International Resource Panel

UNEP

Recycling Rates of Metals

A Status Report

United Nations Environment Programme

Acknowledgments

Editor: International Resource Panel, Working Group on the Global Metal Flows

Lead author: T. E. Graedel; Authors: T.E. Graedel, Yale University, USA; Julian Allwood, Cambridge University, UK; Jean-Pierre Birat, Arcelor-Mittal, France; Matthias Buchert, Öko-Institut, Germany; Christian Hagelüken, Umicore Precious Metals Refining, Germany/Belgium; Barbara K. Reck, Yale University, USA; Scott F. Sibley, US Geological Survey (USGS), USA and Guido Sonneman, UNEP, France.
This report has greatly benefitted from the review process of the related article in the Journal of Industrial Ecology (Graedel et al., 2011)

The full report should be referenced as follows:
UNEP (2011) Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Graedel, T.E., Allwood J., Birat J.-P., Reck, B.K., Sibley, S.F., Sonnemann, G.

The authors of this report thank the following additional workshop participants for their expert perspectives and contributions: Stefan Bringezu, Wuppertal Institute, Germany; Werner Bosmans, European Commission, Belgium; Ichiro Daigo, University of Tokyo, Japan; Kohmei Halada, NIMS, Japan; Seiji Hashimoto, NIES, Japan; Petra Mo, WorldSteel Association, Belgium; Susanne Rotter, Technical University of Berlin, Germany; Mathias Schluep, EMPA, Zurich, Switzerland; Raymond Sempels, International Zinc Association, Belgium; Fritz Teroerde, ELG Metals, USA/Germany; George Varughese, Development Alternatives, India; Zheng Luo, OEA/EAA, Germany. We are especially thankful to Christina Meskers, Umicore, for her valuable contributions to the manuscript.

We are grateful for comments on earlier drafts of this report by J. Bullock (Attorney), A. Carpentier (Eurometaux), D. Fechner (GKSS), W. Heenan (Steel Recycling Institute), A. Hlada (International Antimony Association), A. Lee (International Copper Association), R. Mishra (A-1 Specialized Services & Supplies), H. Morrow (International Cadmium Association), C. Risopatron (International Copper Study Group), M. Schlesinger (Missouri University of Science and Technology), U. Schwela (Tantalum-Niobium International Study Center), G. Servin (European Copper Institute) and D. Smale (International Lead-Zinc Study Group).

Guido Sonnemann, UNEP, supervised the preparation of this report and provided valuable input and comments.

Thanks go to Ernst Ulrich von Weizsäcker and Ashok Khosla as co-chairs of the Resource Panel, the members of the Resource Panel and the Steering Committee for fruitful discussions. Additional comments of a technical nature were received from some governments participating in the Steering Committee.

Helpful comments were received from several anonymous reviewers in a peer review process coordinated in an efficient and constructive way by Yvan Hardy together with the Resource Panel Secretariat. The preparation of this report also benefitted from discussions with many colleagues at various meetings, although the main responsibility for errors will remain with the authors.

ISBN: 978-92-807-3161-3

UNEP

International
Resource
Panel

Recycling Rates of Metals

*A Status Report**

* This is the second report of the Global Metal Flows working group of the International Panel on Sustainable Resource Management of UNEP

Preface

The recycling of non-renewable resources is often advocated as the solution to potentially restricted supplies. It is indeed true that every kilogram of resources that is successfully recycled obviates the need to locate and mine that kilogram from virgin ores. Unfortunately, however, and notwithstanding their potential value, industrial and consumer products containing these resources have often been regarded as waste material rather than as "surface mines" waiting to be exploited. This is a nearsighted and unfortunate view. As the planet's mineral deposits become less able to respond to demand, whether for reasons of low mineral content, environmental challenges, or geopolitical decisions, we limit our technological future by using these resources once and then discarding them through neglect, poor product design, or poor planning.

How are these philosophical thoughts reflected in practice? Or, to ask the question from a practical perspective, "How well are we doing at recycling?" It may be surprising, but it is certainly true, that recycling rates have not always been clearly defined in the past, and that when definitions have been clear it is found that the data to support their quantification are frequently unavailable. As a consequence, there is considerable uncertainty as to how efficiently non-renewable resources are retained for a second or third use within today's technological product systems.

In this report, the second compiled by the Global Metals Flows Group of UNEP's Resource Panel, a group of experts from industry, academia, and government evaluate recycling rate information for sixty different metals – essentially all the metals of the periodic table of elements. In this effort, recycling rates are carefully and clearly defined, and results then presented for all the metals for three important but different recycling rates. For many of these metals, this is the first time such estimates have ever been presented.

The future availability of metals is a complex topic, and one which depends on a mix of geological knowledge, industrial potential, and economics. We are limited to informed guesswork as to the growth of personal incomes, changing cultural preferences, future technological advances, and the like. We can paint pictures of possible material-related futures, but we cannot predict which will occur. What we can be certain of is that improved rates of recycling will be vital to any sustainable future, and that knowing where we stand today provides a most useful perspective, and one of the foundations upon which we can build a more sustainable world.

Prof. Thomas E. Graedel

Leader of the
Global Metal Flows Working Group

Preface

Nearly 20 years after the Earth Summit, nations are again on the Road to Rio, but in a world very different and very changed from that of 1992. Then we were just glimpsing some of the challenges emerging across the planet from climate change and the loss of species to desertification and land degradation. Today many of those seemingly far off concerns are becoming a reality with sobering implications for not only achieving the UN's Millennium Development Goals, but challenging the very opportunity for close to seven billion people to be able to thrive, let alone survive. Rio 1992 did not fail the world – far from it. It provided the vision and important pieces of the multilateral machinery to achieve a sustainable future.

A transition to a green economy is already underway, a point underscored in UNEP's Green Economy report and a growing wealth of companion studies by international organizations, countries, corporations and civil society. But the challenge is clearly to build on this momentum. A green economy does not favour one political perspective over another. It is relevant to all economies, be they state or more market-led. Rio+20 offers a real opportunity to scale-up, accelerate and embed these "green shoots".

Metals are a core, centre-piece of the global, economy: Whether it be in the manufacture of buildings or cars to the booming production of mobile phone, computers and other electronic goods, metals have become increasingly important to commerce. But metals are also part of the challenge society is facing in its transition to a low carbon, resource efficient 21st Green Economy. Metals are a finite resource, whose management, consumption and production echo to the need to adopt a recycling economy and one where rate of GDP growth are decoupled from rates of resource use.

Understanding, quantifying and estimating the ways metals flow through economies is part of the solution to better managing their impacts and their benefits. Indeed the International Resource Panel, hosted by UNEP and established in 2007, identified metals as a key area in terms of the 21st century sustainability challenge. The Panel's Global Metal Flows Group has identified six, central assessment reports as needed to bring clarity and to promote action towards a sustainable metals economy: stocks in society, current status of recycling rates, improvement options for recycling rates, environmental impacts, future demand, and critical metals.

This, the second report in this area, focuses on current statues of metal recycling rates in society. It provides, from a global perspective, the best scientific information available on the rates of metal recycling in the world. In particular it provides authoritative estimates of current metal recycling rates. This in turn allows evaluations on the amounts of metals that are not recycled and are available to be brought back into the economy by improved recycling rates. It provides governments and industry the relevant baseline information to make more intelligent and targeted decisions on metals management.

This is no easy task and here I would like to congratulate the Resource Panel and its experts and partners for bringing to governments, business and civil society an important piece in the sustainability jigsaw puzzle. Metals encapsulate the 21st century challenge of realizing sustainable development: development that requires and requests a far more intelligent understanding and trajectory that reflects the needs of a planet moving to more than nine billion people by 2050.

Achim Steiner

UN Under-Secretary General and
Executive Director UNEP

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

Coll	Collection
CR	Old Scrap Collection Rate
EAF	Electric Arc Furnace
EOL-RR	End-of-Life Recycling Rate
Fab	Fabrication
LED	Light Emission Diode
Mfg	Manufacturing
OSR	Old Scrap Ratio
Prod	Production
RC	Recycled Content
Rec	Recycling
RIR	Recycling Input Rate
USGS	United States Geological Survey
WM&R	Waste Management and Recycling

Units

ppm	parts per million

Chemical Abbreviations

Ferrous Metals

V – Vanadium

Cr – Chromium

Mn – Manganese

Fe – Iron

Ni – Nickel

Nb – Niobium

Mo – Molybdenum

Non-Ferrous Metals

Mg – Magnesium

Al – Aluminium

Ti – Titanium

Co – Cobalt

Cu – Copper

Zn – Zinc

Sn – Tin

Pb – Lead

Precious Metals

Ru – Ruthenium

Rh – Rhodium

Pd – Palladium

Ag – Silver

Os – Osmium

Ir – Iridium

Pt – Platinum

Au – Gold

Specialty Metals

Li – Lithium

Be – Beryllium

B – Boron

Sc – Scandium

Ga – Gallium

Ge – Germanium

As – Arsenic

Se – Selenium

Sr – Strontium

Y – Yttrium

Zr – Zirconium

Cd – Cadmium

In – Indium

Sb – Antimony

Te – Tellurium

Ba – Barium

La – Lanthanum

Ce – Cerium

Pr – Praseodymium

Nd – Neodymium

Sm – Samarium

Eu – Europium

Gd – Gadolinium

Tb – Terbium

Dy – Dysprosium

Ho – Holmium

Er – Erbium

Tm – Thulium

Yb – Ytterbium

Lu – Lutetium

Hf – Hafnium

Ta – Tantalum

W – Tungsten

Re – Rhenium

Hg – Mercury

Tl – Thallium

Bi – Bismuth

Steel Alloy Family

HSLA steels – High Strength-Low Alloy Steels

SS – Stainless Steel

ST – Steel

Others

Si – Silicon

P – Phosphor

S – Sulfur

TiO_2 – Titanium Dioxide

$BaSO_4$ – Barium Sulfate

PGMs – Platinum Group Metals

PET – Poly(ethylene terephthalate)

Executive Summary

The recycling of metals is widely viewed as a fruitful sustainability strategy, but little information is available on the degree to which recycling is actually taking place. This report provides an overview on the current knowledge of recycling rates for sixty metals. We propose various recycling metrics, discuss relevant aspects of the recycling of different metals, and present current estimates on global end-of-life recycling rates (EOL-RR) [i. e., the percentage of a metal in discards that is actually recycled], recycled content (RC), and old scrap ratios (OSR) [i. e., the share of old scrap in the total scrap flow]. Because of increases in metal use over time and long metal in-use lifetimes, many RC values are low and will remain so for the foreseeable future. Because of relatively low efficiencies in the collection and processing of most metal-bearing discarded products, inherent limitations in recycling processes, and because primary material is often relatively abundant and low-cost (thereby keeping down the price of scrap), many EOL-RRs are very low: for only eighteen metals (aluminium, cobalt, chromium, copper, gold, iron, lead, manganese, niobium, nickel, palladium, platinum, rhenium, rhodium, silver, tin, titanium, and zinc) is the very important EOL-RR above 50 % at present. Only for niobium, lead, and ruthenium is the RC above 50 %, although sixteen metals are in the 25 – 50 % range. Thirteen metals have an OSR > 50 %. These estimates may be used to assess whether recycling efficiencies can be improved, which metric could best encourage improved effectiveness in recycling and to provide an improved understanding of the dependence of recycling on economics, technology, and other factors.

