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Challenges in Metal Recycling

Barbara K. Reck and T. E. Graedel

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REVIEW

Challenges in Metal Recycling

Barbara K. Reck* and T. E. Graedel

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. We review these topics, distinguishing among common, specialty, and precious metals. The most beneficial actions that could improve recycling rates are increased collection rates of discarded products, improved design for recycling, and the enhanced deployment of modern recycling methodology. As a global society, we are currently far away from a closed-loop material system. Much improvement is possible, but limitations of many kinds—not all of them technological—will preclude complete closure of the materials cycle.

The generation now between the ages of 20 and 30 is, in many parts of the world, the first to have grown up with the recycling bin as a normal part of life. Discarded paper, cans, and bottles have designated places to go, and often go there. The situation is less certain for products used for a number of years before being discarded—computers, refrigerators, automobiles—for which recycling procedures have been diverse and sporadic. And few know what happens to obsolete equipment used on behalf of individuals but owned by corporations or organizations—medical imaging machines, aircraft engines, and the like.

The recycling of products in the "occasionally discarded" or "owned by somebody else" categories is complicated by the rapid expansion of the designer's materials palette that has taken place in the past several decades (*1*, *2*). Today, virtually every stable element in the periodic table is used so as to take advantage of its unique physical and chemical properties. The result is that many products are more functional and reliable than before. An unintended consequence is that recycling has become much more complicated and challenging.

Several reviews of metal recycling have appeared in recent years (*3*–*5*). They discuss central issues such as recycling technologies, economic limitations, and methods of enhancement. Some open questions still remain: How much is going on, and what are the trends? What are its limits? Is a closed-loop materials economy possible? It is these systems-level topics that are the focus of the present work.

The Current Status of Metal Recycling

How well is the world doing at recycling the diverse mix of elements in modern products? Two metrics answer this question best: recycled content and end-of-life recycling rate (EOL-RR). Recycled content describes the share of scrap in metal production, which is important to get a sense of the magnitude of secondary supply. This indicator, however, has two limitations. First, lifetimes of metal-containing products often span several decades, which, in combination with rapid growth in metal use, means that recycled metal flows will meet only a modest portion of demand for many years to come. Second, it does not distinguish between new (yield loss from fabrication and manufacturing) and old (postconsumer) scrap as input material, making it vulnerable to artificially increased rates based solely on preconsumer sources (fabricators may be given incentives to increase their scrap output to meet secondary demand, making recycled content an incentive for inefficiencies in fabrication and manufacturing). What recycled content means to encourage, instead, is the amount of old scrap that is collected and processed for recycling [also expressed as old scrap ratio (*6*)]. The indicator that measures this more directly is the EOL-RR, defined as the fraction of metal in discarded products that is reused in such a way as to retain its functional properties.

The EOL-RR depends on the collection rate of end-of-life products and the efficiency of the subsequent separation and pre-processing steps, all involving complex interactions of a wide variety of players (*7*). A United Nations panel recently defined and quantified recycling rates for 60 elements (Fig. 1) (*8*). Two messages jump out at once from the figure. The first is that EOL-RRs for the commonly used "base metals" (iron, copper, zinc, etc.) are above 50% (although, as the report is careful to point out, usually not very far above 50%). The second, and striking, impression

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is the number of elements that are seldom if ever recycled. It turns out that most of these are increasingly used in small amounts for very precise technological purposes, such as red phosphors, high-strength magnets, thin-film solar cells, and computer chips. In those applications, often involving highly comingled "specialty metals," recovery can be so technologically and economically challenging that the attempt is seldom made. Overall, modern technology has produced a conundrum: The more intricate the product and the more diverse the materials set it uses, the better it is likely to perform, but the more difficult it is to recycle so as to preserve the resources that were essential to making it work in the first place.

The benefits of recycling are many, the most obvious being the potential to reduce the extraction of virgin ores, thus extending the life of those resources. The environmental impacts of metal production are reduced substantially when recycled materials rather than primary materials are used (*9*), and recycling a metal is generally much more energy-efficient than acquiring it from a mine (*10*–*13*). Depending on the metal and the form of scrap, recycling can save as much as a factor of 10 or 20 in energy consumption (*14*).

