Understanding Steel Recovery and Recycling Rates and Limitations to Recycling

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Executive Summary

In an era in which waste recovery, recycling, and recycled content are high on society's agenda, improvement of recycling performance is on the radar screens of almost every product manufacturer. Increased impetus for more extensive recycling is the focus of an emerging environmental initiative to decouple increasing consumption from needs for additional resource extraction. A central goal is to reduce environmental impacts of consumption.

To achieve improvement in recycling rates first requires an understanding of what recycling statistics mean and current recovery and recycling rates. In this report we examine recycling rates for steel, the metal used in 8-9 times greater quantity than all other metals combined. We found that commonly used definitions of recycling serve to obscure actual recovery and recycling performance, that there are considerable losses of material with each use cycle, and that the often cited claim that steel is continuously recyclable without loss of quality is not true. We also found a much greater potential for steel recovery and recycling than is currently being realized.

The Decoupling Concept

Recycling is receiving renewed attention these days. Based on rising concern about the dual and reinforcing effects of continuing population growth and rising consumption, a program to markedly accelerate progress toward greater recycling of resources has been proposed (OECD 2010, UNEP 2011, Smil 2014). Described by the term "decoupling," the basic premise is that economic growth and increasing consumption does not necessarily require parallel increases in resource extraction and the environmental degradation that often goes with it. The idea is to decouple consumption and resource use by making more efficient use of physical materials, such as steel and other metals, in part through greater recycling. Given that recycling reduces the need for resource extraction, typically requires far less energy consumption than when processing virgin raw materials, and results in lower emissions and other environmental impacts, it is not surprising that this is a key strategy in the decoupling effort.

Getting a Handle on Steel Recycling Rates

Given the goals of the decoupling model, a first priority is to examine those resources used in greatest quantity and those linked to the greatest environmental impacts. Steel qualifies on both criteria since annually used quantities are 8-9 times greater than all other metals combined, and in view of the fact that five of the next nine most-consumed metals (manganese, nickel, titanium, cobalt, and chromium) are commonly incorporated within steel products as alloying components or coatings.

Iron and steel account for about 90% of the mass of all metals consumed in the United States each year. This is also true globally. Iron is a basic element, and its primary use is as a raw material for production of steel. The production of steel first requires the production of an intermediate material called pig iron, which is produced by combining iron and carbon in a smelting process involving use of a high carbon fuel, such as charcoal or coke in the presence of limestone. Pig iron is then used to make steel, wrought iron or ingot iron. Wrought iron is used to make lawn furniture and decorative fencing, and ingot iron is used in making cast-iron products ranging from skillets and outdoor cookers to weight-lifting equipment.

In making steel, a majority of impurities in the pig iron are removed, particularly elements such as silicon, phosphorous, sulfur and some carbon. The resulting steel has a consistent concentration of carbon[1] with the balance relatively pure iron. Steel is used to make a wide range of structural and non-structural products. Other elements are commonly added to steel to create alloys in order to increase such properties as tensile strength, hardness, melting temperature, and resistance to metal fatigue.

Widely Differing Estimates

There is considerable steel recycling activity in North America, so much so that a casual investigation of recycling rates suggests little room for improvement. For instance, steel recovery rates as reported by the Steel Recycling Institute suggest opportunities for only marginal improvement (Table 1). These percentages are often highlighted in promotional literature.

Table 1
Steel Recycling Rates in North America as Reported by the Steel Recycling Institute [a/] [b/]

Steel Recycling Rates by Year		Steel Recycling Rates by Sector – 2013	
2010	88%	Steel containers	70%
2011	92%	Automotive	85%
2012	88%	Steel appliances	82%
2013	81%	Structural steel	97.5%

a/ Steel Recycling Institute (2014a)
b/ Values include recycling of iron

The steel recycling rate is an expression of the quantity of scrap reprocessed in any given year as a percentage of the volume of scrap available. It does not indicate recycled content of steel. Estimates of steel recycling rates differ considerably depending upon who is doing the calculations.

The Steel Recycling Institute estimates shown in Table 1 were obtained using a liberal definition of steel discards (scrap), and volumes of scrap deemed to be unrecoverable were excluded from calculations. When a more strict definition of scrap is used, and all scrap steel discards are considered in calculations, steel recycling rates are much less impressive.