1. Introduction and Scope of Study

Metals are uniquely useful materials by virtue of their fracture toughness, thermal and electrical conductivity, and performance at high temperatures, among other properties. For these reasons they are used in a wide range of applications in areas such as machinery, energy, transportation, building and construction, information technology, and appliances. Additionally, of the different resources seeing wide use in modern technology, metals are different from other materials in that they are inherently recyclable. This means that, in theory, they can be used over and over again, minimizing the need to mine and process virgin materials and thus saving substantial amounts of energy and water while minimizing environmental degradation in the process.

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

- Determine the influence of recycling on resource sustainability
- Provide information for research on improving recycling efficiency
- Provide information for life-cycle assessment analyses
- Stimulate informed recycling policies.

Report 1 – Metal Stocks in Society

Report 2a – Recycling Rates of Metals

Report 2b – Metal Recycling – Opportunities, Limits, Infrastructure

Report 3 – Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles

Report 4 – Future Demand Scenarios for Metals

Report 5 – Critical Metals and Metal Policy Options

The first five reports form the necessary basis for the last report.

This report summarizes the results of the Global Metal Flows working group of UNEP's International Panel for Sustainable Resource Management (Resource Panel) as it addressed metal recycling rates (Graedel et al., 2011). We will discuss definitions of different recycling statistics, review recycling information, identify information gaps, and discuss the implications of our results. The goal was to summarize available information (rather than to generate new data), highlight information gaps, and to fill these gaps through informed estimates.

The elements investigated are not all metals according to the usual chemical definition of **metal**, as metalloids have been included while the radioactive actinides and polonium were excluded. From the alkali metals only lithium (Li) has been included because of its use in batteries, and from the alkaline-earth metals all but calcium have been included. Furthermore, selenium has been included because of its importance as an alloying element and semiconductor. The selected elements (called "metals" hereafter) include

- **Ferrous metals**: V, Cr, Mn, Fe, Ni, Nb, Mo
- **Non-ferrous metals**: Mg, Al, Ti, Co, Cu, Zn, Sn, Pb
- **Precious metals**: Ru, Rh, Pd, Ag, Os, Ir, Pt, Au
- **Specialty metals**: Li, Be, B, Sc, Ga, Ge, As, Se, Sr, Y, Zr, Cd, In, Sb, Te, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Hg, Tl, Bi

The principal metals in each of these groupings are more or less according to popular nomenclature (e. g., the ferrous metals include those whose predominant use is in the manufacture of steel), but the less abundant or widely used elements do not necessarily fit neatly into these four groups (for example, tellurium [Te] could equally well have been included in the ferrous metals). The metal groupings are shown in Figure 1.

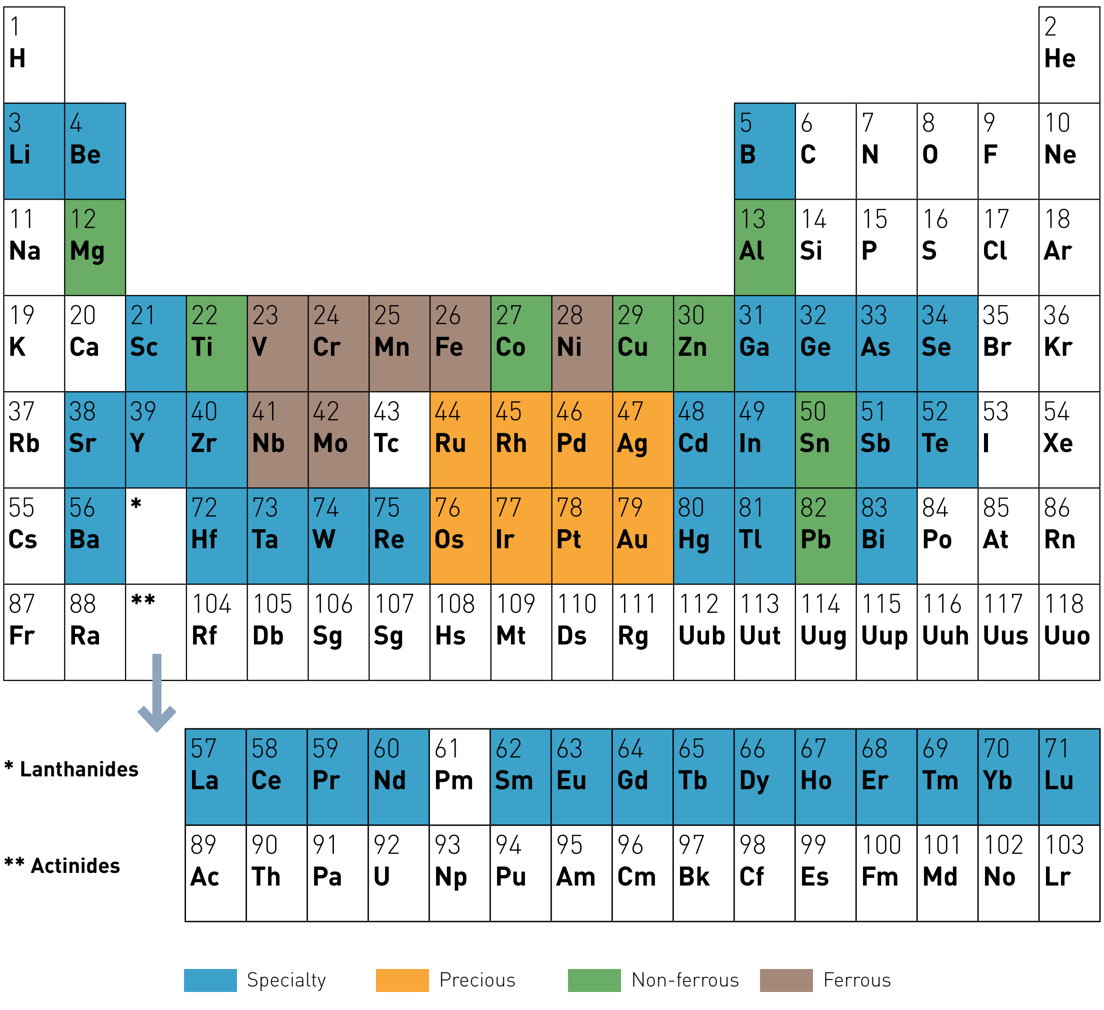


Figure 1. The major metal groupings addressed in this report.

In Appendix A, we list the common uses of each of these metals as a rough guide to their products, product sectors, and recycling prospects.

Metals are predominantly used in alloy form, but not always, and recycling information that specifies the form of the metal is not commonly available. Thus, all information herein refers to the aggregate of the many forms of the metal in question (but as metal, even if often used in a non-metallic form such as an oxide, e. g., $BaSO_4$, TiO_2). This distinction will be addressed in the results where necessary. The results also refer to global average statistics utilized in concert with expert estimations; those for a particular nation or region might differ substantially from these averages.

2. Metal Recycling Considerations

Figure 2 illustrates a simplified metal and product life cycle. The cycle is initiated by choices in product design: which materials are going to be used, how they will be joined, and which processes are used for manufacturing. These choices respond to technical and economic objectives, and alternative designs and materials compete based on technical performance, cost, environmental risk, and potential for supply disruption. Choices made during design have a lasting effect on material and product life cycles. They drive the demand for specific metals and influence the effectiveness of the recycling chain during end-of-life. The finished product enters the use phase and becomes part of the in-use stock of metals. When a product is discarded, it enters the end-of-life phase. It is separated into different metal streams (recyclates), which have to be suit-

able for raw materials production to ensure that the metals can be successfully recycled. In each phase of the life cycle metal losses occur, indicated by the 'residues' arrow in Figure 2.

The life cycle of a metal is closed if end-of-life products are entering appropriate recycling chains, leading to scrap metal in the form of recyclates displacing primary metals. The life cycle is open if end-of-life products are neither collected for recycling nor entering those recycling streams that are capable of recycling the particular metal efficiently. Open life cycles include products discarded to landfills, products recycled through inappropriate technologies where metals are not or only inefficiently recovered (e.g., the informal sector), and metal recycling in which the functionality of the end-of-life metal is lost (non-functional recycling, see below). The distinction between open and closed product systems as made in Life Cycle Analysis (ISO, 2006), where a product system is only considered closed when a material is recycled into the same product system again, is often not applicable to metals as metals with the same properties (or quality) can be used in more than one product.

