CHAPTER

3

Recycling in Context

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3.1 INTRODUCTION

Of the different resources seeing wide use in modern technology, metals are unusual in that they are inherently recyclable. This means that, in principle, they can be used over and over again, thus minimizing the need to mine and process virgin materials while saving substantial amounts of energy and water. These activities also avoid the often significant environmental impacts connected to virgin materials extraction.

Recycling indicators have the potential to demonstrate how efficiently metals are being reused, and can thereby serve the following purposes:

- Determine the influence of recycling on resource sustainability by providing information on meeting metal demand from secondary sources
- Provide guidance for research needs on improving recycling efficiency
- Provide information for life-cycle assessment analyses
- Stimulate informed and improved recycling policies

Notwithstanding these promising attributes of recycling, the quantitative efficiencies with which metal recycling occurs are not very well characterized, largely because data acquisition and dissemination are not vigorously pursued. It is worthwhile, however, to review what we do know, and to consider how that information might best be improved.

3.2 METAL RECYCLING CONSIDERATIONS AND TECHNOLOGIES

Figure 3.1 illustrates a simplified metal and product life cycle. The cycle is initiated by choices in product design: which materials are going to be used, how they will be joined and which processes are used for manufacturing. Choices made during design have a lasting effect on material and product life cycles. They drive the demand for specific metals and influence the effectiveness of the recycling chain during end-of-life (EOL).

When a product is discarded, it enters the EOL phase. It is separated into different metal streams (recyclates), which have to be suitable for raw materials production in order to ensure that the metals can be successfully reused. The cycle is closed if scrap metal, in the form of

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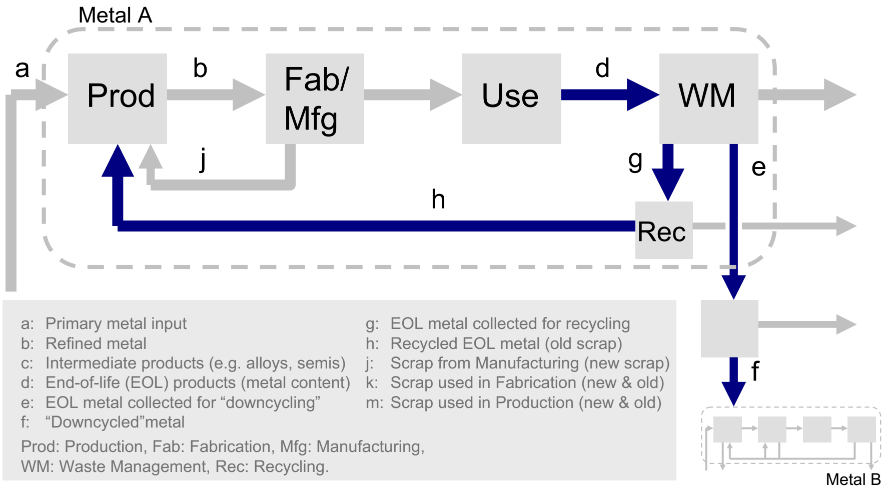

FIGURE 3.1 Flows related to a simplified life cycle of metals and the recycling of production scrap and end-of-life products. Boxes indicate the main processes (life stages): Prod, production; Fab, fabrication; Mfg, manufacturing; WM&R, waste management and recycling; Coll, collection; Rec, recycling. Yield losses at all life stages are indicated by dashed lines (in WM referring to landfills). When material is discarded to WM, it may be recycled (e), lost into the cycle of another metal (f, as with copper wire mixed into steel scrap), or landfilled. The boundary indicates the global industrial system, not a geographical entity. *Reproduced with permission from* Graedel et al., 2011a.

recyclates, returns as input material to raw materials production. The cycle is open if scrap metal is lost to landfills and other repositories (e.g. tailings, slag).

