 (and 78 percent if recycling rates climb to 90 percent) (Table 1). Of note, in all scenarios, the difference between a 40-year lifetime and a 25-year lifetime is more than ten percentage points.

---

roadmap. In the Stated Polices Scenario and Sustainable Development Scenario discussed below, the IEA estimates scrap collection of 88 percent and 90 percent, respectively. *Id.* at 63.

[10] *See* CRU, *Discussion on long term steel demand*, OECD WP6 / Steel Committee Workshop (Mar. 13, 2023) at 6.

[11] International Energy Agency, *Iron and Steel Technology Roadmap – Towards more sustainable steelmaking* (Oct. 2020) at 55, 59 available at https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[12] International Energy Agency, *Iron and Steel Technology Roadmap – Towards more sustainable steelmaking* (Oct. 2020) at 55-56, 59 available at https://www.iea.org/reports/iron-and-steel-technology-roadmap. The IEA also envisions a faster innovation scenario, where emissions reductions are achieved more rapidly.

[13] World Steel Association (2023).

Table 1. Percentage Share of Recycled Obsolete Scrap in Raw Steel Production, 2050, for Different Recycling Rates and Average Product Lifetimes

Rate of Final Demand Growth = 0.6% per annum

	Recycling Rate	
	50 percent	90 percent
25-year lifetime	43	78
30-year lifetime	40	73
35-year lifetime	35	63
40-year lifetime	31	55

Source: Author calculations.

Table 2. Percentage Share of Recycled Obsolete Scrap in Raw Steel Production, 2050, for Different Recycling Rates and Average Product Lifetimes

Rate of Final Demand Growth = 1.2% per annum

	Recycling Rate	
	50 percent	90 percent
25-year lifetime	37	67
30-year lifetime	34	61
35-year lifetime	29	53
40-year lifetime	26	47

Source: Author calculations.

Under a variety of scenarios, the data show that average product lifetimes will play a vital role in determining scrap's share of global steel production and that scrap-based production will supply a significant portion of global demand. At the very least, recognizing the role of ferrous scrap and accurately estimating global scrap availability will be key to decarbonization efforts.

Moreover, further developing our understanding of differences among countries in recycling rates and product lifespans will be important, especially for China and how it compares with other countries. As detailed below in Section 3, our model suggests that Chinese product lifespans may be as low as 25 years – significantly lower than the 40-year assumption underlying many global scrap supply calculations. This is important because Chinese steel production has increased rapidly in recent decades, rising from 222 million metric tons in 2001 to 1,035 million metric tons in 2022.[14] In fact, in every year since 2009, China has comprised at least 45 percent of global steel production, reaching 57 percent in 2020.[15] Given this dramatic rise in Chinese production, many analysts and also the Chinese government project a substantial increase in Chinese scrap availability, which will significantly affect global scrap supply.[16] This is especially true from 2030 onwards as the massive quantity of steel produced in China each year reaches the end of its lifespan and begins to add to the global scrap supply.

---

[14] World Steel Association (2023).

[15] World Steel Association (2023).

[16] China's National Development and Reform Commission (NDRC) approximates Chinese steel scrap use of 320 million tons by 2025. NDRC, *14th Five-Year Circular Economy Development Plan* (July 2021). China's Metallurgical Industry Planning and Research Institute similarly expects Chinese scrap generation to rise to more than 340 million metric tons by 2025, representing a 31 percent increase from 2020. Platts, *China's steel scrap imports in 2023 may not breach 1 mil mt mark: sources*, Hellenic

Having established that steel product lifespans are a key factor in determining the extent to which scrap-based steel production will be able to supply global steel demand in the coming decades, we examine in the following sections the available information for actual product lifetimes for steel-containing products. In particular, Section 2 provides a review of the previous academic literature, and Section 3 contains original estimates of product lifetimes.

Shipping News (Mar. 27, 2023). The Chinese Society for Metals has estimated that China's steel scrap availability will increase further to 380 million metric tons by 2030. *Id.* These forecasts represent far greater Chinese scrap availability than other estimations, such as World Steel Association's projection of 305 million tons of Chinese steel scrap use by 2030, that are relied on in other scrap availability calculations. World Steel Association, *Is it time for China to switch to electric arc furnace steelmaking?* (Feb. 13, 2018).

SECTION 2: Inferences from Review of Academic Literature

Steel product lifespans play a crucial role in determining global scrap availability and, thus, informing potential decarbonization pathways. As illustrated in the Appendix, the existing academic literature provides a wide range of estimated steel product lifespans with a simple average of approximately 40 years. Unfortunately, there is a lack of supporting detail on the basis for estimates of steel end-use product lifespans. In many instances authors reference previously published studies that, in turn, lack details underlying the assumptions used. As noted in the Introduction, most of these estimates appear to be based on (a) industry and academic judgments on average lifespans in major end-use categories (such as vehicles, infrastructure and appliances) and (b) estimates of the allocation of overall steel use among end-use categories, historically and in the future. Further, many of the reviewed studies are dated.