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

- Home scrap is material generated during fabrication or manufacturing that can be directly reinserted in the process that generated it. Home scrap recycling is general-

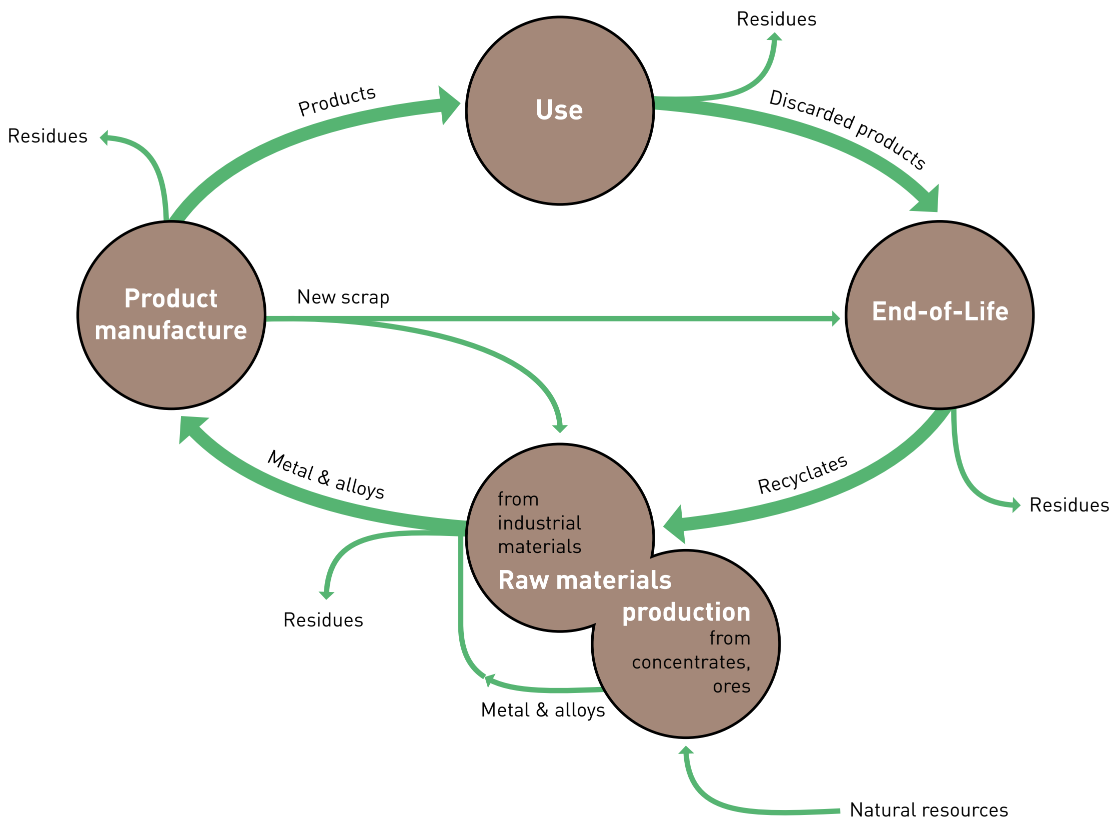


Figure 2. The life cycle of a material, consisting of production, product manufacture, use, and end-of-life. Recyclates are those materials capable of reentering use after reprocessing. The loss of residues at each stage and the reuse of scrap are indicated. (Reproduced with permission from Meskers, 2008.)

ly economically beneficial and easy to accomplish. It is excluded from recycling statistics and not further discussed here.

- New (or pre-consumer) scrap originates from a fabrication or manufacturing process and is mostly of high purity and value. Its recycling is generally economically beneficial and easy to accomplish although it becomes more difficult the closer one gets to finished products (e. g., rejected printed circuit boards). New scrap is typically included in recycling statistics.

- Old (or post-consumer) scrap is metal in products that have reached their end-of-life. Their recycling requires more effort, particularly when the metal is a small part of a complex product.

- Functional recycling is that portion of end-of-life recycling in which the metal in a discarded product is separated and sorted to obtain recyclates that are returned to raw material production processes that generate a metal or metal alloy. Often it is not the specific alloy that is remelted to make the same alloy, but any alloys within a certain class of alloys that are remelted to make one or more specific alloys. For example, a mixture of austenitic stainless steel alloys might be remelted and the resulting composition adjusted by addition of reagents or virgin metal to make a specific stainless steel grade.

- Non-functional recycling is that portion of end–of-life recycling in which the metal is collected as old metal scrap and incorporated in an associated large magnitude material stream as a "tramp" or impurity elements. This prevents dissipation into the environment, but represents the loss of its function, as it is generally impossible to recover it from the large magnitude stream. Although non-functional recycling is here termed a type of recycling, it will lead to an open metal life cycle as discussed above. Examples are small amounts of copper in iron recyclates that are incorporated into recycled carbon steel.

- Recycling failures occur when metal is not captured through any of the recycling streams mentioned above, including during use (in-use dissipation, as the corrosion of sacrificial zinc coatings on steel), at end of life (to landfills), and whenever metals are not recovered from recycling fractions (e. g., final wastes, slag, effluents, dust).

3. Defining Recycling Rates

Recycling rates have been defined in many different ways, from different perspectives (product; metal; metal in product) and for many different life stages; sometimes the term is left undefined. Attempts to rectify this situation (e. g., Sibley, 1995; Sibley, 2004; Eurometaux, 2006; Bailey et al., 2008; Reck and Gordon, 2008) have suggested more consistent approaches . In this report, we build upon that work to define recycling efficiencies at end-of-life (collection, process efficiency, recycling rate) and in metal production (recycling input rate, old scrap ratio).

At end of life (EOL), the recycling efficiency can be measured at three levels:

1. How much of the end-of-life (EOL) metal is collected and enters the recycling chain (as opposed to metal that is landfilled)? (**old scrap collection rate, CR**)

2. What is the efficiency in any given recycling process (i. e., the yield)? (**Recycling process efficiency rate**, also called recovery rate [e. g., van Schaik, A. et al, 2004]).

3. What is the **EOL-recycling rate (EOL-RR)**? The EOL-RR always refers to functional recycling (unless noted differently), and includes recycling as a pure metal (e. g., copper) and as an alloy (e. g., brass).

In contrast, the non-functional EOL-recycling rate describes the amount of metal that is collected but lost for functional recycling and that becomes an impurity or "tramp element" in the dominant metal with which it is collected (e. g., copper in alloy steel; more examples are provided in Appendix E).

The end-of-life recycling rate is strongly influenced by the least efficient link in the recycling chain, which is typically the initial collection activity.

Figure 3 provides a simplified metal life cycle based on which the above-mentioned EOL metrics can be calculated:

1. Old scrap collection rate: CR = e / d

2. Recycling process efficiency rate = g / e

3. EOL-RR = g / d
(refers to functional recycling only).

Non-functional EOL-RR = f / d.

In metal production, two other metrics are of importance, the recycling input rate and the old scrap ratio. The **recycling input rate (RIR)** describes the fraction of secondary (scrap) metal in the total metal input of metal production (as an approximation, primary metal input is calculated as extracted ore minus losses through tailings and slags). The RIR corresponds to the **recycled content (RC)** in the fabricated metal (flow c). The RIR is identical to the recycled content (RC) when the latter is calculated as follows (see Appendix H for further details):

4. RC = (j + m) / (a + j + m)

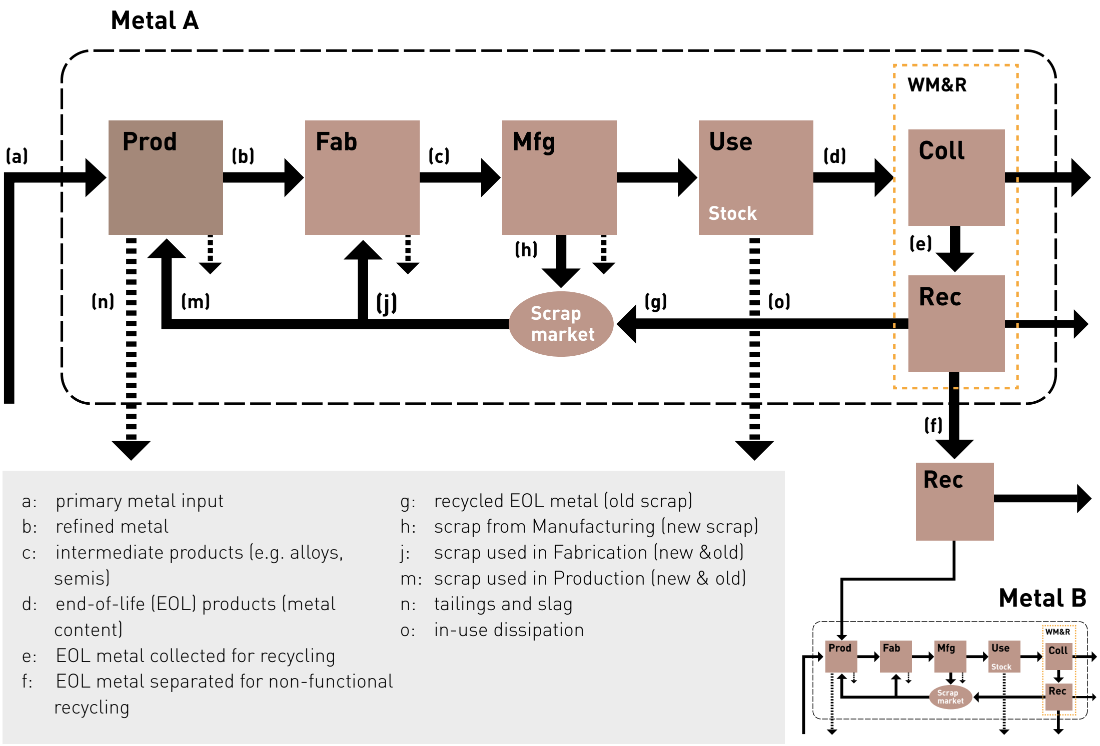


Figure 3. Metal life cycle and flow annotation: Flows related to a simplified life cycle of metals and the recycling of production scrap and end-of-life products. Boxes indicate the main processes (life stages): Prod, production; Fab, fabrication; Mfg manufacturing; WM&R, waste management and recycling; Coll, collection; Rec, recycling. Yield losses at all life stages are indicated through dashed lines (in WM referring to landfills). When material is discarded to WM, it may be recycled (e), lost into the cycle of another metal (f, as with copper wire mixed into steel scrap), or landfilled. The boundary indicates the global industrial system, not a geographical entity.