The different types of recycling are related to the type of scrap and its treatment:

- The *home scrap* portion of new scrap recycling, in which metal is essentially recovered in its pure or alloy form within the facility of the metal supplier. This type of recycling tends to be economically beneficial and easy to accomplish. It is generally absent from recycling statistics, however, because it takes place within a single facility or industrial conglomeration.
- The *prompt scrap* portion of new scrap recycling, in which metal is essentially recovered in its pure or alloy form from a fabrication or manufacturing process and returned to the metal supplier for reprocessing and reuse. This type of recycling is generally economically beneficial and easy to accomplish. It may not be identified in recycling statistics, but can sometimes be estimated from process efficiency data.
- EOL, metal-specific ("functional") recycling, in which the metal in a discarded product is separated and sorted to obtain recyclates that are returned to metal suppliers for reprocessing and reuse. This type of recycling is generally accomplished for high-value metals, especially if they are easily accessible (Streicher-Porte et al., 2005; Dahmus and Gutowski, 2007). The processes are straightforward if the metal is in pure form, but are often challenging and expensive if the metal is a small part of a very complex product (Chancerel and Rotter, 2009; Oguchi et al., 2011).
- EOL, alloy-specific recycling, in which an alloy in a discarded product is separated and returned to raw materials production for

recovery as an alloy. Often it is not the specific alloy that is remelted to make the same alloy, but any alloy within a certain class of alloys that is remelted to make one or more specific alloys by adding small amounts of other alloying elements to achieve the desired elemental composition. For example, a mixture of austenitic stainless steel alloys might be remelted and the resulting composition adjusted by addition of reagents or virgin metal to make a specific austenitic alloy. A similar approach is followed in aluminum recycling.

- EOL metal-unspecific reuse (nonfunctional recycling, or "downcycling"), in which the metals or alloys in a discarded product are downgraded or downcycled by incorporation into a large-magnitude material stream in which its properties are not required. This prevents the metal or alloy from being dissipated into the environment, but represents the loss of its function, as it is generally impossible to recover it from the large-magnitude stream. The recycled metal does not replace primary metal in metal production, so that the energy benefits of recycling cannot be taken advantage of. Equally discouraging is the fact that the recycled metal potentially lowers the quality of the produced metal alloy by becoming an impurity or tramp element. Examples are small amounts of copper in iron recyclates that are incorporated in recycled carbon steel, or alloying elements being incorporated in slag during final recovery of the major alloy element.

3.3 DEFINING RECYCLING STATISTICS

There are four approaches to measuring the efficiency of EOL metal recycling (Graedel et al., 2011a):

1. How much of the EOL metal (in products) is collected and enters the recycling chain (as opposed to metal that is landfilled)? (*Old scrap collection rate*)
2. What is the *EOL recycling rate* (metal-specific)? (*EOL-RR*)
3. What is the efficiency in any given recycling process (i.e. the yield)? (*Recycling process efficiency rate*)
4. What is the nonfunctional EOL recycling rate (downcycling)? (*nonfunctional EOL-RR*)

Figure 3.1 provides an annotated waste management and recycling system from which the EOL metrics can be calculated:

1. Old scrap collection rate = e/d
2. EOL-recycling rate = g/d
3. Recycling process efficiency rate, example EOL = g/e
4. Nonfunctional EOL-recycling rate = f/d

The *recycled content* (*RC, sometimes termed the "recycling input ratio"*) describes the fraction of recycled metal contained within the total metal flow metal production. In the simplified diagram of Figure 3.1, it is defined as $(j+m)/(a+j+m)$. The calculation of the recycled content is straightforward at the global level, but difficult if not impossible at the country level. The reason is that information on the recycled content of imported produced metals is typically not available (flow b, i.e. the share of $m/(a+m)$ in other countries is unknown), in turn making a precise calculation of the recycled content of flow c impossible.

A final metric, the *old scrap ratio* (*OSR*), provides information on the composition of the scrap used in metal production. It is the fraction of old scrap g in the recycling flow (g + h). Recycled content and OSR are closely linked in that the OSR reveals the share of old versus new scrap used in metal production, thus providing information on the efficiencies at different life cycle stages.

In terms of its significance, the most important metric is the EOL recycling rate, which indicates how effectively discarded products are recovered and recycled. Of limited relevance for metals, however, is the widely used metric "recycled content", for two reasons. First, calculations can usually be carried out only at the global level, leaving little room for incentives at the national level. Second, the share of available old scrap depends on the level of usage a lifetime ago. As this use rate was typically much less than today, there is not enough old scrap available to allow for a recycled content close to 100%. Note also that a high share of new scrap may be the result of an inefficient manufacturing process, and is therefore of limited relevance as a measure of recycling merit.

In order to arrive at and present global estimates of metal recycling statistics that are as comprehensive as possible, a detailed review of the recycling literature was conducted by the United Nations Environment Programme (Graedel et al., 2011b). The three periodic table displays in Figures 3.2–3.4 illustrate the consensus results in compact visual display formats.

