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Recycling and Sustainable Utilization of Precious and Specialty Metals

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1.1 Introduction

The need for increased and more effective recycling of our technology metal supply is urgent. This supply consists of both precious and specialty metals. Both sets of metals are essential to functioning of our high-technology products, but for economic reasons there is much more interest in recycling the former than the latter. Average recycling rates for precious metals are above 50% [1], but huge differences exist depending on their application. For example, from chemical and oil refining process catalysts used in "closed cycles" over 90% of the precious metals contained therein are recovered even in case of long lifecycles of over 10 years. Closed cycles prevail in industrial processes where precious metals are used to enable the manufacture of products or intermediates. Hence, a closed cycle is typically taking place in a business-to-business (B2B) environment with no private consumers involved in its different steps. In such systems, the user of the metal-containing product (e.g., the chemical plant) returns the spent product directly to a refiner who recovers the metals and returns them to the owner for a new product cycle. In most cases, the metals remain the property of the user for the entire cycle and the metal-refiner conducts recycling as a service (so called toll refining). Third parties are hardly involved, and, if so, only as other-service contractors (e.g., burning off carbon-contaminated oil refining catalysts), but not taking property of the material. With such a setup, the whole cycle flow becomes very transparent and professionally managed by industrial stakeholders, resulting in very small metal losses.

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Recycling rates are usually much lower in “open cycles” taking place in a business-to-consumers (B2C) environment. Typical examples are electronics and car catalysts. The owner of the spent product (e.g., an ELV or a PC), who might be number *x* in line after a number of preceding (second-hand) product owners, does not return the product directly to a metals refiner. Instead, the product goes through a usually, long, complex and sometimes opaque chain of collectors and scrap dealers until it reaches the real metal recyclers, in a consolidated way. In this process, ownership of the metal changes each time a transaction occurs, transparency is low, business transactions can be rather strange and special, and resulting metal losses are usually much higher than in B2B closed-loop systems. Important impact factors that determine the overall recycling rates of open cycles are intrinsic value, the ease or difficulty of accessing the relevant component or product, and legal or other boundary conditions that can help channel consumer products into appropriate recycling processes along the chain. An example on the high side (>95% recycling rate) is jewelry, where the high metal and emotional value of a gold ring, for example, prevents losses. Recovery rates of platinum group metals (PGM) can be 60–70%, in the case of automotive catalysts [2], which are quite successfully recycled (easy to disassemble from a car and high intrinsic value). However, metallurgical recovery rates for PGM are>95% with the gap being due to exports of end-of-life (EoL) cars and long and opaque chains before a spent catalyst reaches a precious metals refinery. On the low side with average precious metal recycling rates below 15% are EoL electronic wastes (e-wastes). This low recycling rate is caused by poor collection, often inappropriate pre-treatment, and a high share of precious metal-containing fractions that enter sub-standard or informal recycling processes. Such processes operate with untrained personnel using crude equipment and result in severe adverse environmental and health effects [3]. Recovery rates of precious metals from e-wastes, if treated in state-of-the-art integrated smelter operations, would be>95%, but the waste materials need to get there. The concept of open versus closed cycles has been described [4]. Summarizing, in open cycles metal losses are significantly higher than those that would be found in metallurgical refining. The net effect is that highly efficient state-of-the-art technology [2] is used for only a small portion of waste products containing these precious and specialty metals. Products that are recycled properly are mainly those of high economic value and/or those from closed industrial loops. Recycling of specialty metals from such products is even more challenging. Metals in these products face the same limits of open cycles, but in addition with a lower economic value their recovery is far less attractive, and in some cases there are also thermodynamic limits. As has been elaborated [2,3,5] and is discussed later in this chapter, advanced metallurgical processes can co-recover a number of specialty metals if they fit chemically into a specific extraction system, e.g., in addition to the precious metals, Se, Te, Sb, Sn and In, partially, can be extracted pyrometallurgically by the collector metals Cu, Pb or Ni. However, others like Ta, Ga, and rare earth metals do not extract well. This situation leads overall to very low recycling rates for many specialty metals. Although of high strategic importance in our society, many specialty metals are not recycled but are usually discarded to the commons after one, often brief, use.

The subject of recycling is central to the thrust of this book. Most chapters have sections dealing with the status of metal recycling. For example, Ueda *et al.* [6] describe Pt metal recovery at Tanaka Kikinzoku Kogyo K.K. in Japan. From these accounts, one can obtain an appreciation for the successes, inadequacies, and challenges associated with metal recycling throughout the world. The amount of e-waste generated globally is enormous, estimated by several chapter authors as being 30–50 million tons yearly [7,8] with an estimated growth rate of 4–5% [8]. These numbers are startling and provide evidence for why it is incumbent on involved stakeholders to find technical and practical ways to improve global recycling processes [9,10]. However, it needs to be understood that only a fraction of this global waste is relevant for the recycling of precious and specialty metals. This fraction comprises of EoL information and communications technology (ICT) devices encompassing cellular phones, computer and network hardware, etc., and of audio-video devices (radio, television, etc.). White goods as well as electric household devices such as vacuum cleaners, toasters or electric tools are of importance for the recycling of steel, base metals (e.g., Cu) and plastics but contain very small amounts of precious and specialty metals. In addition, especially for electronic devices, miniaturization and new types of products lead to a reduction of weight although sales numbers are still on the rise. Examples are TVs (CRT-TV > 30 kg; LCD-TV ≈ 16 kg, LED-TV ≈ 14 kg) and computers (desktop PC ≈ 12 kg, notebook 2–3 kg, tablet 0.3 kg) [11]. Continuing on the current course has dire consequences for Earth's metal supply as well as negative consequences for the global environment and health of Earth's inhabitants, human and otherwise [3].

Recycling of metals from modern high-technology products, including waste electronics, EoL vehicles, and automotive catalytic devices is a complex procedure. Current recycling procedures from collection of EoL products to disassembling them into component parts to recovering target metals have been presented and discussed [9]. Important global benefits are derived from effective recycling, including the possibility of 'mining' target metals at a fraction of the economic and environmental costs associated with mining virgin ore [2,3]. However, there is a fundamental difference between a geological and an urban mine deposit. In general, a geological deposit is characterized by the composition and grade of its ore and by the total volume of the ore body leading to an estimation of the tonnage of target metals to be extracted. In a mining deposit, the ore body is concentrated in a specific location. It might be difficult to access and to mine the ore, but it exists in a defined space and it stays there. Hence, if total ore volume and metal prices justify, the necessary infrastructure will be built up and mining will start. The high investments and capital costs of operating a mine, consequently, force many operators to keep the mine running even at depressed prices as long as at least the variable operating costs can be covered.

In these respects, the challenge for secondary deposits, such as are found in an urban mine, is much greater. Although the "ore grade" might be significantly higher than in natural deposits, the urban mining activities are scattered over a vast area. In the case of consumer products, this area comprises millions of individual households. To make a real urban mine, it is first necessary to bring or pull the millions of devices — think about mobile phones or computers — towards the recycling facilities. Once there is a big pile of EoL devices at the gate of a recycling facility, it forms a real deposit, but not before. High metal prices and metal content in an EoL device (i.e., a high intrinsic value) can **push** these devices towards recycling, as it is the case with jewellery scrap or catalysts. However, if the intrinsic value is not sufficiently attractive, then **pull** mechanisms like waste legislation or business models such as leasing or deposit systems will be needed to generate an economically viable urban mine. Also, other than in primary mines, the system is much more vulnerable to price fluctuations. Decreasing metal prices can immediately stop the push mechanism, as the logistical costs involved are mainly variable. So, metallurgical recycling operations down the chain, which usually have high capital costs to bear, might be "overnight" faced with decreasing feeds. Hence, in the urban mine not only can the logistics be more challenging than in primary mines, but the economic drivers and feedback effects are often more complex. This is the reason that societal and legislative frame conditions are crucial for harvesting the urban mine.