For instance, consider the 2012 Steel Recycling Institute (SRI) reported recycling rate as shown in Table 1, in comparison to iron and steel recycling rate estimates for the same year by the U.S. Geological Survey (2014), and the Canadian Steel Producer's Association (CSPA) (2015):

- 2012 steel recycling rate as reported by SRI: 88%
- 2012 steel recycling rate as reported by USGS: 59%
- 2012 steel recycling rate as reported by CSPA: ~60%

[1] Up to 2% by weight.

The differences lie in the definitions of recycling used as a basis for calculation, and in what is and isn't counted when considering the volume of scrap.

The recycling rate is only one measure of the efficiency with which steel is produced and reused at the end of product life. Other measures include the old scrap recovery rate, recycled content, and the end-of-life recycling rate. All of these measures yield values that are far below those shown in Table 1.

To understand reported recycling rates and why they differ, it is necessary to have a cursory understanding of the various types of steel scrap, and the basic steelmaking processes in which scrap is used.

Definitions and Effects on Reported Recovery and Recycling Rates

Steel scrap (steel potentially available for recycling) is classified in three main categories:

- *Home scrap* – Home scrap, also known as runaround scrap, is material in the form of trimmings or rejects generated within a steel mill during the process of producing iron and steel. As this scrap never leaves the steel mill site, and has known physical properties and chemical composition, it is typically immediately or quickly reprocessed. Home scrap accounts for approximately 21% of scrap recycled in the U.S. (USGS 2014). In 2012, home scrap averaged 11% of ferrous inputs to steel manufacturing across the U.S. industry as a whole (Morici et al. 2013).
- *New scrap* – New scrap, also known as prompt scrap, is generated within manufacturing plants involved in fabricating steel products. This scrap is often returned directly to the mill that produced the steel, usually within weeks or months. The chemical composition of this scrap is generally well known. Also, this scrap is typically clean, meaning that it is not mixed with other materials. New scrap accounts for approximately 22% of scrap recycled in the U.S. (USGS 2014). The quantity of new scrap incorporated into U.S.-made steel averages about 15% of total raw material inputs (Yellishetty et al. 2012).
- *Old scrap* – Old scrap, also known as obsolete scrap, is steel that has been discarded at the end of product life. The greatest volume of old scrap is composed of junk vehicles, old appliances and machinery, old railroad tracks, and steel from demolished buildings. Steel in mixed solid waste also includes cans and other containers as well as a wide variety of discarded consumer products. Because old scrap is often material that has been in use for years or decades, chemical composition and physical characteristics are not usually well known. It is also often mixed with other trash. For all of these reasons, old scrap is the most difficult and costly form of steel to reuse. Incorporation into recycled products may require cleaning, sorting, removal of coatings, and other preparation prior to use. Old scrap accounts for approximately 57% of scrap recycled in the U.S. (USGS 2014).

In reporting recovery rates and recycled content the following methods of calculation are commonly used:

$$[1]\ \text{Recovery rate (\%)} = \frac{\text{quantity of scrap recovered}}{\text{quantity of scrap available}} \times 100$$

$$[2]\ \text{Recycling rate (\%)} = \frac{\text{quantity of scrap reprocessed}}{\text{quantity of scrap available}} \times 100$$

$$[3]\ \text{Recycled content (\%)} = \frac{\text{quantity of scrap reprocessed}}{\text{total quantity of material}} \times 100$$

In equations [1] and [2] note the term "quantity of scrap available" in the denominator. This means that discarded steel (i.e. old scrap) deemed unrecoverable is not included in the recovery rate and recycling rate calculations. In calculating the recycling rate and recycled content (equations [2] and [3]), the amount of scrap reprocessed includes home, new, and old scrap.

A number of green building programs provide recognition of recycled content, but often require differentiation of pre-consumer scrap (also called post-industrial scrap) and post-consumer scrap. The definition of post-industrial recycled content takes into account new scrap but most often excludes home scrap. Therefore, the percentage of pre-consumer scrap is calculated as follows:

$$[4]\ \text{Pre-consumer recycled content (\%)} = \frac{\text{quantity of new scrap reprocessed}}{\text{total quantity of material used}} \times 100$$

Post-consumer recycled content considers only the content traceable to reuse of old scrap. It is calculated in this way:

$$[5]\ \text{Post-consumer recycled content (\%)} = \frac{\text{quantity of old scrap reprocessed}}{\text{total quantity of material used}} \times 100$$

There are two reasons for the previously discussed large differences in 2012 recycling rates as reported by the Steel Recycling Institute (88%) and those reported by USGS (59%) and CSPA (~60%). First, calculation of the 88% rate includes home, new, and old scrap, whereas the USGS and CSPA rates are based solely on the volume of old scrap recycled. Second, volumes of scrap deemed unrecoverable were not included when calculating the SRI recycling rate.