Thus, any reliance on a 40-year estimate without additional testing may be flawed. Therefore, it will be important that further studies continue to build on the previous published literature, especially as scrap collection and recycling systems are developed globally and steel decarbonization policies are pursued.

SECTION 3: Average Lifespans Implied from Data on Apparent Steel Consumption and Obsolete Scrap

As discussed in Section 2 and the Appendix, within the publicly available academic literature, there is a lack of supporting detail on the assumptions used for finished steel product lifespans.[17] As such, this study attempts to fill the void in the literature by developing original estimates of average steel product lifetimes based on data on apparent steel consumption and obsolete scrap usage in important steel producing and consuming countries. This work back tests against the actual past experience of global steel markets to estimate steel product lifetimes. These estimates suggest that average steel product lifespans may be lower than 40 years and instead fall within the 25-35 year range.

Our approach estimates the average lifespan by calculating mean absolute deviations (MAD) of differences between obsolete scrap generated in a given year and apparent steel consumption in the past. For example, obsolete scrap generated in 2020 is compared with apparent steel consumption over numerous lagged years, starting with apparent steel consumption in 2020 (indicating a lag year of 0), 2019 (1 year lag), and continuing back to 1980 (40 year lag). Annual differences are then taken and the MAD and associated averages and standard deviation are calculated. Our estimated average lifespan is the lag year that minimizes the MAD average or standard deviation, depending on the availability of data in specific countries. n.

To illustrate, Figure 1 provides an example of the MAD with apparent steel consumption in the United States represented by the dotted blue line and obsolete scrap generated represented by the green line. The MAD is effectively the spread between steel consumption and scrap generation. Analyses using steel consumption and scrap data are primarily based on the MAD due to its simplicity and that it does not require further estimation of explanatory variables.

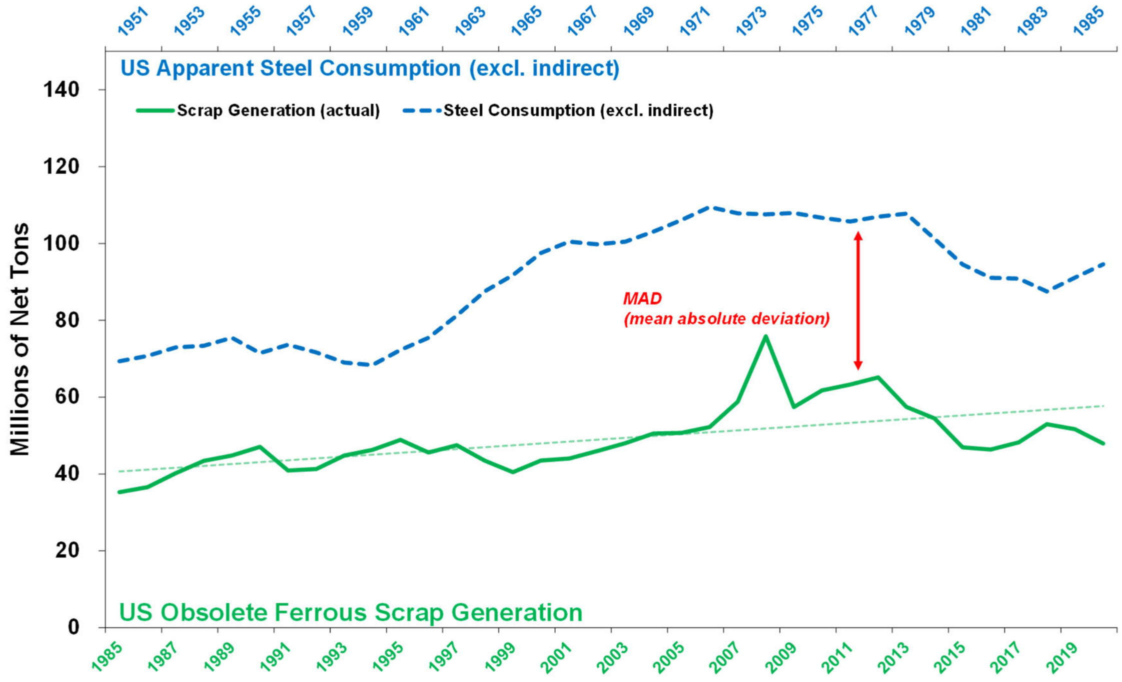
For the United States, the lowest MAD standard deviation implies an overall steel life span of 34 years (Figure 2). In other words, the difference in the annual estimate of obsolete steel scrap generated in the United States and apparent steel consumption 34 years earlier provided the lowest MAD standard deviation. This result is consistent regardless of whether indirect obsolete scrap imports are included.[18] As such, under this methodology, 34 years is the estimated average steel product lifespan in the United States.