Of equal importance to the technical and economic aspects of recycling is the involvement of stakeholders in decisions and actions involving recycling and sustainable utilization of precious and specialty metals [3,9]. Stakeholders include the public; media personnel; local, regional and national decision makers; industry executives; scientists and engineers; and others. Issues of importance might include: wastage of a critical recoverable resource, depletion of a non-renewable resource; environmental damage associated with inefficient mining and recycling, and target metal recovery technologies; and/or irresponsible mining of virgin ore. It is a major purpose of this chapter to supply information intended to make stakeholders aware of these issues and of the advantages of overcoming them by involvement of an informed public and media, passage and enforcement of appropriate legislation, and working together to conserve our valuable metal resources. It has been observed [12] that an effective way of promoting innovation on environmental matters is to pass and enforce legislation requiring compliance. This action often prompts companies involved to consider and develop new technologies to achieve compliance with the legislation. Another way to express the principle is that 'necessity is the mother of invention.'

The magnitude of the global waste problem is large and is expected to continue to increase into the indefinite future. Since technology metals are integral parts of electronic and other high-tech wastes, it is desirable to recycle these metals to aid in conserving our metal supply. With present usage, there is a constant drain on the global technology metal resource. In this chapter, several aspects of recycling are presented and discussed with the aim of improving metal sustainability. Global benefits of recycling specialty and precious metals are explored. Urban or above ground mining of metals is presented as a viable but little used means of conserving our metal supply. Reasons for this situation are complex, but urban mining holds great promise of providing a means of conserving the technology metal supply. Technologies currently used are evaluated in terms of the needs in formal and informal recycling. The need for innovation in all areas of recycling is stressed. Important roles are suggested that interested stakeholders can fill in ensuring that responsible and sustainable utilization of precious and specialty metals occurs. The chapter material makes clear that there are negative consequences to society and to the planet of inadequately maintaining metal sustainability.

1.2 How did we come to this Situation?

Our world faces major societal challenges that are unique to our time. These challenges include a rapidly growing global population, increasing global demand for high-technology consumer products, growing global affluence as the standard of living increases steadily in non-Organization for Economic Cooperation and Development (OECD) nations, management of our global energy supply amid demands for greater clean chemistry and non-greenhouse-gas-emitting energy sources, and improving stewardship over Earth's critical resources. An important common component of these challenges and a major critical resource is our global metal supply, particularly our technology metals. These metals are the group of specialty and precious metals that are essential for the functioning of high-technology products due to the specific and often unique chemical and physical properties of the metals. In general, these properties cannot be duplicated by other metallic or non-metallic substances without significant loss of function, making their replacement difficult [13]. Sustainability of our high-tech society at its present level depends on continued availability of these technology metals. An increasingly important part of metal use is recognized to be the need to recycle these important resources when the products containing them reach their EoL state. Generally, the global track record of society in recycling technology metals is poor [3,14].

The use of technology metals as essential components of high-tech products is a recent one. It is instructive to learn how this role developed and how the need for recycling has become critical. Metal recycling is as old as man's use of metals, extending into antiquity. The dozen or so metals available for use in earlier times were valuable for many reasons, including weapons, structural material, infrastructure, transportation, trade items, currency, and ornament. In general, these metals were used in bulk where they were familiar to those who used them. The impact of metal use on developing civilizations over the ages has been enormous [15] and has accelerated during the past half century [3]. In principle, metals are indestructible and can be reused indefinitely without loss of function, provided there is an economically viable means to recover them from EoL products and to purify them. Recovering metals for reuse was a simpler task prior to the 20th century. Fewer metals were involved, generally major metals used in large-scale operations, such as Fe, Co, Ni, Cu, Zn, Sn, and Pb, and the precious metals Au and Ag used for jewelry, coins and (religious) artifacts. Environmental laws were largely non-existent and recycling usually involved working with large quantities of waste metals. Environmental damage caused by metals was mainly limited to specific areas of mining and refining and was largely accepted as part of the price to be paid. Serious health effects from metal poisoning were present but were poorly understood, and few safety features were available to workers. Environmental effects were largely ignored.

This situation had changed significantly by the mid-20th century. Blank spaces in the periodic table up to U were completed with the identification of Pm in 1947. Intensive studies of the chemical and physical properties of the newly discovered elements paid rich dividends in providing a base for those trained in material sciences to design and construct products never before envisaged that could accomplish tasks formerly relegated to science fiction. The metals essential to these products were used in small quantities and were usually hidden behind casings, so they were little known to the public who used the products. This lack of knowledge can be ascertained quickly by asking literate users of high-tech devices, such as an iPhone, if they are familiar with, say, Dy, Tb, Nd, or In. The answer is usually no with the added comment that chemistry was not one of their favorite subjects.

During the last half of the 20th century and continuing to the present, a remarkable change has occurred with the appearance of new products containing these technology metals which literally transformed global society, including our personal lives, and how we do business, communicate, transmit information, entertain ourselves, produce clean energy, catalyse reactions to produce new products and control unwanted emissions, diagnose and treat a myriad of medical conditions, and many more. These products are used with little or no knowledge by users of the essential role of the technology metals in their function or of the consequences of depleting our technology metal supply. It is desirable to change this situation and make every effort to make the public and other stakeholders aware that in discarding e-waste and other wastes containing technology metals, as is done at present, we are sending enormous amounts of valuable and critical metal resources to locations in the commons where they are unrecoverable with current technologies.

Changes in global society are slowly bringing a realization that resources are finite and that mankind has a responsibility to manage them for the good of present and future generations.

This recognition of responsible stewardship is a positive development and needs to be encouraged. Metals are among the most important resources on the planet and their very nature makes it possible to recycle them repeatedly without loss of function, unlike other resources such as those based on fossil fuels or synthesized from organic compounds. The unique and remarkable physical and chemical properties of metals make possible the advanced society we all enjoy. However, without proper control, metals can harm the environment and have devastating effects on human health. Environmental and human health disasters such as Minamata Bay and Toyama Bay in Japan in the mid-20th century [16–18], involving uncontrolled release of Hg and Cd, respectively, into the environment, contributed immeasurably to the early movement in OECD nations of establishing and enforcing legislative controls on metal emissions. Most non-OECD nations still lag far behind in metal sustainability efforts. Rare earth mining in China [19] and essentially uncontrolled use of Hg in artisanal Au mining in China [20] and Peru [21] illustrate the externality effects of improper use of metals.

Beginning in the 1960s, new products began to appear that were characterized by the incorporation in them of a wide range of technology metals. These metals imparted novel properties and functions unlike any seen previously. One of the earliest of these products was color television, which was made possible by the unique phosphor properties of Eu that produced the red color on television screens. Europium is still the metal of choice for production of this color on screens, illustrating the uniqueness of this property to Eu. The unique electronic properties of rare earth metals made them favorite targets for use in novel product development. The resulting spectacular growth in rare earth mining and production is shown in Figure 1. Neodymium and Dy together with Fe and B were fabricated to form miniature magnets of superior strength, making miniaturization of high-tech products and other devices possible.