Zoom

The calculation of the RIR is straightforward at the global level, but difficult if not impossible at the country level. The reason is that information on the recycled content of imported produced metals is typically not available (flow b, i. e., the share of m/(a+m) in other countries is unknown), in turn making a precise calculation of the recycled content of flow c impossible.

The **old scrap ratio (OSR)** describes the fraction of old scrap (g) in the recycling flow (g+h).

5. $OSR = g / (g + h)$

In combination with the recycled content, this metric reveals the quantity of metal from EOL products used again for metal production and product manufacturing, and enhances understanding of the degree to which the use of scrap from various stages of the metal life cycle is occurring.

For a better interpretation of these metrics some influencing factors have to be considered. The recycled content depends on the amount of scrap available and on the scrap quality: The new-scrap availability depends on the degree of metal use and the process efficiency in fabrication and manufacturing. The old-scrap availability is a function of metal use a product lifetime ago, in-use dissipation over the product lifetime, and the efficiency of the EOL collection and recycling system. High growth rates in metal demand in the past, together with long product lifetimes (often several decades), result in available old scrap quantities that are typically much smaller than the metal demand in production, leading to RCs much smaller than 100 %. Even a very efficient EOL recycling system would not provide enough old scrap for a high recycled content with a high OSR. Comparisons of RCs across metals are problematic due to different growth rates in metal use over time, different end uses with different respective lifetimes, different production processes (sometimes limiting the amount of scrap used), and varying tolerances in metal production to scrap impurities (van Schaik et al., 2004; Gaustad et al., 2010).

The recycling process efficiency will vary from metal to metal, depending on the material type or metals grade for which a process is optimized, and although it can be high it will never reach 100 % due to thermodynamic and other limitations (Castro et al., 2004). Current recycling statistics by nature provide only historical data. In order to better align product design, life cycle management and recycling processes and measures it will become increasingly important to use predictive models. Such models have been developed by Van Schaik and Reuter (2010), but go beyond the scope of this report.

4. A Review of Available Information for Recycling Rates

The set of global-average metal recycling rates that we derive represents an order of magnitude estimate that was derived from a review of the recycling literature and informed estimates by industry experts. The years for which figures are available vary, but many apply to the 2000–2005 time period; in most cases the statistics change slowly from year to year. This literature review was followed by a workshop in which experts discussed the relevance and accuracy of the published information, which is clearly of varying quality and differ by region, product, and available technology, all of which make it challenging to quote definitive values for any of the recycling metrics. For used or end-of-life electronics, automotive vehicles, and some other products, significant exports take place from industrialized to transition and developing countries where the recycling process efficiency rate is often low. Additionally, for the base metals and gold, especially, informal recycling in developing countries is extensive. Thus, no attempt was made to specify exact recycling rates; rather, the experts chose five ranges for recycling values in cases where familiarity with the recycling industry enabled such choices to be made, even in the absence or paucity of published data. Because of the independence of data sources, and the underlying uncertainties, mass balance cannot always be achieved when combining the results of the various metrics, nor should one expect to do so, and the consensus numbers compiled here by the experts need to be understood as a first comprehensive assessment which will require further review and elaboration over time. Nonetheless, we regard the magnitudes of the results to be approximately correct on a global average basis as of the time of publication of this paper.

The detailed results of these exercises are presented in the Appendix. The three periodic table displays in Figures 4–6 illustrate the consensus results in compact visual display formats.

The EOL-RR results in Figure 4 relate to whatever form (pure, alloy, etc.) in which substance-specific recycling occurs. To reflect the level of certainty of the data and the estimates, data are divided into five bins: > 50 %, > 25–50 %, > 10–25 %, 1–10 %, and < 1 %. It is noteworthy that for eighteen of the sixty metals do we estimate the EOL-RR to be above 50 %. Another three metals are in the > 25–50 % group, and three more in the > 10–25 % group. For a very large number, little or no end-of-life recycling is occurring, either because it is not economic, or no suitable technology exists.

Similarly, Figure 5 presents the recycled content data in similar form. Lead, ruthenium, and niobium are the only metals for which RC > 50 %, but sixteen metals have RC in the > 25–50 % range. This reflects a combination in several cases of efficient employment of new scrap as well as better than average end-of-life recycling.

The old scrap ratio results (Figure 6) tend to be high for valuable materials, because these materials are used with minimal losses in manufacturing processes and collected at end of life with relatively high efficiency. Collection and recycling at end of life are high as well for the hazardous metals cadmium, mercury, and lead. Overall, 13 metals have OSR > 50 %, and another 10 have OSR in the range > 25–50 %.

Where relatively high EOL-RR are derived, the impression might be given that the metals in question are being used more efficiently than those with lower rates. In reality, rates tend to reflect the degree to which materials are used in large amounts in easily recoverable applications (e. g., lead in batteries, steel in automobiles), or where high value is present (e. g., gold in electronics). In contrast, where materials are used in small quantities in complex products (e. g., tantalum in electronics), or where the economic value is at present not very high, recycling is technically much more challenging.

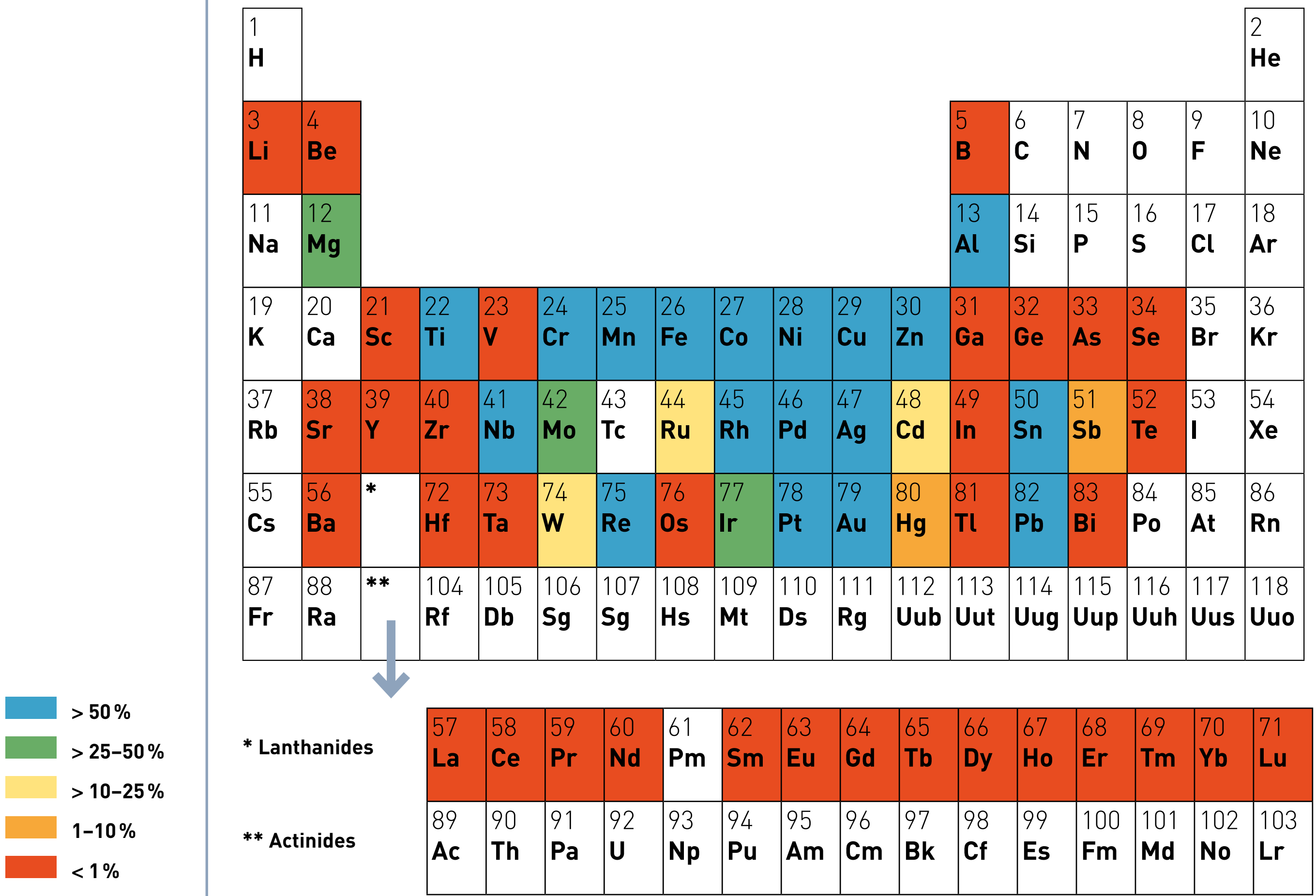


Figure 4. EOL-RR for sixty metals: The periodic table of global average end-of-life (post-consumer) functional recycling (EOL-RR) for sixty metals. Functional recycling is recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use. Unfilled boxes indicate that no data or estimates are available, or that the element was not addressed as part of this study. These evaluations do not consider metal emissions from coal power plants.