Factors influencing the recycling efficiency are the volumes involved and the economic value of the metal. Metals that are typically used in large quantities (enabling economies of scale) represent the largest fraction of currently recycled metals. These metals, which occur in relatively pure form and are straightforward to remelt, include steel, aluminum, copper, zinc, lead, and nickel. Their EOL-RRs are above 50%, and the lifetimes of the products in which they are used often span several decades. Recycling infrastructures are well established.

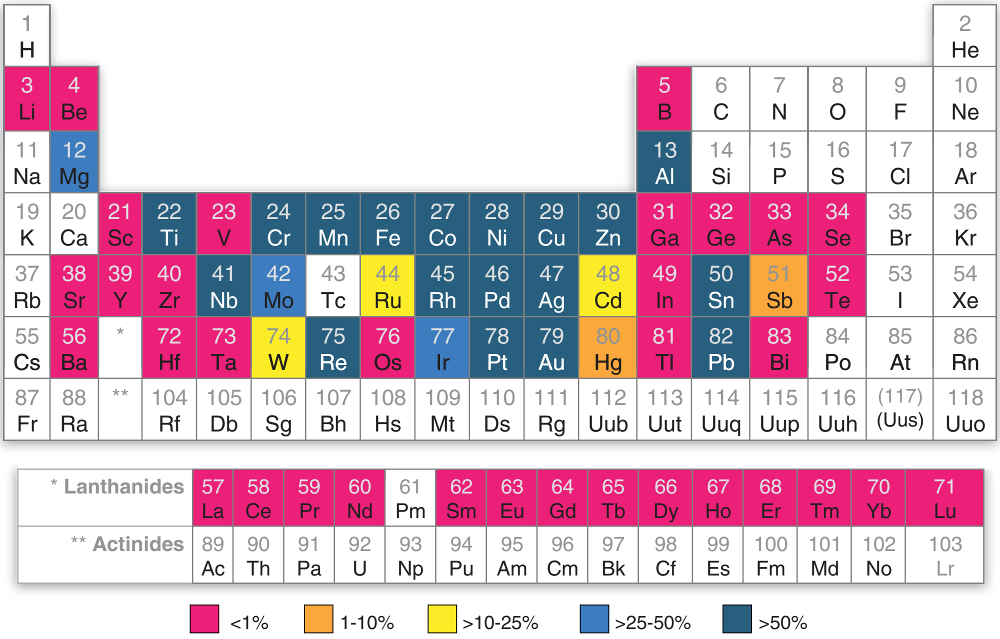

Fig. 1. Global estimates of end-of-life recycling rates for 60 metals and metalloids, circa 2008 [adapted from (*6*)].

At the other end of the spectrum are metals used in only small amounts. "Specialty" metals are used to enable enhanced performance in modern high-technology products such as jet engines, solar cells, and consumer electronics. In such applications, mixing of materials is extensive, separation technology is challenging, and the economics are often unfavorable because of the small amounts involved. The trend to use specialty metals is increasing, and given the short lifetimes of many electronic devices, end-of-life losses will also increase sharply soon unless better recycling management options are found. Most of the materials shown in red in Fig. 1 fall into the specialty metals group [e.g., indium (*15*), rare earth elements (*16*)].

A special case of metals used in small amounts are those with high economic value, such as precious metals. Their value is a key incentive for recycling (*17*), yet their end-of-life recycling rate is at best on the order of 60% (*6*). The reason is that despite high recycling rates for traditional uses in jewelry or industrial catalysts, the collection and recycling of platinum, palladium, and rhodium from automotive catalysts is more challenging. Here, collection rates fluctuate around just 50% in developed countries, largely as the result of exports of used vehicles to developing countries with minimal recycling technology (*18*). The same factors are also involved in the meager 5 to 10% recycling of platinum group metals in electronics (*19*). Within developing countries, informal recycling and low-technology processing combine to sharply limit the recovery of precious metals from consumer products (*20*).

Hazardous metals recycling takes place only occasionally and at low rates. Cadmium is mostly recycled in the form of nickel-cadmium batteries, where low collection rates limit the recycling efficiency (*21*, *22*), and global recycling rates of mercury-containing fluorescent light bulbs are found to range at best from 10 to 20% (*23*). Lead is an exception. Eighty percent of today's lead use is for batteries (*24*, *25*) in gasoline- and diesel-driven automobiles and for backup power supplies, and collection and pre-processing rates from these uses are estimated to be within 90 to 95% as a result of stringent regulation worldwide (*25*). The result is a nearly closed-loop system for lead use in batteries.