---

[17] This lack of detail is understandable as: (1) there are differences in lifetime across steel end-market categories; (2) historical data are limited in availability; (3) estimates of obsolete scrap generation need to be derived from net mill receipts as well as import and export data, which may be difficult to obtain; and (4) there are other influences that affect scrap generation, such as price and other economic factors.

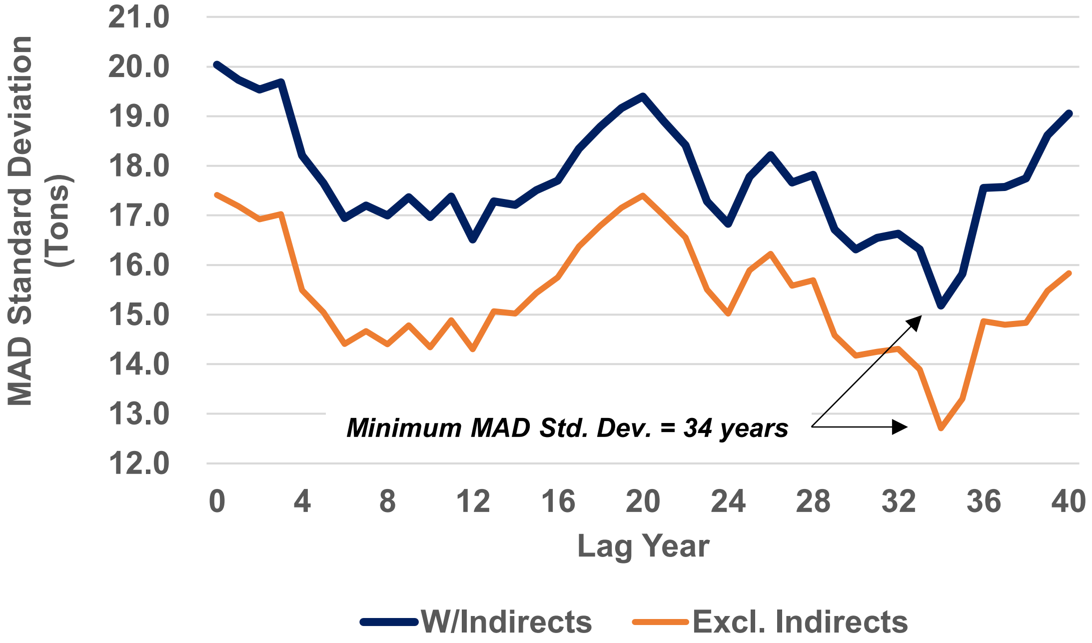
[18] Indirect obsolete scrap refers to steel products imported into the United States that have reached the end of their product lifespans and are subsequently recycled.

Figure 1: Using Mean Absolute Deviation (MAD) to Estimate Average Product Lifetimes



Sources: Steelfacts, U.S. Dept. of Commerce, Census, U.S. Dept. of Interior, USGS.

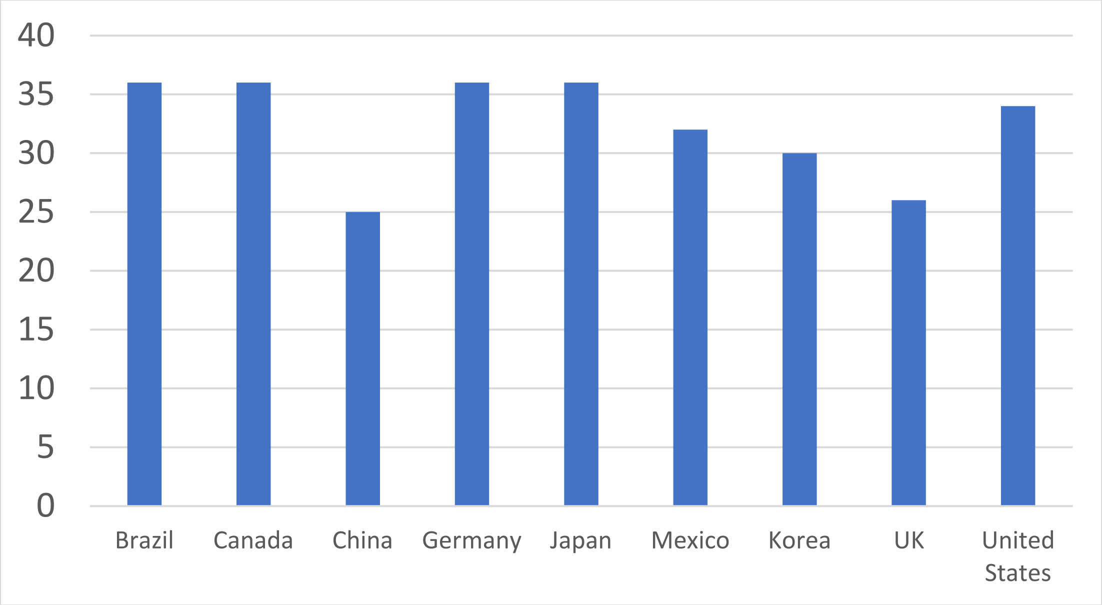
Figure 2: MAD Standard Deviations for the United States (with and without indirect steel imports)