Zoom

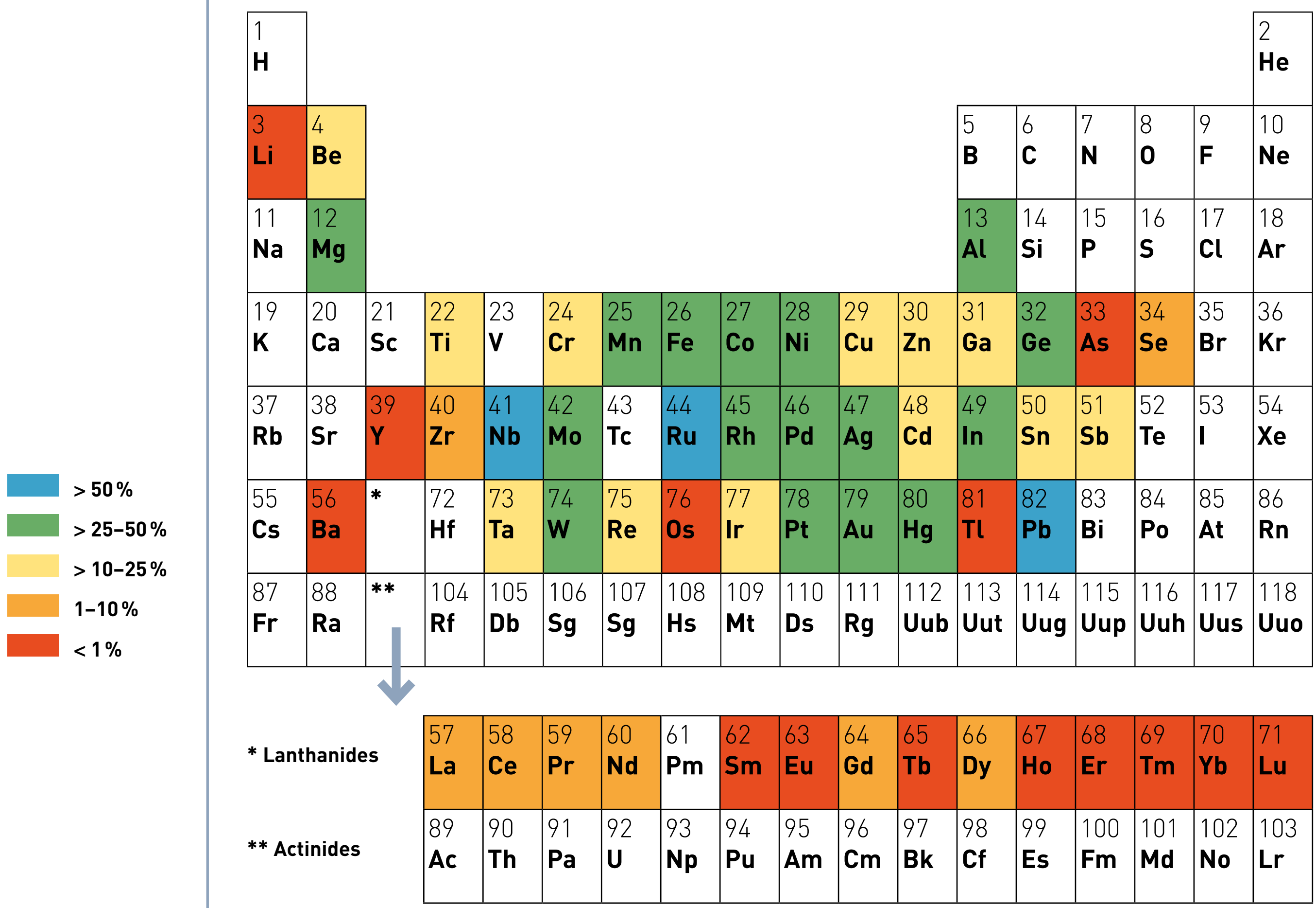


Figure 5. The periodic table of global average recycled content (RC, the fraction of secondary [scrap] metal in the total metal input to metal production) for sixty metals. Unfilled boxes indicate that no data or estimates are available, or that the element was not addressed as part of this study.

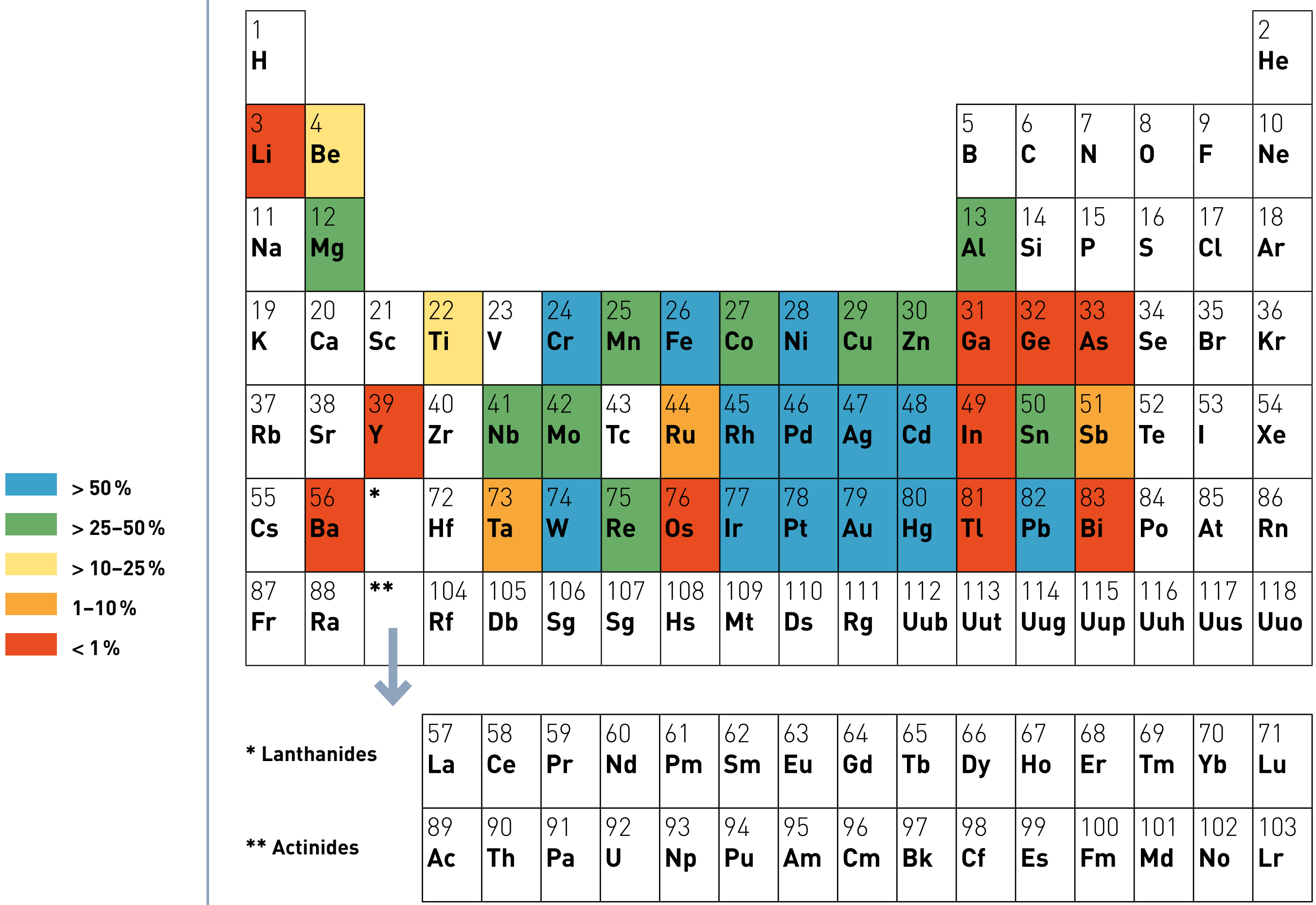


Figure 6. OSR for sixty metals: The periodic table of global average old scrap ratios (OSR, the fraction of old [post-consumer] scrap in the recycling flow) for sixty metals. Unfilled boxes indicate that no data or estimates are available, or that the element was not addressed as part of this study.

5. Recycling Policy Considerations

The "metal recycling universe" is much more complex than is often realized. It is also rapidly evolving, and encompasses a number of challenges related to sustainable development, including:

- Coping with fast growing streams of discarded products and materials.
- Recovery of post-consumer material resources, including scarce metals, thereby contributing to resource conservation, supply security, and metal price stability.
- Adapting to the manufacture of new products that contain increasingly complex mixes of materials, including composites.
- Protecting the environment and human health from hazardous emissions caused by inappropriate waste management or recycling practices.

Society's response to these challenges is not very advanced, as indicated by the relatively low global-level recycling statistics in this report. The numbers will vary from year to year due to changes in a number of underlying factors: metal use a product lifetime ago, share of different end use sectors, product lifetimes, product composition, product weight, and recycling efficiencies (van Schaik and Reuter, 2004; Reuter et al., 2005; Müller et al., 2006; Reck et al., 2010).

Can recycling efficiencies be improved? That is, can materials cycles be transformed from open (i. e., without comprehensive recycling) to closed (i. e., completely re-employed), or at least to less open than they are at present? A major challenge is that open cycles are typical for many metals in consumer goods such as cars, electronics, and small appliances (Hagelüken, 2007), due to:

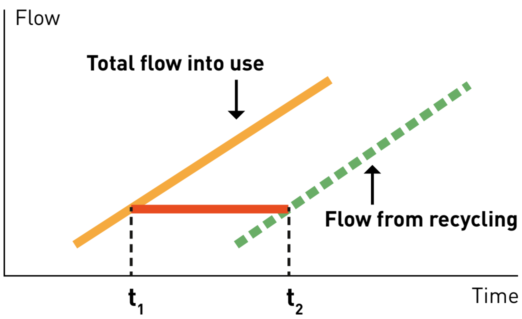
- Product designs that make disassembly and material separation difficult or impossible.
- A high mobility of products and the unclear material flows that result. These are caused by multiple changes of ownership, and sequential locations of use spread around the globe.
- A generally low awareness about a loss of resources, and missing economic recycling incentives due to low intrinsic value per unit. Nevertheless, their combined mass flows have a big impact on metal demand (Hagelüken and Meskers, 2008).
- Lack of an appropriate recycling infrastructure for end-of-life management of complex products in many developing countries and emerging economies. In industrialized countries many hibernating goods (in drawers and closets) and small devices going into the trash bin (e. g., mobile phones) reduce significantly the recycling efficiencies.
- Recycling technologies and collection facilities that have not kept pace with complex and elementally diverse modern products.

In practice, the effectiveness of recycling is a consequence of three related factors. The first is economics, because the net intrinsic value of the discarded materials must be high enough to justify the cost and effort of recycling. Where that value is not present, incentives such as deposit fees or other cost subsidies usually based on legal requirements may make it so, at least at the consumer level. The second factor is technology: Does the design of the discarded product, and the ways in which materials are joined or merged enable or inhibit available recycling processes? The final factor is societal: Has a habit of recycling been established? Do public campaigns promote recycling targets? To the degree that these factors are addressed, improved rates of reuse and recycling are likely. Many of these issues are discussed in detail in Graedel and van der Voet (2010).