Ecotoxicity challenges can also arise from the disposal of metal-containing nanomaterials. Although modern solid-waste incinerators are found to efficiently remove engineered nanomaterials from flue gas, the disposal problem is only shifted to subsequent processing steps such as landfills, as the incineration process does not change the stable structure and properties of these materials (*26*), which is likely also the case in recycling processes.

Metal life cycles from cradle to grave. The potential for recycling depends on approaches and actions taken at each stage of the life cycle. This can be illustrated by example (Fig. 2A). The left panel shows the 2005 global life cycle for nickel (*27*). Of the 650 Gg (thousands of metric tons) of nickel that were discarded from use, about two-thirds was returned. Together with manufacturing scrap (165 Gg of Ni), recycled nickel provides about one-third of the nickel required for fabrication and manufacturing—obviously well worth doing, but with the potential for further improvement. By contrast, the right panel shows the 2007 global life cycle for neodymium (*16*). In this cycle, 15.6 Gg of Nd was used in fabrication and manufacturing, but only 1.2 Gg of Nd was discarded from use (mostly because products containing neodymium are rather recent arrivals on the market and have not yet become obsolete). Little to none of that material is currently being recycled, and if it were, it would not play a major supply role. In years to come and as discards mount, however, neodymium recycling has the potential to be of benefit. Although the two elements represent the two extremes in end-of-life recycling, it is sobering to note that even the overall life cycle efficiency of the more efficient one, nickel, is only 52%—that is, almost half of the extracted nickel is only used once before being lost as production waste, waste in landfills, or for