The EOL-RR results in Figure 3.2 relate to whatever form (pure, alloy, etc.) recycling occurs. To reflect the level of certainty of the data and the estimates, data are divided into five bins: >50%, 25–50%, 10–25%, 1–10% and <1%. It is noteworthy that for only 18 of the 60 metals are the EOL-RR values above 50%. Another three metals are in the 25–50% group, and three more in the 10–25% group. For a very large number, little or no EOL recycling is occurring.

Similarly, Figure 3.3 presents the recycled content data. Lead, ruthenium, and niobium are the only metals for which RC >50%, but 16 metals have RC in the >25–50% range. This

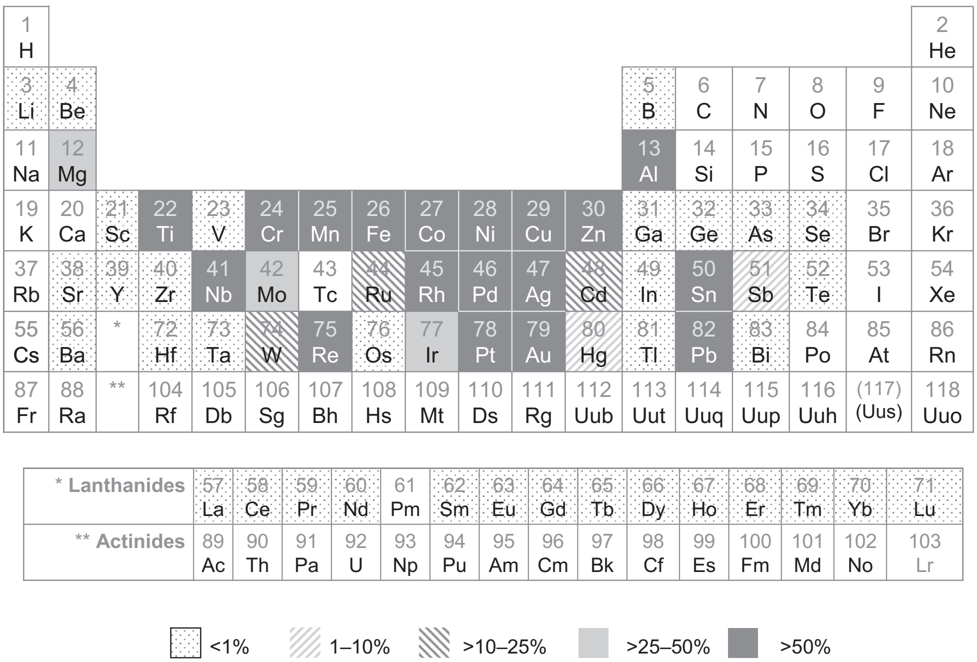

FIGURE 3.2 The periodic table of end-of-life recycling for 60 metals. White entries indicate that no data or estimates are available.