Because all of the commonly used recycling formulas do not account for unrecovered discards, there is an effort underway to focus instead on recovery and processing of old scrap for recycling (UNEP 2011, Graedel et al. 2011, Reck and Graedel 2012). Reck and Graedel (2012) explain that recycled content is meant to encourage an increase in the amount of old scrap that is collected and processed for recycling. They also note that inclusion of new scrap (pre-consumer scrap) in recycling rate calculations creates the possibility of manipulating recycled content percentages. Use of new metrics for measuring recycling performance has been proposed (UNEP 2011), with "old scrap" defined as end-of-life scrap:

$$\textbf{Old Scrap Recovery (OSR) (\%)} = \frac{\textbf{quantity of old scrap recovered}}{\textbf{quantity of old scrap generated}} \times \textbf{100}$$

The OSR metric provides a measure of what portion of end-of-life scrap is recovered for reuse or recycling.

$$\textbf{Recycled Content (RC) (\%)} = \frac{\textbf{quantity of old scrap used in steel production}}{\textbf{total quantity of inputs to steel production}} \times \textbf{100}$$

The RC indicates the extent to which end-of-life scrap is actually used in making new steel products. Note that this is the same formula, though expressed in slightly different terms, as that for post-consumer recycled content [equation 5].

$$\textbf{End of Life Recovery Rate (EOL-RR)(\%)} = \frac{\textbf{quantity of old scrap recycled}}{\textbf{quantity of steel in old scrap}} \times \textbf{100}$$

The EOL-RR is a measure of the extent to which ferrous metal contained in end-of-life steel products is actually recycled.

Using these formulas to calculate iron and steel recovery and recycling rates again shows considerable variation depending upon who is doing the calculating. And, as before, those wanting to show high recovery and recycling numbers tend to exclude scrap losses when performing calculations. Rates as determined in various studies are shown in Table 2.

Table 2
Iron and Steel Old Scrap Recovery (OSR), Recycled Content (RC) and End-of-LIfe Recycling Rates (EOL-RR) as Determined in Various Studies (UNEP 2011)

OSR (%)	RC (%)	EOL-RR (%)
54 1/	52 2/	52 3/
52 2/	41 3/	67 4/
66 3/	28 4/	78 5/
65 4/		90 6/

Note: References are reproduced from UNEP (2011) to show the origins and dates of various estimates. Full citations for these sources do not appear in the literature cited section of this report.

1/ UNEP working group consensus (2011)
2/ Worldsteel (2009)
3/ USGS (2004); estimates for 1998.
4/ Wang et al. (2007)
5/ Birat (2001)
6/ Steel Recycling Institute (2007)

As an addendum to Table 2, old scrap steel recovery from mixed solid waste in the U.S. was only 33% in 2012 (EPA 2014). In addition, Rem et al. (2012) estimated recycled content for steel production globally at 37%. The Bureau of International Recycling (2014) estimated the 2012 and 2013 global recycled content figures at 36.6% and 36.1%, respectively; these estimates and those of Rem and colleagues are comparable to those shown in the center column of Table 2.

Regarding recycled content, the low RC values do not necessarily indicate poor performance on the part of steel manufacturers. Globally, the percentage of reused scrap is partially a function of scrap supply, which is typically limited in recently developed or emerging economies that have only recently put large quantities of steel into use.

Steel Recycling Mills

The vast majority of scrap recycled in the U.S. is processed using one of two steel production technologies:

- Basic oxygen furnace (BOF)
- Electric arc furnace (EAF)

As is discussed in more detail in subsequent paragraphs, EAF technology is limited to production of large structural shapes such as bars, beams, and columns due to inability to totally remove contaminants from the scrap steel processed. Contaminants create performance problems in thinner, lighter products. BOF technology, in which the portion of old scrap steel used as input is strictly controlled, is employed in production of flat products, such as rolled steel used to make automobile bodies, steel studs, and numerous other products.