Source: Author calculations based on CRU – Steel Market Outlook and U.S. Dept. of Interior, USGS data.

Using this approach, the lifespan year that minimizes MAD average or standard deviation is the basis for the estimated lifespans for Brazil, Canada, China, Germany, Japan, Mexico, South Korea, the United Kingdom, and the United States (Figure 3).

Figure 3. Estimated Average Product Lifetimes in Selected Countries



Source: Author calculations based on CRU – Steel Market Outlook and U.S. Dept. of Interior, USGS data.[19]

These implied product lifespans are lower than previous 40-year estimates. For five of the nine countries, the implied product lifetime is approximately 35 years (*i.e.*, Brazil, Canada, Germany, Japan and the United States). China and the United Kingdom have the lowest implied lifespans, at approximately 25 years.[20] The other three countries reviewed have lifespans between 25 and

---

[19] The data used in the MAD analyses include annual steel consumption and obsolete scrap generation covering the following historical periods: for the United States, steel consumption from 1945 through 2020 and obsolete scrap generation from 1991 through 2020; for all other reviewed countries, steel consumption from 1967 through 2020 and obsolete scrap generation from 2003 through 2020. With a longer dataset, the MAD analysis for the United States is based on minimizing the MAD standard deviation. Minimizing the MAD average is the basis for the other reviewed countries.

[20] The authors note the lack of historical data associated with obsolete scrap generation in countries outside of the U.S. For China, only 20 years of data have been evaluated in this analysis. As such, as more data on obsolete scrap generation become available, estimates for average finished steel product lifespans may change.

36 years. A weighted average of the product lifespan for these nine countries based on 2022 raw steel production volumes is approximately 30 years.[21]

These implied product lifespans are suggestive but should not be considered definitive. They do not explicitly consider how changes over time in prices, costs, public policies and incentives to recycle influence decisions about when to scrap steel-containing products. But these estimates do provide a testable, data-driven alternative to the lifespan estimates derived using the other methods described in Section 2 and the Appendix, which also are not definitive and are only as good as the subjective estimates of product lifetimes that underly the lifespan estimates.

---

[21] *See* World Steel Association (2023).

Conclusion

Ferrous scrap has an important role to play in decarbonizing the global steel industry. A key factor in determining the extent to which scrap-based production can be used to decarbonize is the global availability of scrap. Global scrap's contribution to meeting the steel industry's demand for ferrous input depends on recycling rates, rates of growth in steel demand, and steel product lifespans – as influenced by economic considerations (prices and costs) and public policies that encourage or discourage recycling.

As shown in Section 1, the approximate lifetime of a steel-containing product has a significant impact on the share of total steel production that can be supplied by scrap. In the scenarios reviewed, the difference between a 40-year lifespan and a 25-year lifespan is more than ten percentage points of world steel-production share. This analysis also illustrates the importance of policies to promote scrap recycling, as increasing recycling rates will play an important role in decarbonization efforts.

Many estimates of global scrap availability assume that the average steel product lifetime is 40 years. However, as the analysis in Section 3 shows, the average lifetime for steel products may be below 40 years and instead in the range of 25 to 35 years. This calls both for continued research into the lifespans of steel-containing products and for being cautious about attaching a high degree of precision and accuracy to global scrap supply calculations that rely on a 40-year estimate.

Appendix – Academic Literature Review

Within the academic landscape, material flow analysis (MFA) is a frequently used method to assess past, present, and future stocks and flows of metals around the globe. MFA is the quantification of the stocks and flow of materials (such as water, carbon, copper, aluminum, iron, steel, etc.) within a system (be it a city, country or economy) over a defined period of time. Most metal-related MFA studies aim at understanding the pathways of metals in an economy, the magnitudes of their stocks and flows (from inputs to stocks in-use to end-of-life recycling potential), and how these stocks and flows evolve over time.