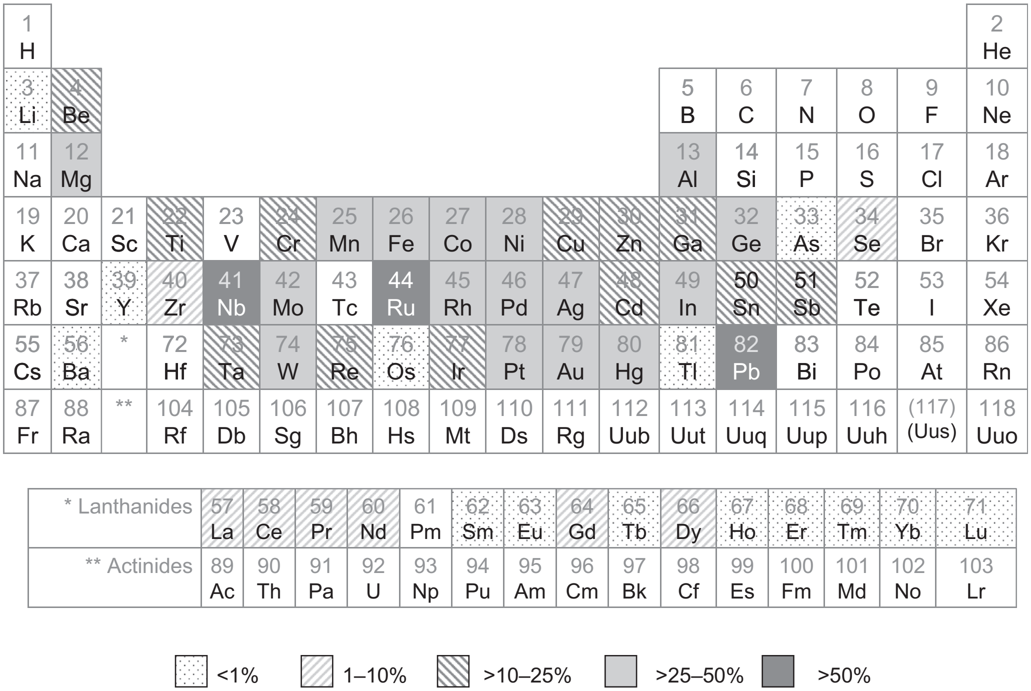

FIGURE 3.3 The periodic table of recycled content for 60 metals. White entries indicate that no data or estimates are available.

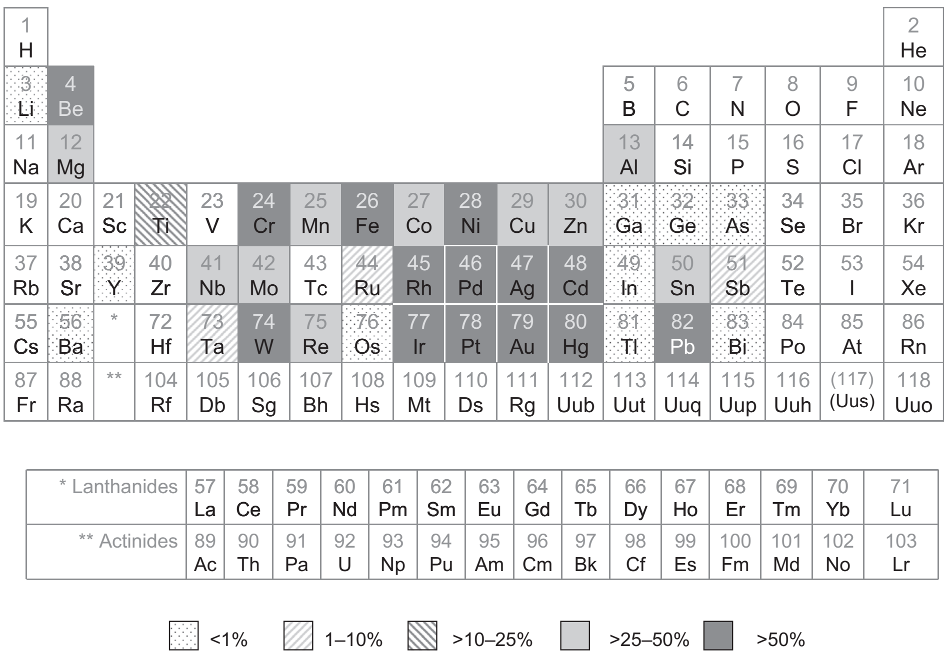

FIGURE 3.4 The periodic table of old scrap ratios for 60 metals. White entries indicate that no data or estimates are available.

reflects a combination in several cases of efficient reuse of new scrap as well as better than average EOL recycling.

The OSR results (Figure 3.4) tend to be high for valuable materials, because they are utilized with minimal losses in manufacturing processes and collected at EOL with relatively high efficiency. Collection and recycling at EOL are high as well for the hazardous metals cadmium, mercury and lead. Overall, 13 metals have OSR >50%, and another 10 have OSR in the range >25–50%.

For cases in which relatively high EOL-RR are derived, the impression might be given that the metals in question are being used more responsibly than those with lower rates. In reality, rates tend to reflect the degree to which materials are used in large amounts in easily recoverable applications (e.g. lead in batteries, steel in automobiles). In contrast, where materials are used in small quantities in complex products (e.g. tantalum in electronics), recycling is much less likely, and the rates will reflect this challenge.

3.4 PROCESS EFFICIENCIES AND RECYCLING RATE CONSTRAINTS

A common perception of the recycling situation is that if a product is properly sorted into a discard bin it will be properly recycled. This turns out never to be even approximately correct, because the recycling system comprises a number of stages (Figure 3.5): collection, preprocessing (including separation and sorting), and end processing (usually in a smelter). Losses occur at every stage, and generally the stage with the lowest recycling efficiency is the very first: collection. Higher efficiencies at the subsequent stages cannot make up for low first-stage performance, as suggested by the efficiencies shown in Figure 3.5.