Steel produced in mills using these technologies is referred to as BOF and EAF steel. The percentage of scrap that can be processed in a BOF mill is generally less than 30-35%. The recycled content of steel from North American BOF mills is about 30%. In contrast, up to 100% scrap can be used as input to an EAF mill. In the United States about 60% of steel is produced in by the EAF process, with the average recycled content of EAF steel about 90%.

Unrecoverable Discards

In an extensive examination of discarded and end-use steel products, Damath (2010) found that end-use products discarded in the U.S. during the 2004-2009 period contained an average of approximately 87.2 million tons of ferrous material. Of this, an average of 65 million tons were recoverable scrap and 47.5 million tons were recovered, leaving 17.5 million tons of recoverable but unrecovered scrap, and 22.2 tons of unrecoverable scrap.[2] This translates to 54.4% recovery, with 25.5% of total discards unrecoverable. Damath also estimated that 448.7 million tons of obsolete ferrous scrap would be generated during the period 2010 through 2014, with about 104 million tons of this unrecoverable.

A surprising finding is that discarded construction materials generated more recoverable obsolete ferrous scrap (33.2%) during 2004-2009 than any other end-use product category. Also surprising with regard to unrecoverable discards is that 32% of steel construction material discards are not recoverable.

The reason for the large quantity of unrecoverable discards, as explained by Damath, is twofold. First, about 1% of steel in use is lost through corrosion, wear, and tear. Secondly, and more important, is the reality that many end-use products are discarded in a manner or place that does not allow for recovery of their ferrous material. He noted that such material includes much of that sent to dumps or landfills, material destroyed in secondary use, and material in products discarded in remote locations.

Steel discards (i.e., steel in landfills or steel scattered across the landscape in the form of obsolete vehicles or equipment) are sometimes viewed as simply part of a large steel inventory that can be mined at some future date. As of the end of 2009 this "inventory" was estimated at 1.18 billion tons. Realistically, however, a portion of this material will never become available, in part due to ongoing corrosion losses estimated at 0.36 percent per year, and low quality and/or retrieval cost issues (Damath 2010).

Infinite Recyclability – Fact or Fiction?

In recent industry literature, steel is described as "100% recyclable at the end of its long life" (Steel Recycling Institute 2014b), "100% recyclable without loss of quality" (Worldsteel Association 2013), and "infinitely recyclable" (SSMA 2011). Infinite recyclability is echoed in a recent OECD report (2010). These claims, however, are at odds with reality. As explained by Reck and Graedel (2012), "Metals are infinitely recyclable in principle, but in practice, recycling is often inefficient or essentially nonexistent because of limits imposed by social behavior, product design, recycling technologies, and the thermodynamics of separation." A major issue with regard to steel is contamination that occurs with each round of recycling. Yellishetty et al. (2012) put it this way: "Beyond the difficulty in recovering all steel for recycling, there are also problems related to separation of various metals used in steel alloys and coatings."

Approximately 10% of the steel scrap that becomes available globally each year (about 50 million tons) is post-consumer scrap that is contaminated with various metallic and non-metallic mineral elements (Rem et al. 2012). Obsolete scrap may also be mixed with or coated with other

[2] 87.2 – 65.0 = 22.2 million tons of unrecoverable scrap; 65.0 – 47.5 = 17.5 million tons of recoverable, but unrecovered scrap; 47.5/87.5 x 100 = 54.4% recovery; 22.2/87.5 x 100 = 25.5% of discards unrecoverable.

materials such as glass and plastics. Moreover, the chemical composition of obsolete scrap fluctuates widely depending on its origin and degree of processing (Janke et al. 2000).

The major source of contamination of steel scrap is the steelmaking process itself. As reported by Yellishetty et al. (2011), there are many different grades of steel with many different physical and chemical properties made by adding various metals to steel in the form of alloying elements. Metals introduced into the steelmaking process to create alloys include aluminum, chromium, cobalt, copper, magnesium, nickel, silicon, tungsten, and vanadium. Metals are also sometimes added as coatings to increase corrosion resistance, with zinc and tin the most common. Phosphorous and sulfur are also often added to steel as part of the manufacturing process.