To estimate past, current, and/or future stocks in-use and material flow, MFA studies employ either top-down or bottom-up methods. Top-down approaches derive the stock of a material from the net flow within a system (or the difference between inflows (or consumption) and outflows (or end-of-life discard)). Most top-down studies assume some type of probability distribution for either category or product life spans including Normal, Log-Normal, Beta, Weibull, and others or provide sensitivity analysis. By comparison, the bottom-up approach directly estimates the stock by summing up a material within a system at a given time (with data derived from production and consumption data, import/export sources, through interviews, etc.). Given the difficulty of obtaining comprehensive data, most bottom-up studies are isolated to select products (refrigerators or air conditioners for example) in specified countries. As such, most MFA analyses use top-down methods.

For metals, there are two primary inputs for MFA studies including the definition of end-use categories and/or product segments (such as construction, transportation, machinery, steel girders, lintels, door frames, etc.) and the associated life spans. Mueller (2014) provides a review of MFA studies published between 1999 and 2013, concluding that results across studies are more dependent on the estimates for mean lifespans rather than the probability distribution assumption. As such, the following provides a review of previous steel-related MFA academic studies focused on category and product lifespan assumptions. Overall, across MFA studies, despite the crucial role of lifespan estimates, there is a lack of quantitative data analysis in determining reliable estimates.[22]

Muller (2006) studies iron stocks in the US from 1900-2004 and concludes with a perfect recycling system, the country could substitute scrap for domestic mining.[23] To estimate scrap availability, the study uses assumes steel sector life spans are Normally distributed, with uncertainties incorporated by sensitivities. The study assumes four end use categories for steel including, construction, transportation, and machinery. For example, the construction segment assumes a medium lifespan of 75 years, low of 50, and high of 100 years. Muller (2011) extends the analysis to estimate steel saturation rates in industrialized countries including the US, UK, France, Canada, Australia and Japan. Unfortunately, as many other studies cite these works, the authors do not provide details behind their lifespan assumptions.

---

[22] Further, lifespan information is also essential in developing forecasts and scenarios for future metals demand and scrap availability.

[23] The country also reached an iron saturation point in 1980 of 11 to 12 Mt/capita.

Pauliuk (2012) estimates in-use stocks of steel in 200 countries to identify how stocks evolve over time. The study estimates lifespans across transportation, machinery, construction, and products steel use sector using a model that minimizes the difference between estimated scrap supply and historical demand for scrap.[24] Under the assumption that scrap supply equals apparent scrap demand given a balanced market, the study estimates steel use saturation levels of 13 ± 2 tons per capita globally. Four end use categories are identified, each with the life spans based Muller (2006, 2011). Uncertainty around average lifespans incorporated via multiple scenarios (33% longer, 33% shorter, etc.). Morfeldt (2013) develops a Scrap Availability Assessment Model (SAAM) to analyze relationships between global steel demand, recycling and scrap availability. Across four end use categories, average lifespans are based on Muller (2011), with sensitivities analyzed (including lifespans 10 years longer and shorter).

Hatayama, (2010) estimates steel in-use stocks from 1980 to 2005, with forecasts through 2050 for 42 countries across Europe, CIS, Africa, the Americas, Japan, and China. In addition to the four end use categories used by Muller (2011), the study identifies civil engineering, packaging, appliances, and ship building. Average lifespan estimates used in the Americas are identical to those in Mueller (2006) for construction (75 years), machinery (30) and transportation (20). Assumptions for other regions are relatively shorter. For example, lifespans for steel in civil engineering and buildings (construction) are assumed to be 60 years in Europe, CIS and Africa, ~32 years in Japan and China. This study does not provide details on how steel is allocated to the end use categories.

Similar to Hatayama, Oda (2013) forecasts future availability of steel scrap through 2050 across: (i) Europe, CIS, North America, South America, and Africa; and (ii) Asia, Oceania, and the Middle East. Average lifespan assumptions for construction are slightly lower compared to Mueller (2011) (67 years for construction) and 17 years for transportation,[25] with machinery at 20 years. The study references Hatayama (2010) and Muller (2006, 2011) for lifespan assumptions, among others.

Davis (2006) analyzes rates of scrap generation and recycling in the UK. Due to rates of wear and tear, component failure and product obsolescence, lifetime of a particular type of good will not be constant but can be described by a distribution of lifetimes. The study assumes 9 steel in-use sectors including those not previously mentioned of mechanical and electrical engineering and metal goods. Due to lack of precise information on actual life spans, the study employs three probability distributions (residence time, Weibull, Log-Normal) and sensitivities around average estimates (minimum and maximum). Study assumes a 60-year lifespan for construction and a 13-year lifespan for transportation.