Closed cycles are typical for many industrial goods such as industrial machinery, tools, and process catalysts. Although the required recycling technology does not differ much from that for consumer goods, the recycling efficiencies are usually much higher due to a high awareness of the involved stakeholders, economic recycling incentives, transparent and professional handling throughout the product lifecycle, and a rather limited change of ownership and location of use.

Policies and practices that could stimulate improved recycling need to consider:

- Taking a holistic view on life cycles and recycling chains in order to identify interactions and interlinkages between different metal cycles and also between product and metal cycles.
- Measuring discard streams to identify what is actually being lost.
- Managing material throughout the recycling sequence.
- Employing effective and appropriate technologies.
- Carrying out each step of the recycling sequence in an environmentally sound manner.
- Enhancing interregional stakeholder cooperation to more effectively track global material flows.



Zoom

Figure 7. The time delay in the recycling of metals in products.

Policies involving recycled content goals are intended to provide an incentive for recycling. However, given the limited availability of secondary metals, such an incentive serves no real purpose (Atherton, 2007). The intent of such policies could better be achieved by also encouraging a high old scrap ratio (i. e., the old scrap in the recycled content). Such an approach would provide an incentive to increase the end-of-life recycling rate and make fabrication processes more efficient. Nonetheless, so long as global metal use continue to increase and metals are used in products with extended lifetimes (Figure 7), even complete recycling can satisfy no more than a modest fraction of demand.

A large research and data collection effort is needed in the case of many of the metals in order to locate missing information and to obtain more reliable recycling statistics. Measures of recycling performance are needed for informed policy directions and to evaluate the effects of public policy and societal performance. In addition, in-depth research is necessary to develop new recycling technologies and infrastructures for specific applications (especially emerging technologies).

Despite the challenges of improving recycling rates, however measured, recycling generally saves energy and minimizes the environmental challenges related to the extraction and processing of virgin materials. The data presented in this report, and the discussions related to how the data are measured and how they might change over time given certain technological or societal approaches, provide information likely to be useful in moving society toward a more efficient level of resource utilization in the future. The information in this report clearly reveals that in spite of significant efforts in a number of countries and regions, many metal recycling rates are discouragingly low, and a "recycling society" appears no more than a distant hope. This is especially true for many specialty metals which are crucial ingredients for key emerging technologies. Policy and technology initiatives to transform this situation are urgently needed.

References

Atherton, J. 2007. Declaration of the metals industry on recycling principles, **International Journal of Life Cycle Assessment**, 12: 59–60.

Bailey, R., B. Bras, and J. K. Allen. 2008. Measuring material cycling in industrial systems. **Resources Conservation and Recycling** 52(4): 643–652.

Castro, M.B.G., J.A.M. Remmerswaal, M.A. Reuter, and U.J.M. Boin. 2004. A thermodynamic approach to the compatibility of materials combinations for recycling. **Resources, Conservation, and Recycling**, 43: 1–19.

Eurometaux, 2006. Recycling rates for metals. European Association of Metals (Eurometaux). Brussels, Belgium. http://www.eurometaux.org/Publications/BrochuresandLeaflets.aspx (Last accessed, August 2010).

Gaustad, G., Olivetti, E., and Kirchain, R. 2010. Design for recycling: Evaluation and efficient alloy modification. **Journal of Industrial Ecology** 14 (2): 286–308.

Graedel, T.E., and E. van der Voet, Eds. 2010. **Linkages of Sustainability**, Cambridge, MA: MIT Press.

Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., and Sonnemann, G. 2011. What Do We Know About Metal Recycling Rates? **Journal of Industrial Ecology**, DOI: 10.1111/j.1530–9290.2011.00342.x.

Hagelüken, C. 2007. The challenge of open cycles, **R'07, 8th World Congress**, L.M. Hilty, X. Edelmann, A. Ruf (eds.), CD-ROM.

Hagelüken, C., and C.E.M. Meskers. 2008. Mining our computers, **Electronics Goes Green Conf**, 2008, H. Reichl, N. Nissen, J. Müller, O. Deubzner (eds), pp. 585–590, Stuttgart.

ISO. 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. ISO 14044: 2006(E), Geneva.

Meskers, C.E.M. 2008. Coated Magnesium – Designed for Sustainability, The Hague: PhD thesis, Delft University of Technology, ISBN 978-9-064643-05-7.

Müller, D. B., T. Wang, B. Duval, and T.E. Graedel. 2006. Exploring the engine of anthropogenic iron cycles. **Proceedings of the National Academy of Sciences of the United States of America** 103(44): 16111–16116.

Reck, B.R., and R.B. Gordon. 2008b. Nickel and chromium cycles: Stocks and flows project Part IV. **JOM**, 60 (7): 55–59.

Reck, B.K., M. Chambon, S. Hashimoto, and T.E. Graedel. 2010. Global Stainless Steel Cycle Exemplifies China's Rise to Metal Dominance. **Environmental Science & Technology** 44(10): 3940–3946.

Reuter, M.A., U.M. J. Boin, A. Van Schaik, E. Verhoef, K. Heiskanen, Y. Yongxiang, and G. Georgalli, eds. 2005. The metrics of material and metal ecology. Vol. 16, **Developments in mineral processing**. Amsterdam: Elsevier Science.

Sibley, S.F. and W.C. Butterman. 1995. Metals recycling in the United States. **Resources Conservation and Recycling** 15(3–4): 259–267.

Sibley, S.F. 2004. **Flow studies for recycling metal commodities in the United States**. Reston, VA: US Geological Survey.

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

Van Schaik, A. and Reuter, M.A. 2010. Dynamic modeling of e-waste recycling system performance based on product design. **Minerals Engineering** 23: 192–210.

Appendix A. Most Common Uses for the Metals of the Periodic Table

Ferrous Metals

(The ferrous metals are predominantly iron-based, and mostly magnetic)

V – Vanadium is used in HSLA (high strength-low alloy) steels
Cr – Chromium is the chief additional constituent of stainless steels
Mn – Manganese is present at 0.3 –1.0 % in nearly all steels
Fe – Iron is the basis and chief constituent of all the ferrous metals
Ni – Nickel is often a constituent of stainless steels and superalloys
Nb – Niobium is used in HSLA steels and superalloys
Mo – Molybdenum is employed in high-performance stainless steels

Non-Ferrous Metals

(The non-ferrous metals contain no iron, and are used in quantities second only to the ferrous metals)

Mg – Magnesium is used in construction and transportation
Al – Aluminium is used principally in construction and transportation
Ti – Titanium is used in paint and transportation
Co – Cobalt's major uses are in superalloys, catalysts, and batteries
Cu – Copper sees wide use in conducting electricity and heat
Zn – Zinc's major use is in coating steel (galvanizing)
Sn – Tin's major uses are in cans and solders
Pb – Lead's main use is in batteries

Precious Metals

(The precious metals have historically been prized for their relation to wealth and status, but are increasingly employed in technologically-sophisticated products)

Ru – Ruthenium major uses are electronics (hard disk drives) and process catalysts/electrochemistry.
Rh – Rhodium's major use is in auto catalysts
Pd – Palladium's major use is in auto catalysts
Ag – Silver's principal uses are in electronics, industrial applications (catalysts, batteries, glass/mirrors), and jewelry
Os – Osmium sees very occasional use as a catalyst, but has little industrial importance.
Ir – Iridium's major uses are electro-chemistry, crucibles (for mono-crystal growing) and spark plugs.
Pt – Platinum's major use is in auto catalysts
Au – Most gold is used in jewelry, but some in electronics

Specialty Metals

(The specialty metals are typically present in industrial and consumer products in small amounts, but for their specific physical and chemical properties. The use of specialty metals is increasingly related to high-level product efficiency and function)

Li – Lithium's major use is in batteries
Be – Beryllium's principal use is in electronics
B – Boron is used in glass, ceramics, and magnets
Sc – Scandium is used in aluminium alloys
Ga – Gallium's principal use is in electronics: ICs, LEDs, diodes, solar cells
Ge – Germanium is used in night vision (infrared) lenses (30 %), PET catalysts (30 %), fiber optics, and solar cell concentrators
As – Arsenic metal is used in semiconductors (electronics, photovoltaics) and as an alloying element; arsenic oxide is used in wood preservatives and glass manufacture
Se – Selenium is employed in glass manufacture, manganese production, LEDs, photovoltaics, and infrared optics
Sr – Strontium is used in pyrotechnics, ferrite ceramic magnets for electronics
Y – Yttrium is used as a phosphor
Zr – Zirconium's principal use is in nuclear reactors
Cd – The principal use of cadmium is in batteries (85 %), and in pigments (10 %)
In – Indium's principal use is as a coating in flat-panel displays
Sb – Antimony is used as a flame retardant (65 % of use), and in lead acid batteries (23 %)
Te – Tellurium's uses include steel additives, solar cells, and thermoelectrics
Ba – Barium in the form of $BaSO_4$ is used as a drilling fluid (perhaps 80 % of use) and as a filler in plastic, paint and rubber (about 20 %)
Hf – Hafnium is used in nuclear reactors and to a small degree in electronics.
Ta – Tantalum's principal use is in capacitors in electronics
W – Tungsten's principal use is in cemented carbide cutting tools
Re – Rhenium is a superalloy component employed largely in (gas) turbines (perhaps 60 % of use), and catalysts
Hg – Mercury retains its use in chlorine/caustic soda production; in other applications it is being phased out
Tl – Thallium sees occasional use in medical equipment
Bi – Bismuth's principal uses are as a metallurgical additive and an alloy constituent.