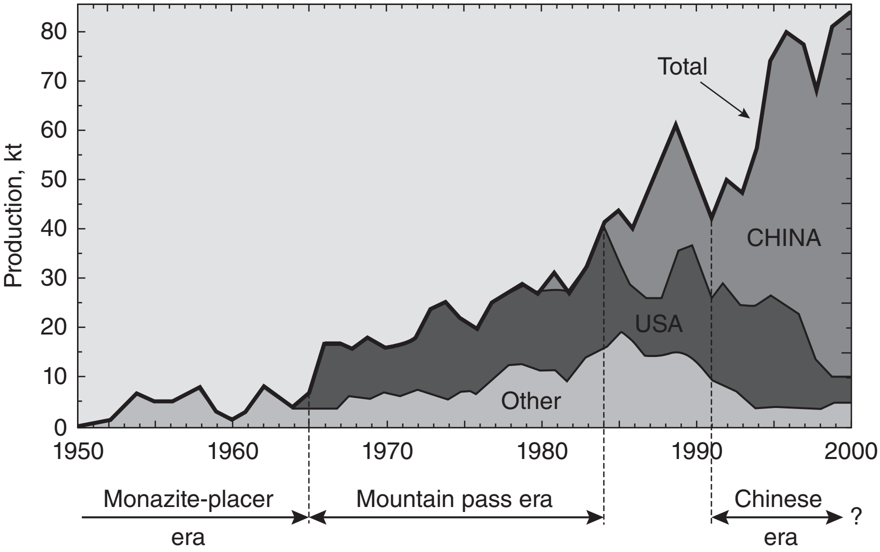

Figure 1 *Global rare earth oxide production trends, 1950–2000. The Mountain Pass deposit is in California, U.S.A. Reproduced from Wikipedia: <https://en.wikipedia.org/wiki/Rare_earth_element> Accessed from website March 10, 2016. kt=kilotonnes. (See insert for color representation of the figure.)*

Another significant discovery was that In had the nearly unique ability, when coupled with Sn, to form the transparent conductive coating now used in all flat screen devices [3]. The list could go on. In mid-20th century, a few metals were used largely for bulk purposes. By 1980, 25 were in use, but in 2015 over 40 are needed for products used in our high-technology global society [2]. Recycling rates for many of these technology metals in electronic products remain <1% [1].

1.3 Magnitude of the Waste Problem and Disposal of End-of-Life Products

The magnitude of the global waste problem is enormous and is steadily growing. Williams [7] indicates that e-waste is one of the chief sources of metal and organic pollutants in solid waste and the fastest growing waste stream. Williams cites one estimate that 41.8 million metric tonnes of electrical and electronic products were discarded globally in 2014, with a rise to 50 million metric tonnes predicted by 2018. The number beyond that date is expected to continue to rise due to global population increase, greater consumer affluence, increased production of new products to replace old ones, and, inevitably, the introduction of additional new products containing technology metals. In other words, there is no leveling off of the generation of e-waste. Osibanjo et al. [8] report that the amount of generated e-waste increases annually by about 4–5%. Williams [7] points out that a 1987 Nokia Cityman mobile phone weighed 770 g and contained few elements, whereas a modern Nokia smartphone weighs about 100 g and contains more than 40 elements. The increased number of elements is closely connected to the greatly increased number of functions the modern phone can perform. What is the fate of the technology metals in these discarded products? The simple answer is that they are to a great part lost to the commons [1].

Main options for disposal of EoL products include storage or stockpile, landfill, incineration, use as second-hand units, and formal/informal recycling of constituents [22]. Estimates are that nearly half of the 1.8 billion new cell phones purchased in 2014 will end up ‘hibernating’ in drawers within a few years [23]. This statistic is a reflection on the lack of effective collection systems for high-tech products. The effectiveness of collection systems is a bit higher in the European Union and Japan where more attention is focused on this activity [7]. In the U.S., no national program exists and individual states have programs ranging from non-existent to fair. In non-OECD nations like China [7] and Nigeria [24], few formal collection systems exist, but informal systems are fairly successful. The number of electronic products discarded in 2010 in the U.S.A., 400 million [25], was matched by an equal number discarded in China [3]. These numbers increase globally each year. Adding the expected number of waste electronic products from Europe and other nations, one can appreciate the growing magnitude of the global waste management problem. It has been estimated that of the 27% of generated e-waste collected for recycling in the U.S. in 2010, up to 80% was shipped illegally [25] to non-OECD nations, such as China, India, and Nigeria, where some may be reused. However, the ultimate fate of most of these exported waste electronic products is that they are manually dismantled or burned and have a few metals of value recovered by the process known as informal recycling [3].

Landfills are the most common means for disposal of waste worldwide [25]. Amounts of e-waste deposited in landfills are large. For example, a large fraction of e-waste products generated in the U.S. was probably stored in drawers, consigned to landfills, or incinerated.

In the latter two cases, contained metals are usually unrecoverable by present technology and, hence are lost to the potential metal supply. Potential dangers in landfills include leakage due to improper sealing, weather events, population increases in the area with subsequent human exposure to the contents, and inevitable deterioration of the site with time. Effectiveness of landfills varies with global location. In OECD nations, legislative action has resulted in environmental laws mandating requirements for landfills. In non-OECD nations, such laws, if they exist, are usually less stringent and enforcement is spotty. Sridhar and Hammed [24] point out that in some African nations, there is simply no money for maintenance of landfills; hence they become open dumps. Landfills require space, which is often at a premium and which often is the source of ongoing environmental problems. Furthermore, the amount of e-waste discarded in landfill grows steadily each year.

Incineration is becoming the method of choice worldwide for waste disposal [3]. Less space is required and potential environmental dangers of landfills are avoided. However, incineration is not without problems. It is a thermal process and has the drawbacks associated with high-temperature operations. The high energy input required for high-temperature incineration is usually obtained from electricity, which is produced from coal combustion with attendant emissions of carbon dioxide and metals, such as Hg [3]. Incineration results in ash which contains residual metals. Disposal of the ash poses environmental problems similar to those associated with landfills. Space is conserved in incineration, but dispersion of toxic and other metals into the commons remains a concern. Effectiveness of regulatory and environmental controls on incineration processes and atmospheric emissions varies significantly from location to location, especially between OECD and non-OECD nations. Metals in the ash resulting from incineration are concentrated and could be recovered, although at present this is usually not done in the U.S. In Europe, an increasing amount of bottom ashes is treated for recovery of the base metals, steel, Cu, and Al, but recovering precious and special metals from such ashes faces physical limits.