Spatari (2005) analyzes the complete life cycle flows of copper extracted and used during the twentieth century in the US, Mexico, and Canada. The study uses nine end use sectors for copper, with those aligning with steel use including construction having an assumed useful life

---

[24] Specifically, on a country-by-country basis, the study models scenarios of varying steel use sector percentages (11 to 30% of steel output goes into transportation; 10 to 32% into machinery; 31 to 47% into construction and 10-15% toward products). Lifespans are also varied over the scenarios.

[25] The assumed lifetime durations include the time lag between discarding by consumers and remelting in steel mills and foundries and are assumed to remain constant over the course of the entire simulation period (to 2050).

of 40 years and 14 years for transportation.[26] Uncertainties are incorporated by in the inclusion of Weibull probability distributions.

Igarashi (2008) models the flow of steel scrap in Japan, South Korea and Taiwan based on a population balance model to estimate future steel demand and subsequent scrap flows. The study assumes seven end use categories including segmenting buildings and infrastructure and passenger cars from trucks. Assumed average lifespans are shorter relative to other reviewed studies covering other countries. As an example, construction (equally split between buildings and infrastructure) has an average lifespan of slightly under 32 years with transportation (split between passenger cars and trucks), slightly over 12 years. Lifespan uncertainties are incorporated using Weibull probability distributions. As with Hatayama (2008), the study does not provide detail as to how steel is allocated to end use categories.

Cooper's Ph.D. dissertation (2013) presents a global assessment of the potential for reusing steel and aluminum components using a combination of top-down and bottom-up analyses to allocate end product uses. The study uses potential lifespans of various steel and aluminum products which are collected from industrial partners and from published, product-specific literature. Weighted on in-use tonnage for 2008, the study shows an average expected product lifespan is 35 years, ranging from 53 years in construction to 11 years in metal products.[27] No uncertainty around product lifespans appears to be included in the study.

Sansom (2002) employs life cycle assessment (LCA) methodology for steel used in the construction sector for the EU. This study used uses the following static life span assumptions for steel products used in the sector. Aligning with Mueller (2006, 2011) and others, for construction purposes, the assumed average lifespan is 75 years. Fifteen other end products are identified, each with a corresponding lifespan. For the construction related products, the study references the Dutch Environmental Relevant Product Information (2000). The authors do not address uncertainty around lifespan estimates used in the study. Lui (2006) uses a cradle-to-grave model to understand the resource loop for construction steel to identify "feeds" into and "leaks" from the system. For identified product lifespans, the study references Samson (2001).

Quantifying Steel End Use Lifespans in Academic Studies

Of these academic papers, eight studies provide adequate details on estimates for the allocation of overall steel consumption by end use sector and associated lifespans. Based on this information, it is possible to derive implied overall steel lifespans, with individual sectors lifespans weighted by the associated sector allocation.[28] Table 3 provides a summary of the implied overall steel lifespans by study. As shown, four of the reviewed studies address steel use and recycling potential in the US. The simple average of these studies provides an average

---

[26] Assumed lifespans for Spatari for construction is based on a weighted average from infrastructure (55 years), wiring (27), plumbing (44) and onsite waste (1 year). Similarly, transportation is weighted on motor vehicles (11) and "other transport" (33 years).

[27] The relatively short lifespan of metal products is due to short-lived domestic appliances, such as refrigerators, and disposable steel packaging, such as food cans.

[28] Best attempts are made to align end use sectors across the studies. For example, Igarashi (2008) provides details for end use in civil engineering and buildings. These are collapsed into a "construction" category, with an associated estimated lifespan as the simple average.

lifespan of ~41 years, with minimum and maximum estimates of 27 and 60 years, respectively.[29] Three studies address steel use in the UK with an implied average lifespan of 38 years and minimum and maximum of 24 and 51 years. Two studies model the flow of global steel, with an implied average lifespan of 39 years, ranging from a minimum of 33 years to a maximum of 53 years. Tables 4 and 5 provide additional detail about the lifetime assumptions used in the eight academic studies.