The Lanthanides

La – Lanthanum is usually employed as a battery constituent
Ce – Cerium is used largely as a catalyst
Pr – Praseodymium is used in glass manufacture and magnets
Nd – Neodymium is used in magnets
Sm –Samarium is used in magnets
Eu – Europium is used as a phosphor
Gd – Gadolinium is used in ceramics and magnets
Tb – Terbium is used in magnets
Dy – Dysprosium is used in magnets
Ho – Holmium is used in magnets
Er – Erbium is a major constituent of fiber-optic amplifiers
Tm –Thulium has no significant uses
Yb – Ytterbium is used as a phosphor
Lu – Lutetium is used as a scintillator in computerized tomography

Appendix B. The Alloy Families of the Major Metals

(Lead Author: T. Graedel)

Because most metals are used in alloy form, and because the recycling of those alloys is of interest in this report, we list and comment below on the principal alloys or alloy groups for the major metals. This information is intended to be informative in an overall way, rather than to provide detailed compositional and performance information (which is readily available from industrial and internet sources).

Steel Alloy Family

- **Carbon Steel.** Carbon steel is mainly an iron-carbon alloy, with very small amounts of carbon (well below 1 %, sometimes less than 10 ppm); other elements enter its composition either as a by-product of ironmaking (P, S) or steelmaking operations (Mn, Si, S, P) or as traces, called tramp elements, which may be introduced from either primary or scrap material.

- **Low-Alloy Steels.** Low-alloy steels (engineering steels) contain less than 5 % total amount of alloying elements, typically Cr, Ni, Mn. In this family, free-machining steels have been custom designed by addition of S, Bi, or Se to generate brittle chips when they are machined.

- **High-Strength Steel.** Alloying at the level of up to a few hundred ppm of as many as a dozen metals (Nb, Ti, B, V, lanthanides, etc.) is carried out under the term "micro-alloying" to derive a significant strength increase, thus generating high-strength low alloy (HSLA) and micro-alloyed carbon steels.

- **Tool Steel.** The tool steels are alloy steels that are capable of being hardened and tempered. They have from several up to about twenty percent of alloying elements, depending on the application for which they are designed. Common tool steel alloying elements are W, Mo, Cr, V, and Co.

- **Stainless Steel.** Stainless steels are high chromium content steels (15–20 % Cr) with excellent corrosion resistance. In the absence of other significant alloying constituents, the chromium SSs are termed the ferritics. Nickel is often added (at 5–12 %) to improve the corrosion resistance in neutral or weakly oxidizing conditions – this is the austenitic SS group, which can include Mo as well, and sometimes minor amounts of other elements.

Superalloy Family

Superalloys are heat-resistant alloys based on nickel, iron-nickel, or cobalt. They exhibit high strength and resistance to surface degradation at elevated temperatures. Superalloys often include modest amounts of tungsten, rhenium, and other elements. They are high-value materials, and used almost exclusively within industries (e. g., power generation, aircraft engines) that can recover them readily, so recycling is generally simpler than with alloys used more widely.

Aluminium Alloy Family

Aluminium is often used in alloy form with additions of copper, iron, silicon, manganese, magnesium, and perhaps other materials for the purpose of improving metal forming and corrosion resistance. Within the aluminium recycling industry a distinction is made between refiners and remelters and between cast and wrought alloys. Refiners produce standard cast alloys from cast and wrought alloy scrap and some primary material, while remelters produce wrought alloys almost

only from wrought scrap. The difference between cast and wrought alloys is related to their composition.

- Cast alloys contain a maximum of 20 % alloying elements (mainly Si, Mg, and Cu) and the silicon content is more than 5 %.
- Wrought alloys contain a maximum of 10 % alloying elements (Mn, Mg, Si, Cu, Zn) and less than 1 % silicon. For this reason it is very difficult to make wrought alloys out of cast alloys, but it is possible to make cast alloys out of wrought alloys.

Copper Alloy Family

Copper is often used in pure form as a conductor of electricity and heat, but has two major alloy families as well: copper-zinc alloys (brasses) and copper-tin alloys (bronzes). Small amounts of manganese, aluminium, and other elements may be added to bronzes and brasses to improve machinability, corrosion resistance, or other properties.

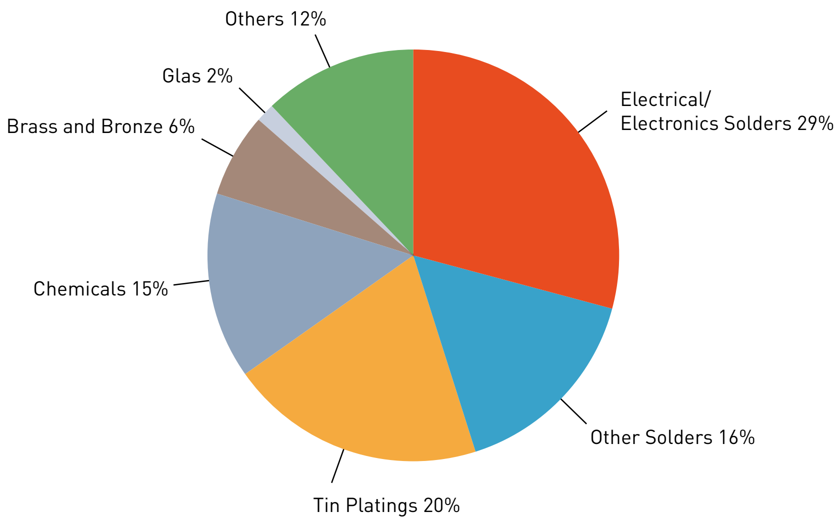


Figure B1. Worldwide applications of tin in 2004 (USGS, 2009).

Tin Alloy Family

The most important use of pure tin is in tin platings, which accounted for around 20 % of the world's tin production in 2004. About 6 % was used in brass and bronze. Most of the tin, however, is utilized in alloy form, with the electrical and electronics industry using around 29 % of the world's tin production in 2004. Other solders accounted for another 16 % (USGS, 2009).

Traditionally, the electronics industry used tin-lead solders, sometimes with additions of a few percentages of silver or other metals. The main solder alloy until 2006 was the tin-lead alloy with 37 % of lead, the rest being tin. The total use of such solders in the electrical and electronics industry until 2006 was around 90,000 t per year globally (USGS, 2009).

Appendix C. Review of Ferrous Metal Recycling Statistics

(Lead Authors: J.-P. Birat, S.F. Sibley)

Recycling rate estimates for iron, steel, and its major alloying metals (collectively called ferrous metals) are given in the following table. The range of the figures, often obtained by different methods, is wide and the figures are consistent only if a large level of uncertainty in the data is assumed. However, with these existing data an EOL-RR of 70–90% can be estimated for iron and steel.

Metal	OSR (%)	RC (%)	EOL-RR (%)
V			< 1[a]
Cr	60[h], 72[i]	20[i], 18[h]	87[i], 93[h]
Mn	33[a], 67[j]	37[j]	53[j]
Fe	54[a], 52[b], 66[c], 65[d]	28[d], 41[c], 52[b]	52[c], 67[d], 78[e], 90[f]
Ni	66–70[m, o], 88[n]	29[m], 41[n]	57[n], 58–63[m, o]
Nb	44[a], 56[l]	22[l]	50[l], 56[a]
Mo	33[a], 67[k]	33[k]	30[k]

Table C1. Recycling statistics for the ferrous metals group. Blank entries indicate the absence of data or informed estimates.

a Working group consensus
b Worldsteel (2009)
c Fenton, USGS (2004)
d Wang et al. (2007)
e Birat (2001)
f Steel Recycling Institute (2007)
h Johnson et al. (2006)
i Papp, USGS (2004)
j Jones, USGS (2004)
k Blossom, USGS (2004)
l Cunningham, USGS (2004a)
m Reck et al. (2008a)
n Goonan, USGS (2009)
o Reck and Graedel (2010).

For all of the USGS figures in Tables 1, 2, 4, and 5, "recycled content" is roughly equivalent to the USGS "recycling rate"; and "EOL-RR" is roughly equivalent to the USGS "recycling efficiency," with trade and stocks taken into account in the USGS percentage. USGS evaluations are for the USA only, and are likely higher than global averages.

Differing values are the result of different reference years, system boundaries, and/or underlying data in the studies cited.

Appendix D. Review of Non-Ferrous Metal Recycling Statistics

(Lead Authors: J. Allwood, G. Sonnemann)

The nonferrous group drew upon expert industry judgment and elemental cycle research in making its estimates, which are given in Table D1. Most of these metals are widely enough used, and often sufficiently valuable, that their recycling and reuse is reasonably high. This is especially true for lead, which is mostly used in large vehicle and industrial batteries that are returned and subsequently recycled in commercially and industrially linked recycling chains.

Metal	OSR (%)	RC (%)	EOL-RR (%)
Mg	42[h]	33[h]	39[h]
Al	40[a], 50[b]	34[c], 36[a], 36[b]	42[a], 60[c], 70[b]
Ti[q]	11[m]	52[m]	91[m]
Co	50[d]	32[d]	68[d]
Cu	24[e], 78[f]	20[f], 30[e], 37[g, n]	43[e], 53[f]
Zn	19[n], 35–40[p], 71[o]	18[o], 27[n]	19[n], 35–60[p], 52[o]
Sn	50[l]	22[l]	75[l]
Pb	95[i], 96[j]	63[i], 42[k], 51[j]	95[i], 52[k], 68[j]

Table D1. Recycling statistics for the nonferrous metals. Blank entries indicate the absence of data or informed estimates.

a Plunkert, USGS (2006)
b Zheng (2009)
c IAI (2009)
d Shedd, USGS (2004)
e Goonan, USGS (2010a)
f Graedel et al. (2004)
g Risopatron, 2009
h Kramer, USGS (2004)
i Smith, USGS (2004)
j Mao et al. (2008),
k Wilson and White (2009)
l Carlin, USGS (2004)
m Goonan, USGS (2010b)
n Plachy, USGS (2004)
o Graedel et al. (2005)
p Sempels (2009)
q the figures relate to Ti metal or alloy, not oxide.

USGS evaluations are for the USA only, and are likely higher than global averages. The EOL-RR value of 52 % for Pb is an EU15 estimate.

Differing values are the result of different reference years, system boundaries, and/or underlying data in the studies cited.