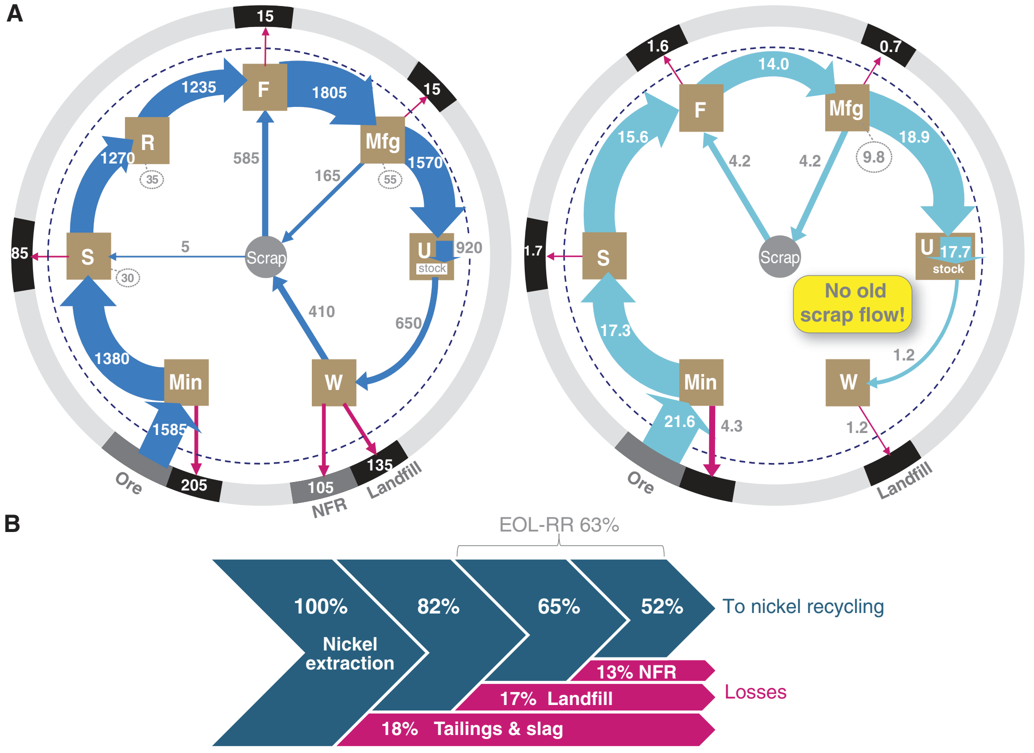

Fig. 2. (**A**) The global cycles of nickel for the year 2005 [left, adapted from (*27*)] and neodymium for 2007 [right, adapted from (*16*)]. The numbers indicate flows of metal within the anthroposphere, in Gg (thousands of metric tons). Flows crossing the dotted line transfer metal to the anthropogenic cycle or vice versa. The width of the arrows is an approximate indication of flow magnitude. Min, mining; S, smelting; R, refining; F, fabrication of semi-products (rolls, sheets, etc.); Mfg, manufacturing; W, waste management and recycling. (**B**) Material efficiencies across nickel's life cycle. Of the extracted nickel, 82% enters fabrication, manufacturing, and end use; 65% enters the recycling processes; and 52% is recycled for another use in which nickel's properties are required (functional recycling). Losses across one life cycle amount to 48%. EOL-RR, end-of-life recycling rate; NFR, nonfunctional recycling.

incorporation as a trace constituent into a recycled stream of iron or copper alloys (Fig. 2B). This confirms the results of Markov chain modeling, which shows that a unit of the common metals iron, copper, or nickel is only reused two or three times before being lost (*28*–*30*), gainsaying the notion of metals being repeatedly recyclable.

Product Recovery and Recycling Technology

An engineer or scientist instinctively thinks of technology when the topic of recycling is raised, but it turns out that social and cultural aspects are at least as important, perhaps more so (*31*, *32*). Metal price is a key driver directly affecting collection and processing efficiencies (*1*, *5*). Extensive manual disassembly of discarded electronics is typically not economically feasible in industrialized countries but may be advantageous in emerging economies such as India and China (*17*, *33*). Figure 3 shows the main steps involved in recycling, the key perspective being that the overall efficiency is the product of the efficiencies at each stage. As with a chain, the weakest link controls the performance of the system. The figure also shows the associated recovery and recycling efficiencies for nickel and neodymium across all end-of-life products, as well as the specific cases of nickel and rhenium from end-of-life aerospace superalloys. The first stage is collection, which refers to the transfer of an unwanted product from the owner to a suitable recycling facility.

Collection, pre-processing, and end processing. Collection rates vary greatly among different waste streams, depending on price, logistics, and other factors. Waste of electrical and electronic equipment (WEEE), in contrast, often has relatively low collection rates despite legislative efforts. In the European Union, 25 to 40% of WEEE is collected and treated in the official system (*34*), the rest being discarded into municipal waste, exported as used products or scrap, or otherwise lost. Current WEEE legislation in the European Union and Japan focuses on mass recovery, which favors steel and base metals used in large quantities, whereas precious and specialty metals, found in small electrical and electronic equipment, are often not recovered (*35*, *36*). Considering this situation, as well as the recent debate on critical metals [e.g., (*37*)], a revision of these priorities seems likely (*34*).

After collection, the postconsumer metal enters a series of pre-processing steps, including repeated sorting (e.g., manual, magnetic, optical), dismantling, and physical and chemical separation (*38*, *39*). Issues of scale are important here. Virgin materials processing is generally large in scale, using processes underwritten by historically low energy prices. In contrast, recycling is often local, more labor-intensive, and smaller in scale. In such a situation, the monetary returns are often not sufficient to justify the purchase of modern "sense and sort" technologies, and much otherwise recoverable material is lost.

The example of a nickel- and rhenium-containing aerospace superalloy shows how price, material combinations, size, and shape can drive the efficiency (Fig. 3). One company estimates that collection rates of these superalloys are around 90% because of their high value and the favorable logistics of a relatively small industry (*40*). Around 80% of the scrap is in solid pieces that can easily undergo grade-specific identification and recycling. The other 20% is in the form of turnings and other small fractions and can be sent to a stainless steel smelter. This translates into an 81% efficiency for nickel, which is required in both the superalloy and stainless steel, but only a 68% efficiency for rhenium (Fig. 3). Similarly, neodymium may be collected at a rate of 30% from electronics or magnets, but with no element-specific recycling technology existing at present, its overall recycling efficiency is near zero and it will either be discarded or become a trace element in recycled metal.