1.4 Benefits Derived by the Global Community from Effective Recycling

Recycling of technology metals, where practiced, has important beneficial features. These have been summarized by Hagelüken [2] and are presented in Table 1. Reduction of the environmental burden of not recycling (Table 1, 1) refers to the fact that, otherwise, EoL products would either be discarded, in an uncontrolled and visually unpleasant way, into the environment with often severe impacts on the commons due to emissions of hazardous

Table 1 *Global Benefits Derived from Effective Metal Recycling Programs*

1. Reduce environmental burden of not recycling
2. Mitigate environmental impact of mining
3. Extend lifetime of and preservation of primary geological resources
4. Reduce geopolitical dependencies involving critical metals
5. Contribute to supply security of technology metals
6. Support ethical sourcing of technology metals
7. Dampen technology metal price fluctuations
8. Create significant employment potential

substances into soil, water and air, or these products would go to controlled landfills or incineration plants. In the latter cases, negative environmental impacts can be minimized by proper management of such landfills or waste incineration plants, but in many countries landfills are far from being well controlled and incineration often takes place in open space or in crude plants without appropriate off-gas treatment. Moreover, especially in populated regions, landfills need land, which is consequently then not available for housing or agriculture. However, it is often the case that such land is later used for these purposes with dire environmental and health effects.

Mining is inherently a process that generates large amounts of waste. This waste derives from the fact that most ore bodies contain a few percent of the target metal, necessitating the removal of a large overburden and separation of a few percent, at most, of the desired metal. As a result, the environmental burden of the mining process is large and grows as the demand for metals increases. As ore is mined to meet the increased raw material demands of society, grades of available ore decrease prompting the need to find new deposits, develop improved technologies to mine, economically, deposits having lower grades, and/or go to greater depths in existing deposits. The gradual depletion of deposits in main parts of Europe and the exploration of new deposits in South America and Africa as well as increasingly stringent environmental regulations in OECD nations have resulted in recent decades in the movement of much mining and ore beneficiation processing to non-OECD nations, which often have less strict regulations or lax enforcement of existing regulations.

Recycling of metals, if effectively done, has the potential to reduce significantly the need to mine new ore to fill the continuing need for metals to replace those discarded in EoL products. This effort has had success in the case of recycling PGM from process catalysts and autocatalytic converters. As elaborated in Section 1.1, the value of PGM and/or the closed industrial cycle has made possible their recovery in significant amounts [6,9]. On the other hand, in open cycles, such as for e-waste, valuable precious metals are recovered at low rates while low-value technology metals, such as indium and rare earth metals, are not recovered at all. Since the need for the products containing these metals is large and increasing, new virgin ore must be mined to meet this demand.

Mining has high energy and water requirements [26,27]. Metals recovered through sound recycling result in significant reduction in the amount of mining required, with associated reduction in coal combustion, carbon dioxide emissions, land and water use, and impacts on the biosphere, e.g. in rain forests, Arctic regions, ocean floors, and so forth (Table 1, 2). A further important benefit of recycling is the reduction in the discard of solid, liquid, and/or gaseous waste into surrounding land, streams, and atmosphere, which is common in many processes, where environmental regulations either do not exist or are poorly enforced. Examples of this waste generation are abundant and are found associated with present mining activities in many countries, such as China [19] and Peru [21].

An additional benefit of recycling is that fewer toxic metals inherent in mining activities as "unwanted companions" enter the technosphere. Examples are As, Hg, Cd, Tl, U, and Th. The first four metals are present, usually as by-products, in sulfide ores from which many of the technology metals are obtained. Thorium and U and their decomposition products are commonly found in rare earth metal deposits. Unless great care is taken, these toxic metals enter the environment through discard to tailings, emissions to the atmosphere, and inefficient beneficiation processes. The effect of these toxic metals on the environment and on human health have been documented [3,16,19–21,28].

Continued use of Earth's metal supply without replenishing it will lead to eventual, serious depletion of this resource. Recycling can delay this scenario and provide time to develop improved mining and processing techniques that might facilitate extraction of metals from lower grades or other undeveloped ore bodies, and to search for alternatives (Table 1, 3). The status of individual technology metals differs. However, a major effect will be that the cost of metals will increase as supply diminishes. Another effect is that, in some cases, such as for certain technology metals deemed critical, demand may exceed supply, resulting in major price fluctuations. Indium is an example of a metal that, in the form of indium-tin-oxide (ITO), is critical to the function of all flat screen devices, which, in turn, are essential to the efficiency of a whole host of modern high-tech products. Indium is one of the rarest of metals in the Earth's crust (Figure 2). Its sole commercial source is sphalerite, ZnS, from which it is recovered as a by-product. Eighty percent of global Zn is mined and processed in China [28], making this Nation a major source of In.

Forty percent of the global supply of In originates in China. Indium is of interest because it is a critical metal, but of low economic value. Hence, there is little economic incentive to recycle In. Some forecast consumption growth rates for LCDs and solar cells project that supplies of In from primary mined Zn sources will be severely affected by the early 2020s [3]. Estimated global reserves of In range from 2,800 (2006) to 11,000 (2007) tons with an annual consumption of 510 tons [3]. Consumption is expected to grow to 1,900 tons annually by 2030. Indium is a scarce commodity, yet its recycle rate is $<1\%$ [1]. Active programs are underway to find material that can replace InSnO in flat screens, but so far none can equal the effectiveness of InSnO. An effective process for economically recycling In would be valuable to provide an alternate supply of this metal.

Iridium is an example of a valuable metal that has a critical use but may be in danger of not being sufficiently accessible. Iridium is one of the scarcest of metals (Figure 3), but is the metal with the greatest corrosion resistance and very specific catalytic properties. Iridium finds multiple uses in commerce where corrosion resistance is required. Iridium alloys enable jet engines to operate at very high temperatures. The longevity of spark plugs results from the use of Ir in their construction. The availability of Ir depends on the mining of Pt ore, where it is found as a by-product. Gordon, Bertram, and Graedel [29] list Pt as an element at risk for supply. Platinum group metals are unusual in that they are found in commercial grades at only a few locations: South Africa, Russia, and Canada [30]. In South Africa, use over the past century has resulted in the need to go to lower grades and deeper operations, both of which have environmental, energy, and water consequences. Thus, Ir is an excellent candidate for recycling as a means of preserving and extending a critical natural resource. The recycling rate for Ir is $<25\%$ [2].

Several technology metals considered critical to domestic, commercial, and military uses in the U.S. are concentrated in a few countries, not all of which are politically stable or friendly (Table 1, 4) [2,13]. Effective recycling programs would reduce concern because they would provide alternate reliable sources of these metals. The PGM mining in South Africa has recently been affected by labor strikes in the PGM mines, although so far this has not had negative impacts on the PGM supply side. In the past few years, China used its monopoly on rare earth metal production and supply as an economic weapon against Japan during conflict over islands in the seas bordering the two nations [13]. This cutback in supply was of great concern to Japan because these metals are essential to the production of high-technology products produced and marketed by Japan. A fallout from this experience