Table 3: Implied Average Steel Lifespans Based on Academic Literature**

	Geographic Focus																				
	U.S.			U.K.			Japan			India			Europe, CIS, Americas, Africa			Asia, Oceana, Mid-East			Global		
Study	**Min.**	**Avg.**	**Max**	**Min.**	**Avg.**	**Max**	**Min.**	**Avg.**	**Max**	**Min.**	**Avg.**	**Max**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max**	**Min.**	**Avg.**	**Max**
Muller (2011)	28	42	57	27	40	55	32	47	64												
Pauliuk (2012)	31	46	61	30	44	59				33	49	65									
Morfeldt (2013)																			33	43	53
Oda (2013)														36			25				
Davis (2006)				14	29	41															
Muller (2006)	32	48	65																		
Spatari (2005)	17	30	59																		
Cooper (2012)																				35	
Average	***27***	***41***	***60***	***24***	***38***	***51***	***32***	***47***	***64***	***33***	***49***	***65***		***36***			***25***		***33***	***39***	***53***
Studies that do not detail both life span and end use segment breakdown assumptions																					
Hatayama (2011)																					
Igarashi (2008)																					

** Weighted average steel end use product lifespan estimates are derived from: 1) end use sector breakdown and 2) associated lifespan assumptions detailed in specified academic studies.

Table 4: Lifespan Assumptions by End Use Segment

	Muller (2011)				Pauliuk (2012)[1]				Morfeldt (2013)[2]			Oda (2013)				Hatayama (2011)[3]				
Geographic Focus	**U.S., U.K. & Japan**				**U.S., U.K., India**				**Global**			**Europe, CIS, Americas, Africa**		**Asia, Oceana, Mid. East**		**Europe, CIS, Africa**	**N. & S. America**	**Japan**	**China**	**Other Asia**
End-Use Segment	**Min.**	**Avg.**	**Max**	**Std. Dev.**	**Min.**	**Avg.**	**Max**	**Std. Dev.**	**Min.**	**Avg.**	**Max**	**Avg.**	**Std. Dev.**	**Avg.**	**Std. Dev.**	**Avg.**	**Avg.**	**Avg.**	**Avg.**	**Avg.**
Construction	50	75	100	25	50	75	100	23	65	75	85	67	29	34	14	60	75	35	33	34
Transportation	15	20	30	8	13	20	27	6	10	20	30	17	7	15	6	13	20	13	17	15
Rail																				
Products					10	15	20	5	5	15	25					16	15	12	22	17
Equipment & Machinery	20	30	40	10	20	30	40	9	20	30	40	20	9	17	7	15	30	12	18	15
Nonclassified shipments																				
Shipbuilding												30	13	30	13	60	60	60	60	60
Other	10	15	20	5								20	9	15	5	25	15	12	10	11

[1] Pauliuk uses life span scenarios (Min = 33% shorter lives; Max = 33% longer)

[2] Morfeldt uses life span scenarios (Min = 10 years shorter lives; Max = 10 years longer longer)

[3] Hatayama uses a Weibull distribution with a shape parameter of 3.5

[4] Spatari reviews copper scrap trends. Avg. life spans based are weighted based on 1990-1999 sector %s (various copper segments are adjusted to best align with other reviewed studies)

[5] Cooper provides graphics on segment life spans. Actual life span estimates based on visual interpretation of these figures in paper and weighted by 2008 global consumption by segment)

---

[29] Using a similar approach using lifespan and sector breakdown assumptions, weighted-average minimum and maximum lifespans for the US are 5 and 21 years, respectively.

Table 4 (continued): Lifespan Assumptions by End Use Segment

	Davis (2006)			Muller (2006)			Spatari (2005)[4]			Igarashi (2008)			Cooper (2012)[5]
Geographic Focus	**U.K.**			**U.S.**			**U.S., Mexico & Canada**			**Japan**	**S. Korea**	**Taiwan**	**Global**
End-Use Segment	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Avg.**	**Avg.**	**Avg.**	**Avg.**
Construction	20	60	100	50	75	100	24	40	81	31.7	33.5	30	53
Transportation	1	13	16	15	20	30	6	14	26	12	12.8	16.4	13
Rail													
Products	5	13	15				8	14	27			5	11
Equipment & Machinery	10	15	20	20	30	40	11	22	33	12.1	12.1	5	19
Nonclassified shipments													
Shipbuilding	60	60	60										29
Other	25	25	25	10	15	20				12.1	12.1	5	11

[1] Pauliuk uses life span scenarios (Min = 33% shorter lives; Max = 33% longer)

[2] Morfeldt uses life span scenarios (Min = 10 years shorter lives; Max = 10 years longer longer)

[3] Hatayama uses a Weibull distribution with a shape parameter of 3.5

[4] Spatari reviews copper scrap trends. Avg. life spans based are weighted based on 1990-1999 sector %s (various copper segments are adjusted to best align with other reviewed studies)

[5] Cooper provides graphics on segment life spans. Actual life span estimates based on visual interpretation of these figures in paper and weighted by 2008 global consumption by segment)