After pre-processing, the material will be sent to a smelter or other thermochemical facility where processing has been optimized (end-processing). In most cases, these are primary smelters, although some facilities—including electric arc furnaces in steel production as well as smelters processing electronic wastes for the recovery of precious metals, copper, and some specialty metals—specialize in processing secondary metals. As Fig. 1 shows, some metals have fairly high overall recycling rates, generally because they are used in large, easy-to-identify applications such as steel beams or lead batteries, but half or more of the metals face the larger challenge of the recycling sequence and its typical efficiencies.

Recycling technology. Collection efficiencies are related to social and governmental factors, but separation and sorting efficiencies relate to recycling technology. It is unfortunate from a materials perspective that, for reasons of scale and economics, often only the more basic technologies (shredding, crushing, magnetic sorting) are routinely applied, whereas more advanced technologies (such as laser, near-infrared, or x-ray sorting) are limited to selected recyclate streams. Disassembly and liberation of materials is often challenged through product design [e.g., laminated permanent magnets in computers (41)].

Although there are notable examples of innovative recycling technologies, many in demonstration mode, much more attention needs to be paid to modernizing and upgrading existing generic approaches if overall efficiencies are to become higher than they are now (1). Such a modernization could go hand in hand with an international division in labor, as is common practice in manufacturing processes. The best-of-two-worlds approach suggested for electronics recommends taking advantage of the low labor costs in developing countries for manual disassembly, and the high efficiency of specialized smelters, typically located in industrialized countries, for end-processing (42). An encouraging example is Peru, which combines formal and informal collection channels for discarded computers: Single materials such as copper, steel, and aluminum are recycled domestically, while a portion of the complex and valuable printed circuit boards are exported to an advanced smelter in Germany (43). However, some of the boards also go to China for informal recycling, with all the associated potential environmental implications (44).

Improved recovery and recycling performance has occurred here and there in recent years, especially when high-value metals are involved. The recent spike in rare earth prices has accelerated research into recycling technologies for specialty metals, particularly in Japan after China had briefly cut off its supply of rare earths (45, 46).

State-of-the-art pre-processing facilities are often still optimized for mass recovery, at the expense of recovery of precious and specialty metals. Targeted disassembly prior to shredding could substantially increase the recovery of precious metals from WEEE (47, 48). A Japanese study estimates that additional separation steps in the collection and presorting of small WEEE have the potential to increase gold recovery from the current 26% to some 43%, tantalum up to 48%, and gallium up to 30% (49). And, sometimes, scarce metals can be replaced by more common metals with only modest loss of product performance. Examples are aluminum-doped zinc oxides substituting for indium tin oxides in liquid crystal displays (50) and various compounds replacing rare earths in capacitors (51).

Thermodynamics. Thermodynamics is an ultimate limitation at the final processing stage (38, 39). Few metals are used in pure form; rather, most are components of alloys or other mixtures. When these materials undergo reprocessing, some elements will be reprocessed to their elemental form (e.g., copper), but many will be reprocessed in alloy form [e.g., nickel, tin (52)]. The reason lies in the often similar thermodynamic behavior of alloying elements that make their separation either very energy-intensive or essentially impossible. This is illustrated by the element radar chart in Fig. 4 (53, 54), showing the behavior of impurities during the metallurgical processing of base metals. Elements distributing to the slag and gas phase can sometimes be extracted in subsequent steps. Elements remaining in the metal phase cannot be separated, with the exception of copper and lead smelting, where consecutive processing steps allow for the removal of the alloying elements (a fact benefiting the recovery of precious metals from electronic waste) (55). The iron metal phase retains both harmful tramp elements (copper, tin) and benign alloying elements (nickel, molybdenum, cobalt, and tungsten). Unless these elements 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 removal of impurities is a much bigger challenge for aluminum (5, 53, 56) and magnesium (54) than for other base metals. Manganese, for example, used in the 3000 series of aluminum alloys, is retained in the metal phase during remelting, producing a melt that would be unsuitable for reuse in any other Al-based system. Unless the 3000 series alloys were separated prior to remelting, the resulting metal would be unsuitable for 95% of all aluminum applications (53). Similarly, lead remaining in copper's metal phase reduces copper's conductivity, making it unsuitable for use in electrical applications (55). This unavoidable circumstance needs to be part of every product designer's knowledge so that metal combinations that cannot be successfully recycled will be minimized. It also highlights the importance of efficient separation during pre-processing steps.