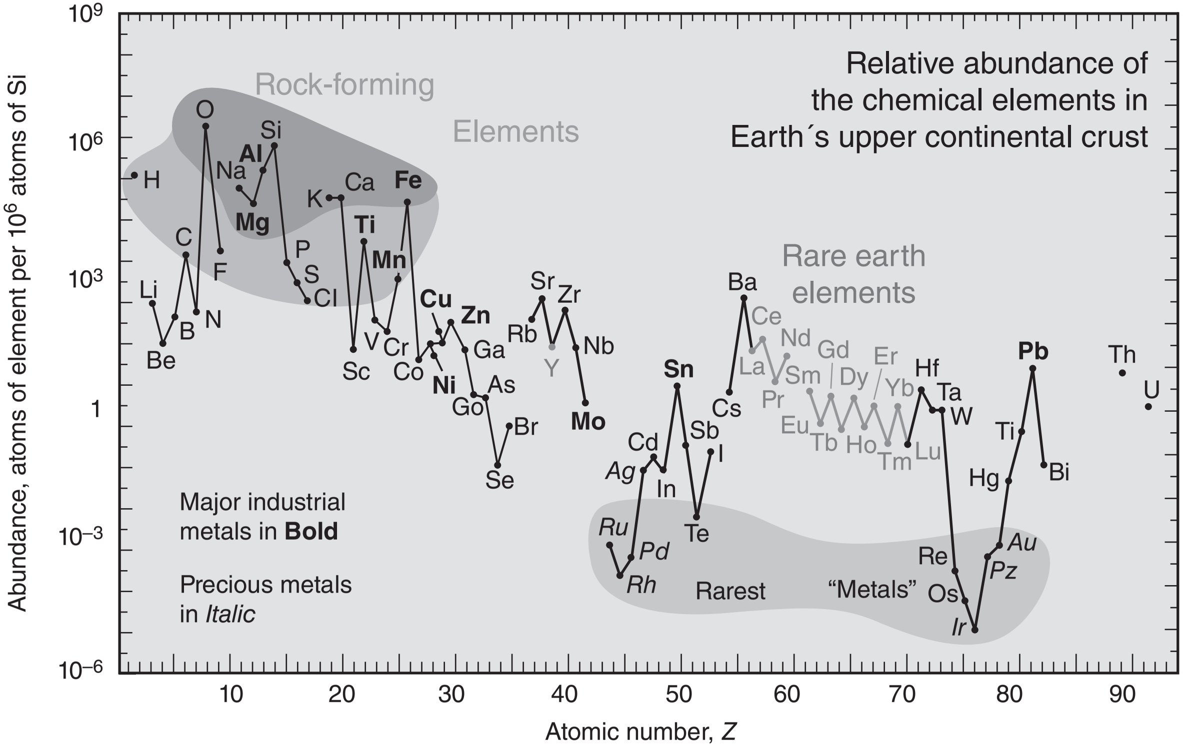

Figure 2 *Abundance (expressed as atoms of element per 10^6 atoms of Si) of the chemical elements in Earth's upper continental crust as a function of atomic number. Many of the elements are classified into (partially overlapping) categories: (1) rock-forming elements (major elements in green field and minor elements in light green field); (2) rare earth elements (lanthanides, La–Lu, and Y; labeled in blue); (3) major industrial metals (global production > ~3×10^7 kg/year; labeled in bold); (4) precious metals (italic); and (5) the nine rarest "metals" — the six platinum group elements plus Au, Re, and Te (a metalloid). Source: U.S. Geological Survey. http://pubs.usgs.gov/fs/2002/fs087-02/*
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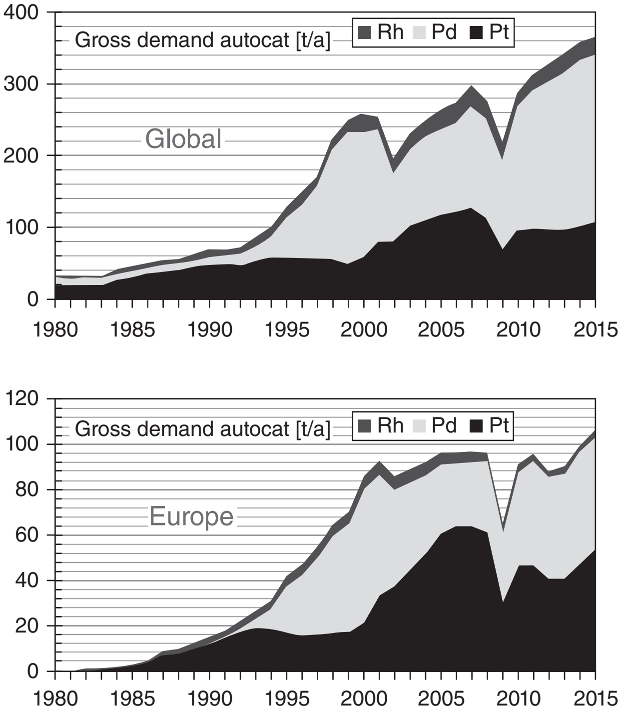

Figure 3 *Gross global and European demand for platinum, palladium, and rhodium for automotive catalysts from 1980 to 2015. (See insert for color representation of the figure.)*

is that greater effort has been expended by Japan to develop recycling capacity, as in recycling Dy from magnets. There has been political unrest in several nations in central Africa for decades [13]. Yet some of these countries are rich in metal resources of value to the world's economy.

A major benefit of recycling is that it could partially decouple the production of the technology metal from the major metal source from which it is derived as a by-product (Table 1, 5). The main objective of producers of commercial metals is production of the major metals, not of by-product metals. Production of technology metals is nearly always tied to the production of a major metal. Examples include (major metal in parentheses) In (Zn); Mo, Re, and Te (Cu); Ga (Zn, Al); and Ru, Ir, and Rh (Pt and Pd). Thus, any success in decoupling this link through recycling is advantageous to the security of the technology metal supply.

Effective metal recycling has the geopolitical advantage that it can make possible a more transparent supply chain reducing or avoiding sourcing of metals from regions involved in wartime activities or in the use of child labor, etc. (Table 1, 6) [13]. An alternative, reliable source of such metals could supply a degree of independence in such cases.

Effective recycling would make possible the dampening of price fluctuations by improving the supply-demand balance and limiting speculation by broadening the supply base (Table 1, 7). The rare earth market would benefit greatly by reliable sources of recycled metals. The rare earth metal market from mining to production and sale of > 99% pure products has been and continues to be dominated by China [13]. The only other producing rare earth facility, MolyCorp, operating in California, filed for bankruptcy protection in 2015. Prices for individual rare earth elements have fluctuated widely during the past five years. The critical rare earth metals represent an interesting example of this problem. Reasons for the growth of markets which require Nd have been presented earlier. Despite the critical need for Nd in high-technology products, the sources of supply are limited primarily to China, except for any stored metal. This situation has attracted the attention of several groups who are developing recycling processes for recovery of Nd from high performance magnets. Dupont and Binnemanns [31] are among the leaders in this effort, as is the Critical Materials Institute in the U.S. At least one group is well on the way to the production of Nd and other rare earth metals from pregnant leach solutions derived from U.S. ore deposits using a molecular recognition technology (MRT) process [32]. The MRT procedure could also be used to recycle these metals. Hopefully, recycling efforts underway will bring some stability to the critical rare earth market by improving the supply-demand balance for these important metals, which presently have a recycling rate of <1%.

Development of recycling facilities and infrastructure would create significant employment potential (Table 1, 8), especially in collection and pre-processing. Informal recycling operations are major employers of individuals of all ages in non-OECD nations [3]. Diverting EoL products from landfills or uncontrolled discards requires a significant workforce. Beyond labor-intensive collection activities, in countries with low labor costs manual dismantling of e-waste and other wastes offers a large job potential and can be a viable alternative to mechanical treatment. Supervised manual dismantling of e-waste can be a way gradually to formalize the informal sector and, together with appropriate training on sound recycling, avoid the negative environmental and health effects of crude "backyard-recycling". Mechanized preprocessing in OECD countries as well as the metallurgical recovery of metals at the end of the recycling chain are less labor-intensive [4,9], but provide job potentials for skilled labor and for suppliers of technical recycling equipment.