Problems posed by non-ferrous minerals in scrap steel recycling have been extensively studied. As noted by Yellishetty et al. (2011) it is well established that each time scrap steel is re-circulated the concentration of residuals rise, thereby making processing more difficult. The presence of copper, tin, nickel and molybdenum in scrap steel have been found to pose the greatest challenge, as they are very difficult to extract from scrap by metallurgical processes and tend to increase in concentration with successive recycling. Copper and tin contamination is especially problematic (Savov et al. 2003, Rod et al. 2006). Chromium, lead, manganese, and zinc can also be difficult to remove completely. The main source of zinc contamination in scrap is the recycling of zinc-coated steel (Janke et al. 2000). The buildup of residual elements over time makes refining difficult, reducing the market value of recycled metal with each cycle of recovery (Wernick et al. 1998, Yellishetty et al. (2011).

When steel is used to make large structural shapes such as bars, beams, and columns, and other steel products that have more lenient residual element restrictions, the residual elements problem resulting from use of scrap in steelmaking is minimized (Rod et al. 2006); in this case, problems are simply buried within a large mass of material such that they have minimal impact on final product properties. Such products are largely produced by the EAF process which uses a large proportion of scrap as input. When making flat products, such as rolled steel used to make things such as automobile bodies and steel studs, contamination must be carefully controlled; these products are produced via the BOF process.

The EAF steelmaking process removes many contaminants in the re-melting process. However, not all contaminants can be removed, and that is why the use of steel produced by this process is limited to large structural shapes. In BOF steelmaking, contaminant removal is even more difficult, a problem that is dealt with by strictly limiting the volume of scrap mixed with pig iron, or in limiting scrap input to home and prompt scrap, the chemical makeup of which is better known than that of old scrap. In this way, contaminants are minimized, allowing BOF mills to produce flat products and rolled steel sheets where the presence of contaminants may present significant problems.

In both the BOF and EAF steelmaking processes many of the alloying elements that are successfully removed from scrap are lost through stack emissions or become incorporated into slag that remains following re-melting. Only a small fraction of these are used in new alloys (Sibley 2011). When very high percentages of scrap are used as input to the recycling process, such as in EAF mills, about 1.085 metric tons of scrap is needed for each ton of steel produced (steelonthenet.com 2014). Therefore, about 8% of the material entering the furnace is lost to the steel production process, ending up either as recaptured contaminants, air emissions, or within slag. The primary metallic hazardous air pollutants from steel manufacturing in the U.S. are manganese, chromium, lead, and nickel (USEPA 2008).

BOF and EAF steelmaking both produce slag, with EAF steelmaking resulting in about half the volume of slag per ton of steel produced as in BOF processing. Slag production rates in the U.S. are about 15-40% of the volume of steel produced, with the percentage varying by region. The slag, which amounts to about 10-15 million tons in the U.S. each year, is either sent to slag disposal sites (Yildirim and Prezzi 2011); or is used in highway construction in the form of asphalt aggregate, granular base, embankment cover, or fill; or is used in making mineral wool insulation (National Slag Association 2013). The ferrous content of slag can be as high as 40%, representing another source of loss in the recycling process (Yildirim and Prezzi 2011).

The scrap steel contaminant problem is not limited to issues in steelmaking. Recovery and recycling of other important metals is also negatively impacted by this problem. As reported by Reck and Graedel (2012), "Unless these elements [those trapped in steel scrap] are required in specialty steels, the steel serves as a sink for these valuable and potentially critical elements from which future recovery is basically impossible."

The contamination issue is likely to become more important over time, creating a barrier to goals of closed-loop recycling. A recent study of the potential for closed-loop recycling of steel in automobiles indicated that the goal will be very difficult to achieve because of the low tolerance for impurities (Hatayama et al. 2014). Dynamic modeling revealed that, without development of new technologies to either reduce impurities or increase impurity tolerance, more than half of old steel scrap generated annually will have to be down-cycled by 2050 because of its high copper content contamination.

Bottom Line

As society seeks to reduce raw material consumption and associated environmental impacts with a goal of achieving closed-loop production-use-recovery-recycling systems for minerals and other materials, it will be important to understand current recycling performance and limitations of recycling and reuse. In the case of steel, by far the metal used in greatest quantity in the U.S. and around the world, significant progress has been made in reuse of scrap. At the same time, there is opportunity for considerable improvement in recovery and recycling processes.

The greatest need for logistical and technological progress in steel recycling is in recovery and processing of scrap, including improvement in contaminant removal and recovery. Commonly used definitions of recycling and methods of calculating steel recovery and recycling rates tend to obscure realities of scrap recovery and reuse, perhaps deflecting attention from areas most warranting investment. Adoption of suggested changes in reporting scrap recovery and reuse may help to refocus on the promise of greater recycling performance.

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