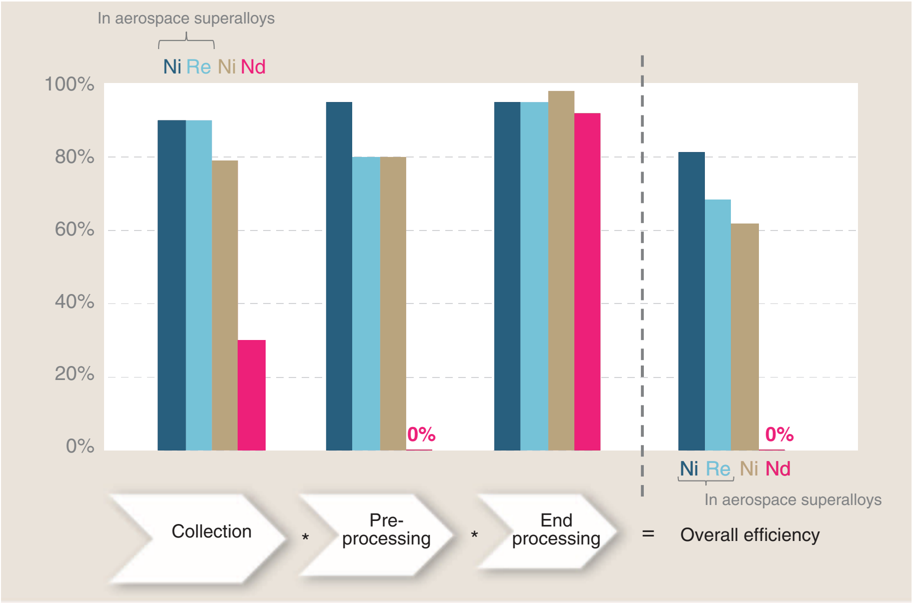

Fig. 3. The sequence of the main steps involved in the recycling of metals. Typical efficiencies are shown for nickel and rhenium in superalloys used in jet engines (40), nickel overall, and neodymium. Collection and end-processing rates for neodymium are estimates shown for illustrative purposes only.

Addressing Future Recycling Challenges

It seems mundane at first telling, but the activity with the greatest potential to improve metal recycling is collection. Such an effort is not so important for iron, copper, or lead, which are typically used in forms that make them easy to identify and reprocess, but is absolutely crucial for the vast majority of metals, used in small quantities in highly mixed products. Collecting discards with high efficiency and with proper care (to avoid mixing that would frustrate later processing) is largely an issue of behavioral habits and incentives, as well as initiatives such as required recycling deposits on consumer goods. Collection and reprocessing of many metals is also hampered by the international trade in used products that sends complex products to countries with inadequate recycling facilities (31, 57). The situation clearly calls for international policy initiatives to minimize the seemingly bizarre situation of spending large amounts of technology, time, energy, and money to acquire scarce metals from the mines, and then throwing them away after a single use.

After attending to collection, the next challenge is to involve the designers of future products in choosing material combinations with recycling in mind. Only designers can reverse the current trend of greater material mixing, but current designs are actually less recyclable than was the case a few decades ago (1). Warnings regarding the increasingly dissipative use of metals are not