1.5 Urban Mining

Metals differ from energy raw materials in an important way. Metals can be kept in an 'eternal' life cycle by proper management. The use of technology metals in personal, consumer, industrial, and military products has grown rapidly in recent decades. More than 80% of global mine production of PGM, rare earth metals, indium, and gallium since 1900 has occurred in the past three decades [2,14]. Many of these metals are still bound in the 'technosphere' or 'anthrosphere.' As a result, products such as automobiles, electronics, batteries, automotive and industrial catalysts, and other high-tech devices that reach their EoL state represent a potential 'renewable' metal resource of great value. This resource has been termed an 'urban' or 'above-ground' mine and proposed as an alternative source of these metals. There is good reason for this proposition. Concentrations of technology metals in many of these products are relatively high. For example, a typical primary Au mine will yield five grams of Au per tonne (g/t). In electronic scrap, this figure was, 10 years ago, as high as 200–250 g/t for computer circuit boards and 300–350 g/t for mobile phone handsets. High metal prices together with progress in materials development and product design then triggered both a significant miniaturization of devices and components and a thrifting of precious metal contents. Since then, Au and Ag in PC motherboards has declined by 40% and Pd by 60%. Similar trends can be recognized for mobile phones [11]. But still, even on today's lower level, grades this high are very uncommon in natural Au deposits. An autocatalytic converter contains approximately 2,000 g/t of PGM in the ceramic block, compared to average PGM concentrations of <10 g/t in most PGM mines. Considering the high environmental impact of primary production of precious metals arising from low ore concentrations, difficult mining conditions, high energy and water use, high chemical consumption, large waste generation, and other factors, recovery of metals from EoL products is appealing. Further environmental and economic benefits are realized if state-of-the-art technologies are used for the metal recoveries. However, use of these advanced metallurgical smelting and refining technologies usually requires collection and transport of the resource-relevant components from EoL products, partly over long distances. This is neither from an economic nor from an ecological point of view a problem as long as not the entire device but only the components/fractions with higher metal concentrations (i.e., circuit boards, catalysts, batteries) are shipped (comparable to shipping primary Cu concentrates or anode slimes to specialized large scale smelters around the world). To achieve this end result, it is required that EoL products be dismantled and pre-processed locally or regionally in an appropriate way. Subsequently, the resource-relevant complex metal fractions need to find their way to sophisticated integrated smelters/refineries. For this last step in the recycling chain, sufficient economies of scale are crucial; hence it does not make sense to install such operations in "every country". This matter is discussed further in Section 1.6.

With the positive scenario presented, one must wonder why urban mining is not employed extensively as a means to augment our metal supply. Major reasons are that most consumer products are widely distributed, difficult to trace around the planet, and the (precious) metal content in any single device is very low. Accordingly, economic exploitation of these urban mines requires collecting sufficient quantities of the dispersed product, such as cell phones or automotive catalysts, to create a true above-ground deposit from which the metal(s) can be mined. This collecting of e-waste fulfills the second basic criterion for an economically viable 'ore body', i.e. sufficient volume. The first criterion, that the 'ore body' have sufficient concentration, is amply fulfilled, as indicated earlier. Fulfilling the second criterion presents challenges which are addressed in several chapters in this book. The challenge of collection of e-waste has been met in informal recycling, but not adequately in formal recycling. The informal recycling situation is discussed in Section 1.6.

In Table 2, the total value of several metals in large quantities of collected mobile phones and laptop computers is given for the year 2010 [2]. Mobile phones contain over 40 different chemical elements including base metals, such as Cu, Ni, and Sn; specialty metals including Co, In, and Sb; and the precious metals Ag, Au, and Pd. Metals, mostly Cu, make up about one quarter of the metal content in each phone. One tonne of scrap mobile phones (equivalent to about 13,000 units without batteries), contained in 2010 an average of 3.5 kg Ag, 340 g Au, 130 g Pd, and as much as 130 kg Cu [2]. Today, these amounts have dropped to 1.3 kg Ag, 300 g Au, 40 g Pd and 125 kg Cu, on average. The value of these metals can approximate up to $10,000/t (although less at current low metal prices), with 80% or more of the total being due to the precious metals present. By contrast, a single unit contains mg of precious metals and ~9 g of Cu. Thus, the net value of one unit is below $1U.S., which

Table 2 *Average content of precious metals, copper, and cobalt in mobile phones and computers, and resulting metals demand from global sales in 2010, compared with world mine production. Reproduced with permission from* [2]

	a) Mobile phones		b) PCs and laptop computers		a + b = Urban mine	
	1,600 million units/year, each with a lithium-ion battery		350 million units/year, of which ~180 million have a lithium-ion battery			
Metal	Unit metal content	Total metal content	Unit metal content	Total metal content	Global mine production (2010)	Share a + b of global mine production
Silver	250 mg	400 t	1,000 mg	380 t	22,900 t	3%
Gold	24 mg	38 t	220 mg	77 t	2,650 t	4%
Palladium	9 mg	14 t	80 mg	28 t	225 t	19%
Copper	9 g	14,000 t	500 g	175,000 t	18Mt	<1%
Cobalt	3.8 g	6,100 t	65 g	11,700 t	88,000 t	20%

t, tonnes; Mt, million tonnes; g, grams; mg, milligrams

does not provide an economic incentive for recycling. It is the sheer number of mobile phones in use that attracts attention for possible metal recovery. About 1.6 billion of these phones were sold worldwide in 2010 alone. In 2014, this number rose to 1.9 billion, including 1.2 billion smart phones. The number of phones produced is increasing yearly to meet demand. The active lifetime of each phone is 2 – 3 years, after which it is out of use in drawers or landfills, or sent to non-OECD nations for reuse or informal recycling [13,22,33]. The estimated ten billion units produced in total by 2010 would contain a total of 2,400 tonnes of Ag, 230 tonnes of Au, and 90 tonnes of Pd. As seen in Table 2, the Au and Ag contents of the combined 2010 sales volumes of mobile phones and computers are equivalent to ~4 % of the global mine production for Ag and Au and ~20% of that of Pd and Co.

The modern automobile is rapidly becoming a ‘computer on wheels.’ The proliferation of electronic devices to control an increasing number of operations requires technology metals, making the automobile an urban mine by itself. As global affluence increases, the number of automobiles grows proportionately, especially in non-OECD countries. One example is the growth in the use of PGM as automotive catalysts. In Figure 31.3, annual demand figures are shown for PGM in automotive catalysts, both globally and for Europe. Cumulative gross demands (6,280 t PGM globally) and recycling volumes (1,250 t) up to 2015 are also shown. In Europe, the large increase in demand for PGM for automotive catalysts began in the mid-1990s. Because of the relatively long lifetime of automobiles (10–15 years), some 4,000 t of PGM are still in use in cars globally. Most of the car catalysts that are recycled today are from the early 2000s, so the potential for future recycling of PGM from cars on the road today is huge [4,9].