Even if efficient collection occurs, efficiencies lower than 100% (which is always the case) combine to generate low EOL-RRs over time. Figure 3.6 shows the situation. Each stage has an imperfect process efficiency; if those efficiencies are multiplied together over several metal use lifetimes, even well-run recycling processes eventually dissipate the metal. Studies have shown that a unit of the common metals iron, copper and nickel is only reused two or three times before being lost (Matsuno et al., 2007; Eckelman and Daigo, 2008; Eckelman et al., 2012), because no process is completely efficient, and losses occur at every step (Figure 3.6).

Finally, product design plays an important role in the recycling efficiency of EOL products. First, does the product design allow for easy accessibility and disassembly of the relevant components? For example, precious metals contained in personal computer motherboards are easily accessible for dismantling and will be recycled, while circuit boards used in car electronics are typically not accessible for recycling (Hagelüken, 2012). Second, can the diverse mix of materials used in complex products be technologically separated at EOL? This challenge of material liberation goes back to thermodynamic

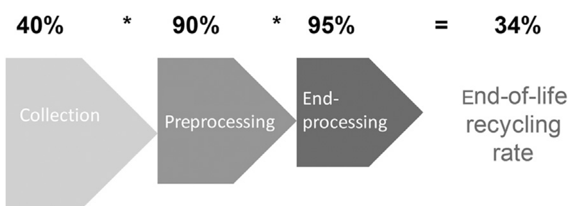

FIGURE 3.5 The steps involved in the recycling sequence. *Adapted from Hagelüken, 2012.*

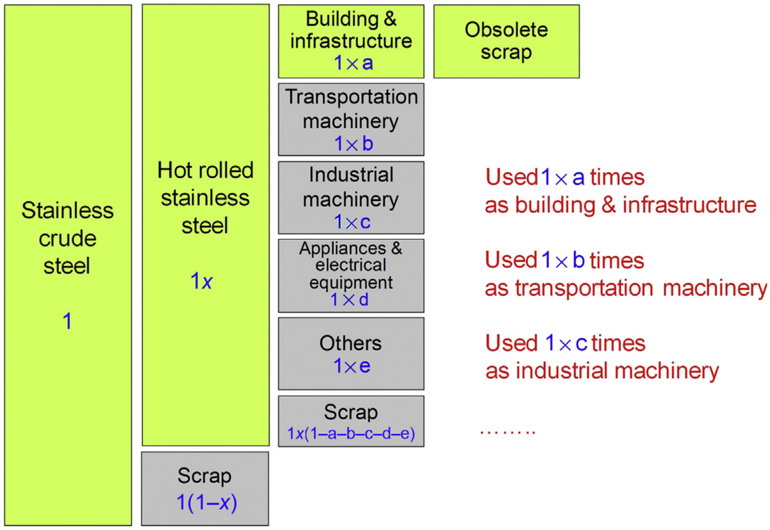

FIGURE 3.6 The efficiencies in the initial step of Markov recycling of a metal cycle. *(Reproduced with permission from Eckelman et al. (2012))*. The efficiency of conversion of stainless crude steel to hot-rolled stainless steel is x, and the resulting stainless steel is divided among five uses, each with its own conversion efficiency. If the metal is later recovered as obsolete scrap when the products are discarded, the process chain and its inevitable losses must be revisited.

principles, but also to the fact that material combinations in products are often very different from material combinations found in ores (Reuter et al., 2013; van Schaik and Reuter, 2004). Well-established technologies from the mining industry can thus be utilized only if elements not found in the respective ores can be removed beforehand (Nakajima et al., 2010).

3.5 PERSPECTIVES ON CURRENT RECYCLING STATISTICS

As can be seen from the figures, there are large differences in recycling rates among the specialty metals, but differences also exist between the different applications of the metals. Some insights into the causes of the relatively low recycling rates in Figures 3.2–3.4 are discussed below:

1. *Hardly any recycling*. This designation is applicable to specialty metals such as antimony, arsenic and barium. These metals are mainly used in oxide or sulfate form, and many of the applications are highly dispersive. Collection is thus very difficult (drilling fluid remains in the hole, preservative remains in wood) or dependent on collection of the product (flame retardants in electronics), hence the old scrap in the recycling flow is very low, as is the recycling flow itself.
2. *Mainly new scrap recycling*. This designation is applicable to specialty metals such as indium and germanium (e.g. Yoshimura et al., 2011). The recycled content is above 25%, but other recycling statistics are very low. These metals are largely used in such applications as (opto)-electronics and photovoltaics. During manufacturing, a large amount of new scrap, such as spent sputtering targets, sawdust or broken wafers, is created. All of this material is recycled, and contributes to a high recycled content in the material supply to the manufacturing stage. Old scrap in the recycling flow is currently low due to the difficulty in collecting the products. Furthermore, the metal content in the products can be low, and recycling technology for these metals in EOL products is often lacking. Yet, research into the

recycling of a variety of specialty metals from discarded products is increasing, and promising first results exist (Rollat, 2012; Yoshida and Monozukuri, 2012).

3. *Old scrap recycling—metal specific*, rhenium, for example. Rhenium is used in superalloys and as a catalyst in industrial applications, which together make up most of its total use. This closed industrial cycle, as well as the high value of Re, ensures very good collection (Duclos et al., 2010). Furthermore, good recycling technologies are in place to recover the metal. New scrap is recycled as well. Because the rhenium demand is growing, and this is met largely by primary production, the share of recycled Re in the overall supply is low.

4. Old scrap recycling—metal unspecific, beryllium, for example. Beryllium–copper alloys are used in electronic and electric applications. The collection of these devices is generally good, and the Be follows the same route as the copper and ends up at copper smelters/recyclers. During the recycling process, the Be is usually not recovered but is diluted in the copper alloy or, most often, transferred to the slag in copper smelters. Hence the old scrap collection rate is quite high but the EOL recycling rate is low.

The way in which a product is designed is also a strong factor in whether recycling occurs. Dahmus and Gutowski (2007) have shown that

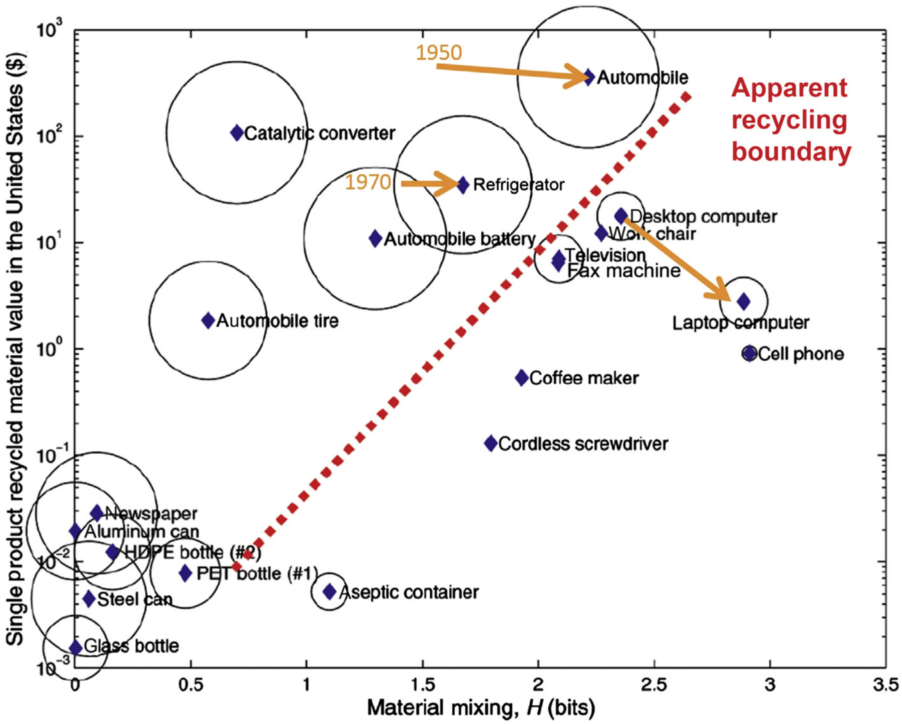

FIGURE 3.7 The relationship between recycled material value and material mixing, for 20 products in the United States, c. 2005. The area of the circle around each data point is proportional to the product recycling rate; products with no circle are generally not recycled. The arrows indicate a trend to increased material mixing, both at the product level (in the case of automobiles and refrigerators) and through substitution (in the case of computers). *Adapted from* *Dahmus and Gutowski, 2007*.

the greater the degree of material complexity in a product, the smaller the probability that recycling will occur (Figure 3.7). In fact, Figure 3.7 indicates that some products have actually increased their required level of material complexity in the past decade, so the product design-recycling situation is trending in the wrong direction.