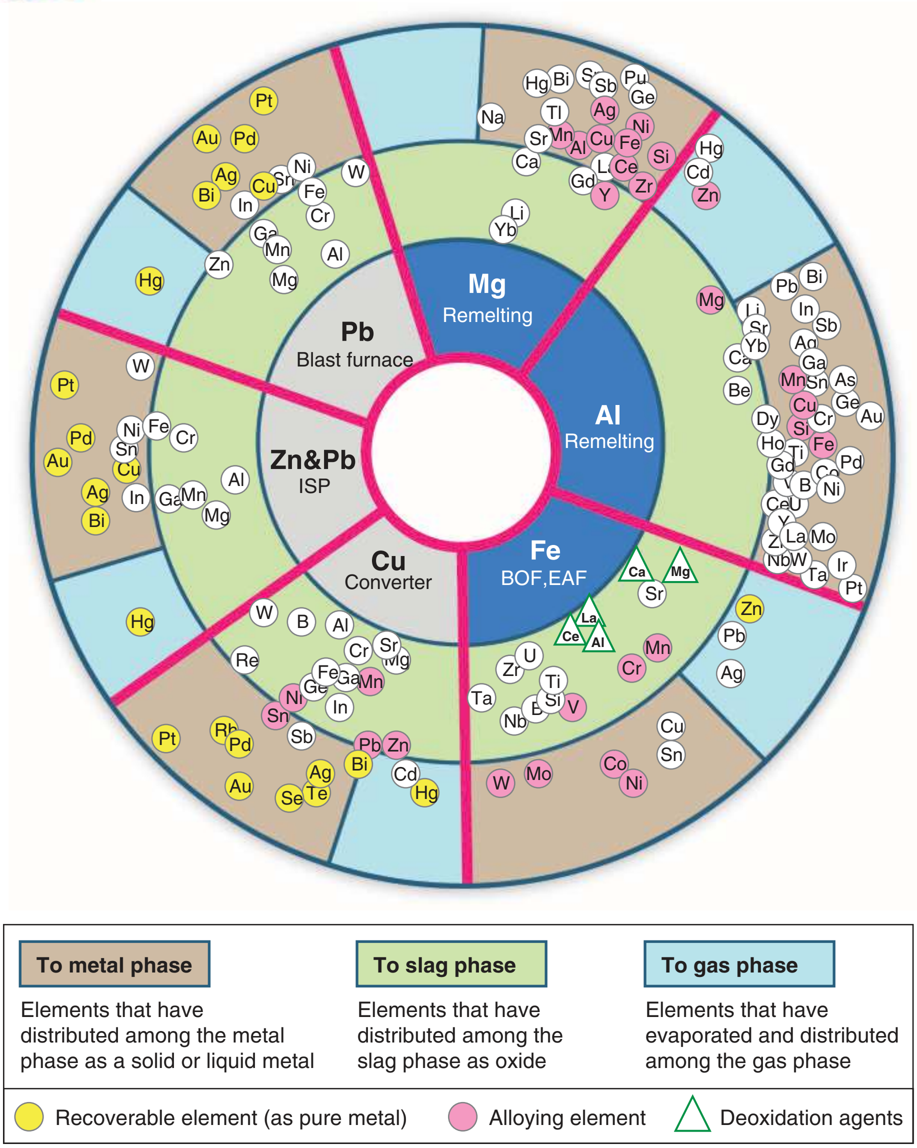

Fig. 4. An element radar chart showing the distribution of alloying elements among metal, slag, and gas phases during thermochemical reprocessing (*54*). BOF, basic oxygen furnace; EAF, electric arc furnace; ISP, imperial smelting process.

new (*3*), but applications such as nanomaterials and microelectronics generally introduce major recycling challenges. Ideally, an information feedback loop to materials scientists and designers would emphasize the consequences of complex designs on the recyclability of products (*58*, *59*), leading, for example, to a redesign of alloys to accommodate more scrap (*56*).

The final frontier is improved recycling technology. It is not much of an exaggeration to say that we manufacture modern products with the best possible technologies we can devise, but generally recycle them with relatively basic approaches. This situation has evolved from a lack of incentives in many directions—little to no support for implementation of new recycling technologies, the unfavorable image of the scrap yard, the frequent specification of virgin material by manufacturers, and sheer lack of knowledge as to the elemental composition of modern products. It is true that recycling is often limited by unfavorable economics, but it is equally true that those economics reflect a lack of attention to design for recycling and a reluctance to invest in the improved separation and sorting equipment that has emerged within the past decade. It is time that corporations, universities, and governments work together to transform the state of today's metal recycling by demonstrating the need for continuing research on improved technologies, the potential benefits of deployment of the improved technologies now available, and the promise suggested by regulatory and financial initiatives that speak to these challenges.

From the standpoint of the sustainability of metals, the world is at a crossroads. After millennia of products made almost entirely of a handful of metals, modern technology is today using almost every possible metal, but often only once. Few approaches could be more unsustainable. If as a global society we can collect and reuse almost everything, design products with optimized recycling in mind, and use transformative technology to make the whole process exemplary, we will be helping to ensure that the materials scientists of the future have for their use the full palette of the wonders of the periodic table, and thereby provide society with increasingly innovative and remarkable products.