However, major deficiencies in recycling of automotive catalysts, mainly related to failure to collect vehicles at the end of their lives, could result in inability to close this cycle, and, thus, seriously undermine the potential of this urban mine. Hagelüken [2] estimated that the cumulative wastage from car catalysts already adds up to 900 t of PGM globally, with Europe contributing about 200 t. Updated for 2015, it can be assumed that about 1,000 t of PGM have been lost from automotive catalysts globally. PGM losses occur at all stages of the life cycle including some dissipative driving losses ‘through the exhaust pipe’ if the road is rough and the car not well maintained, losses from cars that were not recycled, losses from catalysts that were not removed before the car was shredded, losses during inappropriate handling and mechanical pre-treatment of car catalysts, and losses during metallurgical catalyst processing. PGM from these inadvertent losses remain in the commons and are not recoverable. It is expected that wastage of PGM by these losses will be particularly large in the near term in China, India, Brazil, Nigeria, Indonesia, and other non-OECD nations, where car ownership is increasing rapidly, but roads and cars are not as well maintained as in OECD nations and recycling structures are not adequately established.

Recycling PGM from automotive catalysts is relatively easily accomplished, since the catalyst can be rapidly removed from the automobile and the PGM recovered with high yields in state-of-the-art precious metal refineries [34]. Precious and specialty metals that are vital in the operation of many other features of modern automobiles, mainly in car electronics, are not so easily recovered. These metals are located in small amounts throughout the automobile. Removal and collection of the products containing them in EoL vehicles is usually not economic presenting the potential for significant losses of technology metals as their use in automobiles rapidly increases.

1.6 Technologies for Metal Separations and Recovery from EOL Wastes

It is apparent that several ‘urban mines’ for precious metals exist, i.e., automobiles, e-waste, scrap, petrochemical catalysts, to name a few. Effectively recovering metals from these sources requires well set-up recycling chains, starting with collection and product sorting to dismantling and pre-processing to metallurgical separation and purification of metals as the final step of the chain.Technologies applied at these steps range from small to large scale, from manual to automated pre-processing and from highly efficient integrated smelter-refineries to crude recovery processes with low yields and high pollution used in informal recycling. Metal recycling is done efficiently and to near completion in the case of closed cycles, but it is often done poorly in the case of open cycles, especially when final processing is conducted by informal recycling. Globally, most electronic waste is still consigned to landfill, incinerated, or treated in poor-performing “backyard” operations. Extension of sound recycling to this source is desirable, since large quantities of precious and critical metals are otherwise lost while hazardous substances are emitted. In this section, several technologies used and proposed for metal recycling are presented and discussed. Greater detail is provided in several references [3–5,9].

1.6.1 Collection, Conditioning, and Pre-processing of Waste

Before the actual recovery process for precious and specialty metals can take place, collected material to be recycled needs to be conditioned, in most cases. Conditioning may involve, for example, dismantling and/or mechanical pre-processing (e.g., by shredding and sorting) electronic scrap, decanning car catalysts (extracting the catalyst monolith from the steel case) and burning oil refining catalysts contaminated with carbon. Whatever kind of pre-processing is employed, it must always be conducted in a way that the output fractions provide an optimal fit to the subsequent metallurgical recovery processes and that losses of valuable substances during pre-processing are minimized. The layout of any specific recycling chain and its interfaces depends on the type of material to be treated and is crucial for the overall recycling success. Pre-processing is particularly difficult for technology metals in many high-tech products. For example, precious metals contained in circuit boards are associated with other metals in contacts, connectors, solders, hard disk drives, etc.; with ceramics in multilayer capacitors, integrated circuits (IC), hybrid ceramics, etc.; and with plastics in circuit board tracks, interboard layers, etc. Small-size material connections, coatings, and alloys cannot be separated by shredding. Hence, incomplete liberation and subsequent incorrect sorting result in losses of technology metals to side streams, including dust, from which they cannot be recovered by metallurgical treatment [9]. An industrial test with mixed information technology (IT) electronic scrap treated in a modern shredder without prior dismantling of circuit boards revealed that the percentages of Ag, Au, and Pd ending up in fractions from which they could be recovered (circuit board and Cu fractions) were only 12%, 26%, and 26%, respectively [35]. Thus, automotive catalysts, batteries, high-grade circuit boards, and mobile phones or MP3 players need to be removed or sorted out prior to mechanical pre-processing to prevent irrecoverable losses. These components/devices can be fed into a smelter-refinery process directly, with the effect of recovering most of the metals with high efficiency (over 90%) [9]. For larger items and for low-grade electronic scrap, direct feeding to a smelter is usually not applicable and some degree of mechanical pre-processing is required. Instead of intensely shredding the devices, a coarse size reduction, followed by manual or automated removal of circuit board fractions, can be a viable alternative. Trained workers can often remove certain complex target components more selectively than can be done by automated sorting wherever trained manual labor is available and affordable; in many developing and transition countries, for instance, this labor can be used as a valid alternative to dismantle, sort, and remove critical fractions, such as circuit boards or batteries by hand. It would be desirable to combine this manual recovery of metal-containing parts with state-of-the-art industrial metal recovery processes. Unfortunately, such processes are usually located far from the location where the parts are found [2]. Hence, manual dismantling/sorting and informal work organization are not negative *per se*. Such activities can be the adequate solution in some countries as long as training is provided and no crude backyard recovery of metals is taking place as the final step. Unfortunately, use of untrained manual labor coupled with corrosive chemicals in informal recycling processes in non-OECD countries is extensive and has resulted in extensive negative environmental and health conditions, as described in several chapters in this book. One conclusion that can be drawn is that there is no single optimal way to go from the EoL product to recycling of the metals contained therein.

1.6.2 Separation and Recovery Technologies

1.6.2.1 Integrated Smelter and Advanced Refining Technologies

Hagelüken [9] has described the process of recovering a number of metals from a variety of waste products by means of the Umicore integrated smelter. This process is highly efficient and allows the recovery of many metals at rates near 100%. The process, also, produces much less CO_2 than would have been the case with mining an equivalent amount of ore. In one case, working with Germany's ecological research group Öko-Institut, the potential CO_2 benefit was calculated based on real 2007 Umicore Hoboken data and the EMPA/ETH Zurich ecoinvent data base.The 2007 CO_2 emissions of the Umicore process when used to recover 75,000 t of metals from 300,000 t of feed materials was 0.28 Mt, compared to 1.28 Mt CO_2 that would have been generated if the metals were obtained through primary production. The generation of CO_2 is reduced nearly five-fold in this recycling process compared to an equivalent mining process. Recycling metals just in this single facility can thus prevent the emission of 1Mt CO_2 per annum and the environmental footprint of the recovered metals is reduced substantially. This calculation was based on a metal output of 1,100 t Ag, 32 t Au, 32 t PGM, 70,000 t Cu/Pb/Ni and 4,100 t Sn/Se/Te/In/Sb/Bi/As from a mixture of low-grade industrial by-products and higher-grade materials such as circuit boards or catalysts. The savings in emissions would be even larger if only higher grade materials were taken into account [9].

The combination of valuable metals as well as toxic and organic substances with halogens in many EoL products requires special equipment and considerable investments for off-gas and effluent management to ensure environmentally sound operations, *i.e.*, to prevent heavy metal and dioxin emissions, etc. Many plants, in particular in Asian transition countries, are not adequately equipped for metal recovery from such EoL fractions. In such plants, electronic scrap is often 'industrially' treated in noncompliant smelters or leached with strong acids in hydrometallurgical plants with questionable effluent management, with a primary focus on recovering Au and Cu, only.