3.6 SUMMARY

Many different approaches have been taken to quantify the rates at which metals are recycled. Inevitably, recycling rates have been defined in different ways, and this has made it difficult to determine how effectively recycling is occurring. Adopting the recycling rate definitions specified in this chapter will deal with this challenge.

An important realization regarding metal recycling is that it is a sequence of steps. If any one step is done poorly, the efficiency of the entire sequence suffers. Attention needs to be paid to each of the steps, because one step may be the most inefficient for some types of products, other steps for others.

The key questions, of course, are whether overall recycling efficiencies can be improved and, if so, by how much? That is, can materials cycles be transformed from open (i.e. without comprehensive recycling) to closed (i.e. completely reusable and reused), or at least to less open than they are at present? These are issues that turn out to be quite complex, to involve everything from product designers to policies for pickup of discarded electronics. The full range of this detail has seldom been presented to those who are most interested, but much of it will be explored in detail in subsequent chapters of this book.

References

Chancerel, P., Rotter, S., 2009. Recycling-oriented characterization of small waste electrical and electronic equipment. Waste Management 29 (8), 2336–2352.

Dahmus, J.B., Gutowski, T.G., 2007. What gets recycled: an information theory based model for product recycling. Environmental Science & Technology 41 (21), 7543–7550.

Duclos, S.J., Otto, J.P., Konitzer, D.G., 2010. Design in an era of constrained resources. Mechanical Engineering 132 (9), 36–40.

Eckelman, M.J., Daigo, I., 2008. Markov chain modeling of the global technological lifetime of copper. Ecological Economics 67 (2), 265–273.

Eckelman, M.J., Reck, B.K., Graedel, T.E., 2012. Exploring the global journey of nickel with Markov models. Journal of Industrial Ecology 16 (3), 334–342.

Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011a. What do we know about metal recycling rates? Journal of Industrial Ecology 15 (3), 355–366.

Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011b. Recycling Rates of Metals – A Status Report, a Report of the Working Group on the Global Metal Flows to UNEP's International Resource Panel.

Hagelüken, C., 2012. Recycling the platinum group metals: a European perspective. Platinum Metals Review 56 (1), 29–35.

Matsuno, Y., Daigo, I., Adachi, Y., 2007. Application of Markov chain model to calculate the average number of times of use of a material in society – an allocation methodology for open-loop recycling – part 2: case study for steel. International Journal of Life Cycle Assessment 12 (1), 34–39.

Nakajima, K., Takeda, O., Miki, T., Matsubae, K., Nakamura, S., Nagasaka, T., 2010. Thermodynamic analysis of contamination by alloying elements in aluminum recycling. Environmental Science & Technology 44 (14), 5594–5600.

Oguchi, M., Murakami, S., Sakanakura, H., Kida, A., Kameya, T., 2011. A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. Waste Management 31 (9–10), 2150–2160.

Reuter, M.A., Hudson, C., van Schaik, A., Heiskanen, K., Meskers, C., Hagelüken, C., 2013. Metal Recycling. Opportunities, Limits, Infrastructure. A Report of the Working Group on the Global Metal Flows to UNEP's International Resource Panel.

Rollat, A., 2012. How to satisfy the rare earths demand. Rhodia Rare Earth systems initiatives. In: Déjeuner-conférence sur "Les défis de l'approvisionnement en terres rares". European Society for Engineers and Industrialists, Brussels.

Streicher-Porte, M., Widmer, R., Jain, A., Bader, H.P., Scheidegger, R., Kytzia, S., 2005. Key drivers of the e-waste recycling system: assessing and modelling e-waste processing in the informal sector in Delhi. Environmental Impact Assessment Review 25 (5), 472–491.

van Schaik, A., Reuter, M.A., 2004. The time-varying factors influencing the recycling rate of products. Resources Conservation and Recycling 40 (4), 301–328.

Yoshida, M., Monozukuri, N., 2012. Mitsubishi develops eco-friendly, low-cost Ga recycling technology. In: Tech-On! Nikkei Business Publications, Inc. (NikkeiBP). http://techon.nikkeibp.co.jp/english/NEWS_EN/20121203/254051/.

Yoshimura, A., Daigo, I., Matsuno, Y., 2011. Construction of global scale substance flow of indium from mining. Journal of the Japan Institute of Metals 75 (9), 493–501.