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REVIEW

Valorization of Biomass: Deriving More Value from Waste

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Most of the carbon-based compounds currently manufactured by the chemical industry are derived from petroleum. The rising cost and dwindling supply of oil have been focusing attention on possible routes to making chemicals, fuels, and solvents from biomass instead. In this context, many recent studies have assessed the relative merits of applying different dedicated crops to chemical production. Here, we highlight the opportunities for diverting existing residual biomass—the by-products of present agricultural and food-processing streams—to this end.

Times are rapidly changing. Who could have imagined that in 2012 a commercially viable venture would involve shipping ~200,000 tonnes (t)/year of household waste from Italy to Rotterdam for use as a feedstock for electricity generation in Dutch power plants with overcapacity (*1*)? Waste is lucrative business or, as they say in northern England: "Where there's muck there's brass." Since the early 1990s, attention has been diverted from waste remediation to waste prevention, with the emphasis on applying the principles of "green chemistry" (prevention is better than cure) (*2*). Now the focus is moving toward exploiting those wastes that are largely unavoidable.

In its most general sense, the term "waste" covers any organic material apart from the primary material for which the plants were originally grown (e.g., corn stover from maize or lignin from paper pulping). Nearly all wastes currently have some value—for instance, stover for improving the soil in the fields, or lignin as a fuel to power paper mills. Here, we concentrate on ways of getting higher value from the waste, particularly via conversion to chemicals. However, making a commercial case for such a process must necessarily include the cost of replacing the original function of the waste—for example, powering the mills with hydroelectricity. Indeed, one can quantify the value of different "waste valorization" strategies (Table 1).

Because the sources of waste are so diverse, it is convenient to consider the chemistry in terms of four source-independent categories: polysaccharides, lignin, triglycerides (from fats and oils), and proteins. As explained later, lignin is challenging to break down into chemically useful fragments. By contrast, pretreatment of polysaccharides, triglycerides, and proteins can lead to their constituent building blocks: monosaccharides, fatty acids plus glycerol, and amino acids, respectively. There are several recent specialized reviews on the conversion of biomass to chemicals (*3*–*6*). However, exploiting waste in a profitable way is a highly multidisciplinary problem; therefore, we outline here recent developments for a wider audience with the emphasis on optimizing the valorization of the various components of residual biomass.

Waste is perhaps a concept even broader than the definition above, because it applies to any biomass-derived by-product for which supply greatly exceeds demand. For example, glycerol can be a valuable chemical, but it is being generated in increasing quantities by the biodiesel industry and could become a "waste." By applying even a crude valorization analysis, one finds that conversion of glycerol to the chemical epichlorohydrin is economically attractive compared to the alternatives, because the value of this conversion is 3 times that of conversion to transportation fuel and 10 times that of burning to generate electricity—hence Solvay's recent commissioning of a new 100,000 t/year epichlorohydrin plant based on glycerol in Thailand (*7*). In the longer term, glycerol could become a platform molecule leading to many different fine chemicals, but the establishment of such platforms will require a much more mature bio-based chemical industry.

Most biomass waste is a complex and variable mixture of molecules, and separation becomes a key issue. An added complication is that some of both the bio-waste and the materials to be separated are solid; therefore, separation frequently involves organic solvents. If bio-based chemical production is to become self-sustaining, those solvents must also be bio-based and cannot, in the long term, be derived from crude oil. In addition, bio-based solvents would be highly useful materials in their own right. If such solvents can also function as fuel additives and platform chemicals, one would have the basis for a genuinely robust technology (*8*).

Some of the processing of petrochemical hydrocarbon feedstocks involves the introduction of oxygen-containing functional groups by, for

Table 1. Approximate valorization of biomass waste for different uses* (*48*, *58*).

	Value ($/t biomass)
Average bulk chemical	1000
Transportation fuel	200–400
Cattle feed†	70–200
Generating electricity	60–150
	Cost
Landfill	–400

*Taken from (*48*) apart from data for cattle feed. The values are based on costs in the Netherlands, but the order of the values is likely to be similar across the developed world. †Data from (*58*); this range of values depends on the quality of the feed.

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