Table 5: End Use Segment Allocation Assumptions

	Muller (2011)			Pauliuk (2012)			Morfeldt (2013)	Oda (2013)		Hatayama (2011)				
Geographic Focus	**U.S. (2005) est.**	**U.K. (2005) est.**	**Japan (2005) est.**	**U.S. (2004)**	**U.K. (1970-2000)**	**India (1995-1999)**	**Global**	**Europe, CIS, Americas, Africa**	**Asia, Oceana, Mid. East**	**Europe, CIS, Africa**	**N. & S. America**	**Japan**	**China**	**Other Asia**
Construction	36%	32%	47%	47%	43%	47%	40%	37%	51%	*Paper does not list breakout %s but references: US: American Iron and Steel Institute. Annual Statistical Report 2006 and Other: Japan Iron and Steel Exporters' Association. Tekkou Handbook, 1st-9th ed.; Japan Iron and Steel Federation: Tokyo, Japan, 1980-2005 (in Japanese).*				
Transportation	33%	26%	33%	30%	22%	11%	40%	34%	15%					
Products	9%	10%	4%	13%	20%	10%	5%							
Equipment & Machinery	22%	32%	16%	10%	15%	32%	15%	22%	27%					
Shipbuilding								1%	2%					
Other								7%	6%					

[1] %s for sector breakout obtained via visual inspection of graph with reported totals within paper

[2] %s for sector breakout modified from paper categories and assume: construction (includes infrastructure, not built-in appliances); products (includes consumer EEE and built-in appliances) and based on years 1990-1999 per table in pa

Table 5 (continued): End Use Segment Allocation Assumptions

	Davis (2006)	Muller (2006)[1]	Spatari (2005)[2]	Igarashi (2008)			Cooper (2012)
Geographic Focus	**U.K. (2000)**	**U.S. (2004)**	**U.S., Mexico & Canada (1900 - 1999) - Copper**	**Japan**	**S. Korea**	**Taiwan**	**Global**
Construction	26%	48%	58%	*Details not provided*			52%
Transportation	17%	19%	12%				11%
Products	11%		19%				15%
Equipment & Machinery	22%	22%	12%				13%
Shipbuilding	0%						3%
Other	24%	10%					6%

[1] %s for sector breakout obtained via visual inspection of graph with reported totals within paper

[2] %s for sector breakout modified from paper categories and assume: construction (includes infrastructure, not built-in appliances); products (includes consumer EEE and built-in appliances) and based on years 1990-1999 per table in paper

References

Cooper, D., 2013. "Reuse of steel and aluminum without melting", Ph.D. Dissertation, Darwin College. University of Cambridge, Department of Engineering.

Davis, J., Geyer, R., Ley, J., He, J., Clift, R., Kwan, A., Sansom, M., Jackson, T., 2007. "Time-dependent material flow analysis of iron and steel in the UK", Resource Conservation & Recycling. 51, 118e140.

Hatayama H, Daigo I, Matsuno Y, Adachi Y. 2010. Outlook of the World Steel Cycle Based on the Stock and Flow Dynamics", Environmental Science and Technology. 44(16):6457–63.

Igarashi,Y., Kakiuchi, E., Daigo, I., Matsuno, Y., Adachi, Y., 2008. "Estimation of Steel Consumption and Obsolete Scrap Generation in Japan and Asian Countries in the Future", ISIJ International, Vol. 48 (2008), No. 5, pp. 696–704.

Liu, L., 2006. "Tracking the Life Cycle of Construction Steel: The Development of a Resource Loop", M.S. Thesis, University of Kansas.

Morfeldt, J., Nijs, W., Silveira, S. 2013. "The impact of climate targets on future steel production e an analysis based on a global energy system model", Journal of Cleaner Production.

Muller, D.B., Wang, T., Duval, B., Graedel, T.E., 2006 "Exploring the engine of anthropogenic iron cycles", PNAS 103, 16111–16116.

Muller, D.B., Wang, T., Duval, B., 2011. "Patterns in Iron Ore Use in Social Evolution", Environmental Science and Technology 45, 182–188 (and Supplemental Information).

Pauliuk, S., Wang, T., Müller, D.B., 2012. "Steel all over the world: Estimating in-use stocks of iron for 200 countries", Resources, Conservation and Recycling 71, 22–30.

Oda, J., Akimotoa, K., Tomoda, T. 2013. "Long-term global availability of steel scrap", Resources, Conservation & Recycling.

Sansom, M., Meijer, J., 2002. “Life-cycle assessment (LCA) for steel construction, technical steel research (steel structures)”, European Commission.

Spataria, S., Bertram M., Gordon, R., Henderson, K., Graedel, K.E., 2005. “Twentieth century copper stocks and flows in North America: A dynamic analysis”. Ecological Economics. 54 (1), 37–51.