The chapter by Ueda *et al.* [6] describes the recovery of PGM from catalytic converters and other waste at the Tanaka Kikinzoku Kogyo K.K., refinery in Japan. The prediction is made that recycling volumes of PGM from end-of-life automotive catalysts will double from their current volumes in the next few years, so it is possible that the recycled PGM supply will reach approximately 30% of total platinum group metal supply (total of mining and recycling volumes.) These authors [6] state that "Predictions such as this are likely to also impact mine development and management going forward. This and increasing processing capabilities among platinum group metal recovery and refining businesses will become important issues going forward."

1.6.2.2 Informal Recycling

Taizhou has been a prominent e-waste recycling center in China for the past twenty-five years. Its e-waste industry employs around 40,000 people, with an annual dismantling capacity of over 2.2 million tons [36]. Streicher-Porte *et al.* [36] have pointed out some advantages of the manual processing of e-waste. "Informal manual processing has been criticized for its pollution and health impacts, but manual disassembly itself, if well organized and properly protected, can serve as an efficient way of separating reusable, hazardous and valuable components from e-waste, which greatly simplifies the subsequent recovery of materials and improves reusability."

Unfortunately, a major part of electronic scrap and electronic waste is handled in the informal sector in thousands of backyard informal recycling facilities [3,9]. Pre-processing of the EoL products includes open-sky incineration to remove plastics, 'cooking' of circuit boards over a torch for de-soldering, cyanide leaching, and mercury amalgamation. Over and above their disastrous effects on health and environment, the efficiency of such activities is very low, as well. An investigation in Bangalore, India revealed that only 25% of the Au contained in circuit boards was recovered, compared to over 95% in integrated smelters [9]. A UNEP report cited by Hagelüken and Grehl [9] provides a comprehensive overview on the situation in developing countries.

Informal recycling is successful because employment is provided to a large number of individuals who are willing to work for small wages. Average wages per day for e-waste recycling jobs in China are in the range of 50-100 RMB [36]. In the economies involved, this wage is considered good. There is no shortage of workers. The manual disassembly of electronic products is done with little regard for the safety of the worker or protection of the environment. Recovery rates of precious metals from the disassembled products are low with much of the value lost to the commons due to inefficiencies in the process. One of the important challenges in the global recycling industry is how to establish an effective formal recycling industry, perhaps in cooperation with the informal recycling industry, in which these EoL electronic products are collected, disassembled, and the value retrieved by a safe and efficient recovery process. The dynamic relationships between the formal and informal sectors in China have been presented [36].

It has been suggested [33] that efforts be made to introduce clean chemistry methods [37] into the informal recycling system. Whatever is done, at present, the amount of value retrieved from e-waste by informal recycling exceeds that recovered by formal recycling procedures. Those engaged in informal recycling have coupled the availability of large quantities of e-waste from OECD nations, usually shipped illegally, and increasing amounts from non-OECD nations, with the large labor force available in non-OECD nations to produce a thriving business in the recovery of precious metals. However, this form of urban mining is inefficient and has large negative environmental and health consequences. Primitive recovery methods are used by untrained persons, often children, with unknown, but appreciable, loss of precious and other metals to the commons. Despite these limitations, informal recycling is a major contributor to urban mining and its use is expanding. If combined with state-of-the-art metallurgical recovery in integrated smelters, this “best of two worlds” approach can be a valid solution for many developing and transition countries [38].

1.7 Conclusions

Concerned stakeholders need to be made aware of the importance of the technology metal supply to global society. These metals are essential to the continuation of personal, commercial, industrial, and military activities world-wide, yet few people know of them or of their essential role in the high-technology products that have transformed our world. Every effort should be made to educate stakeholders who have much to gain by being aware of these metals. Awareness may be the key word and education should start with the public, from whom, in the long term, come all other stakeholders. Appropriate individuals must be aware and become involved before action can be taken and major changes made to the present global recycling systems. To the extent possible, the long-term vision is to turn the open loop for e-waste, cars, and other resource-relevant consumer products, as it exists today, into a closed one all over the world. Key aspects of this global vision include the following.

1. A paradigm shift is needed to convince industry of the high recycling potentials that exist in urban mines. Successful urban mining operations need to be acknowledged with publicity and the economic and environmental benefits of such mining promoted whenever possible.
2. Attitudes need to change from a waste-management to a resource-management perspective, reflecting the potential that our waste scrap and EoL products have for society. This attitude change will promote collection, appropriate treatment, enactment of appropriate legislation, and enforcement of this legislation. Specifically, for critical technology metals, such as the rare earth elements, Li, Co, and In, measures need to be put in place to advance their recycling even in the absence of (current) value, volume, and environmental drivers. Such action would represent a paradigm shift from present actions.
3. Goals need to be adjusted where appropriate. The current focus on mass is insufficient. Instead, much more emphasis should be placed on the quality and efficiency of recycling and on recovery of critical and precious metals. This goes hand in hand with a certain prioritization. It is indeed reasonable to recover less material mass (e.g., of plastics or steel) if this leads to tangible improvements in the recovery of technology metals. Adjustment of goals would be helped by an informed public, media, and other stakeholders who are aware of what the technology metals are, why they are important, and why their recovery should be prioritized.
4. Recycling practices need to reflect the increasing global emphasis on stewardship and use of green chemistry procedures. Since the recycling industry plays a key role for our future needs, traditional structures of the scrap and metal recovery business with its rather poor prestige do not fit any more. Recycling of high-technology metals plays in the same league as clean technology manufacturing and renewable energy generation. Economic structures; public esteem; new technologies, where needed; and stakeholder cooperation in recycling efforts should reflect this, with more emphasis on transparency and business ethics than is the case today. Opportunities abound for the development of new procedures and technologies to improve formal and informal recycling operations as well as the active pursuit of means to bring the two together to produce more effective and environmentally responsible recycling.
5. Education of the public; media; policy makers at local, regional, and national levels; and industrial organizations concerning the need to responsibly control Earth's technology metal supply must be more effective. Media should be encouraged, wherever possible, to provide balanced coverage of the importance of technology metals in our global society. Media coverage could be significant in educating the public and policy makers on significant issues concerning recycling.
6. Greater efforts must be made to interest young people in fields that are important to recycling and metal sustainability, such as separation science, metallurgy, waste management, and economics. Individuals trained in these and related subjects are needed to generate the new ideas and create the new technologies required to solve many of the pressing recycling problems of the present and future.
7. Policy makers at all levels and in all nations need to be informed about the need to preserve Earth's technology metal supply and the consequences of not doing so. These individuals have responsibility for enacting and enforcing legislation. Many factors are

at play here. Economic considerations, environmental and health concerns, resource depletion, National security, and global warming are but a few of these factors. Recycling today is spotty around the world. Informed and committed policy makers are needed to improve this situation.

8. Finally, the vision from a manufacturer's perspective needs to change. Today, producer responsibility and recycling is often seen as a burden, imposed by law. In fact, responsible recycling is an opportunity for manufacturers to sustainably and with greater reliability get access to the raw materials they need for future production. This reliable access can be a valuable asset. To fulfil this vision, creative business models to close the loop are essential. Recycling EOL products efficiently today provides insurance for the future [2].

Effective recycling systems can make a significant contribution to conserving natural resources of scarce metals, securing sufficient supplies of technology metals for coming generations, contributing to national security, and reducing the environmental burden connected to the mining of metals. Moreover, such systems would dampen metal price volatility and decrease the climatic impact of metal production, which is energy intensive, especially in the case of low-concentration ores mined for precious metals.

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