Appendix E. Review of Precious Metals Recycling Statistics

(Lead Authors: B. Reck, M. Buchert, C. Hagelüken)

Precious metals are sufficiently valuable that they are efficiently recycled except in some applications and/or when used in very small amounts (e. g., silver in mirrors or car glass; platinum/ruthenium in computer hard disks) or when EOL products do not enter into an appropriate recycling chain (open loops, see section 5). Costs of collection are often the determining factor. New scrap may be recycled at very small precious metal concentrations, because collection costs are low. Furthermore, if alternative costs of disposal of new scrap are high, marginal concentrations may be recycled as a cost optimization measure.

The expert judgment of the EOL-RRs for individual product groups are given in Table E1

	EOL Recycling Rates 1)	**Sector-specific EOL recycling rates** Vehicles 2)	Electronics	Industrial applications 3)	Dental	Others 4)	**Jewellery, coins** 5)
Ru	5 – 15		0 – 5	40 – 50		0 – 5	
Rh	50 – 60	45 – 50	5 – 10	80 – 90		30 – 50	40 – 50
Pd	60 – 70	50 – 55	5 – 10	80 – 90	15 – 20	15 – 20	90 – 100
Ag	30 – 50	0 – 5	10 – 15	40 – 60		40 – 60	90 – 100
Os	no relevant end use sectors						
Ir	20 – 30	0	0	40 – 50		5 – 10	
Pt	60 – 70	50 – 55	0 – 5	80 – 90	15 – 20	10 – 20	90 – 100
Au	15 – 20	0 – 5	10 – 15	70 – 90	15 – 20	0 – 5	90 – 100

Relevance of end use sector per metals (% of total gross metal demand)*

- **> 50 % very high**
- **> 25–50 % high**
- **> 10–25 % medium**
- **10 % low**
- **nil (blank)**

Table E1. Estimated end-of-life recycling rates for precious metals for the main end use sectors (global averages, percent, functional recycling only).

1) Total without jewellery, coins (no typical end-of-life management for these products)

2) Autocatalysts, spark plugs, conductive Ag-pastes, excluding car-electronics

3) incl. process catalysts/electrochemical, glass, mirror (Ag), batteries (Ag). In some cases, the available EOL metal is reduced due to prior in-use dissipation (e. g., homogeneous Pt-catalysts).

4) incl. decorative. medical, sensors, crucibles. photographic (Ag), photovoltaics (Ag)

5) incl. medals & silverware

* including metal demand for closed loop systems (e. g., process catalysts, glass and other industrial applications)

below. Consensus overall recycling statistics are provided in Table E2. Precious metals are generally not recycled in a non-functional fashion because their value is too high.

Available annual statistics for platinum-group metals (PGMs) (with the exception of those for automotive catalysts) do not provide data for total (gross) demand, nor for recycling from industrial applications (e. g., process catalysts). In contrast, figures reported therein are net figures, only addressing the additional PGM demand resulting from life cycle losses and market growth (including new applications). In industrial applications, however, most of the demand is met by secondary metal recovered from catalyst recycling. Industrial applications usually have very efficient closed cycles (see section 2) in which substantial EOL flows of PGMs are recycled.

Estimates for PGMs are based on Hagelüken et al. (2005), as updated by the authors. Key references for the electronics recycling rate are Chancerel et al. (2009), Meskers and Hagelüken (2009) and Rochat et al. (2007).

Metal	OSR (%)	RC (%)	EOL-RR (%)
Ru	< 20	50–60	5 –15
Rh	> 80	40	50–60
Pd	> 80	50	60 –70
Ag	76[c], 77[d], > 80	20[e], 30[d], 32[c]	58[d], 97[c], 30–50
Os	< 1[g]	< 1[g]	< 1[g]
Ir	> 80	15 –20	20–30
Pt	58[f], > 80	16[f], 50	76[f], 60 –70
Au	75[a], > 80	29[a], 31[b]	40[b], 96[a], 15 –20

a Amey, USGS, 2006
b GFMS, 2009a
c Hilliard, USGS, 2003
d Johnson et al. (2005)
e Silver Institute, 2009 and GFMS, 2009b
f Hilliard, USGS, 2004
g van Oss, 2009

Table E2. Consensus recycling statistics for the precious metals group. Entries with no reference are the expert opinion of the group, with background from USGS (2004). USGS evaluations are for the USA only, and are likely higher than global averages.

(a) Old scrap in recycle flow & recycled content includes jewellery scrap; EOL-RR (functional recycling only) without jewellery scrap (see Table E1);

(b) PGM statistics (Johnson Matthey, 2009; GFMS, 2009c) do not provide gross demand numbers for industrial applications. Recycled content includes the estimates of the working group for gross demand and recycling for these sectors.

(c) The high RC for Ru is due to the high availability of new scrap.

Differing values are the result of different reference years, system boundaries, and/or underlying data in the studies cited. Data by Hilliard (2003, 2004) refer to USA in 2004, data by Johnson et al. (2005) refer to global level in 1998.

Appendix F. Review of Specialty Metals Recycling Statistics

(Lead Authors: M. Buchert, C. Hagelüken)

Recycling statistics for the specialty metals are given in Table F1. Literature values are available in a few cases, but the bulk of the estimates are derived from the expert knowledge of the group members. Note that many specialty metals, including lithium, barium, and the rare earth elements, are mainly used as oxides or other compounds. The listed recycling rates are independent of form, and include metals, alloys, and metal compounds.

As can be seen from the table, there are large differences among the specialty metals, but differences also exist among the different applications of the metals. For example, the reported antimony recycling rate refers to metal applications only, but about 70% of Sb mine production is used in oxide form, from which only a very small part is eventually recycled.

Several common circumstances explain much of the evaluations in Table F1:

1. Hardly any recycling: this is applicable to specialty metals used in small quantities as part of elementally complex products such as computer chips or as a minor constituent in multi-component alloys. Although these products may enter recycling streams, the specialty metals are often incorporated into base metal recyclates and their individual functionality is lost.

2. Mainly new scrap recycling: this is applicable to specialty metals such as indium, gallium, germanium, and tantalum. The recycled content is above 25%, but other recycling metrics are very low. These metals are largely used in (opto)-electronics and photovoltaics. During manufacturing a large amount of new scrap, such as spent sputtering targets, saw dust, or broken wafers, is created. All this material is recycled and contributes to a high recycled content in the material supply to the manufacturing stage. Old scrap in the recycling flow is low due to the difficulty in collecting the products. Furthermore, the metal content in the products can be low and recycling technology for these metals in EOL products is often lacking.

3. Functional old scrap recycling: rhenium, for example. Old scrap in the recycling flow is over 5%. Rhenium is used in superalloys and as a catalyst in industrial applications, which together make up about 80% of the rhenium use. This closed industrial cycle, as well as the high value of rhenium, ensure very good collection. Furthermore good recycling technologies are in place to recover the metal. New scrap is recycled as well. Because the rhenium demand is growing, and this is met by primary production, the share of recycled rhenium in the overall supply is low.

4. Non-functional old-scrap recycling: beryllium, for example. Beryllium is used as an alloying element in copper alloys used in electronic and electrical applications. In the collection of these devices, the beryllium follows the same route as the copper and ends up at copper smelters/recyclers. During the recycling process the beryllium is usually not recovered, but is diluted in the copper alloy or, most often, transferred to the slag in copper smelters. Hence the beryllium old scrap recycling number is quite high, but functional beryllium recycling is low.

- **Speciality metals**: Li, Be, B, Sc, Ga, Ge, As, Se, Sr, Y, Zr, Cd, In, Sb, Te, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Hg, Tl, Bi

Metal	OSR (%)	RC (%)	EOL-RR (%)
Li	< 1	< 1	< 1
Be	14[k], 75[c]	10[k], 25[c]	7[k], < 1[c]
B	No data		< 1
Sc			< 1
Ga	<1	25–50[e]	< 1
Ge	40[f], 0	50[f], 35, 50[f]	76[f], < 1
As	< 1	< 1	< 1
Se	No data	1–10	< 5
Sr			< 1
Y	0	0	0
Zr		1–10	< 1
Cd	76[d]	25[j], 32[d], 50–75	15[d]
In	1	25–50	<1
Sb	80[a], < 10	20[a], 10–25[b], < 10	89[a], < 5
Te			< 1
Ba	No data		
La		1–10	< 1
Ce		1–10	< 1
Pr		1–10	< 1
Nd		1–10	< 1
Sm		< 1	< 1
Eu		< 1	< 1
Gd		1–10	< 1
Tb		< 1	< 1

Metal	OSR (%)	RC (%)	EOL-RR (%)
Dy		1–10	< 1
Ho		< 1	< 1
Er		< 1	< 1
Tm		< 1	< 1
Yb		< 1	< 1
Lu		< 1	< 1
Hf			< 1
Ta	1–10, 43[h]	10–25, 21[h]	< 1, 35[h]
W	80[i]	46[i]	10–25, 66[i]
Re	~50%	10–25	> 50
Hg	97[g]	25–50	1–10, 62[g]
Tl	0	0	0
Bi	< 1		< 1

a Carlin (2006)
b Roskill (2007)
c Civic (2009)
d Plachy (2003)
e Buchert (2009)
f Jorgenson (2006)
g Brooks and Matos (2005)
h Cunningham (2004b)
i Shedd (2005)
j Morrow (2009)
k Cunningham (2004c)

Table F1. Consensus recycling statistics for the specialty metals group. Entries with no reference are the expert opinion of the group. USGS evaluations are for the USA only, and are likely higher than global averages. Blank entries indicate the absence of data or informed estimates.

Appendix G. Examples for system definition in Figure 3 (metal life cyle)

(Lead Author: B. Reck)

In this paragraph, we provide two examples for functional and non-functional recycling. According to Figure 3 in the main report, functional recycling at end-of-life takes place when the recycling flows remain within the boundaries of metal A (i. e., in the form of the old scrap flow "g"). If instead, metal A is recycled in a way that its original properties are no longer needed it is defined as leaving the system boundary of metal A and entering the cycle of metal B (flows f and following; non-functional recycling). In metal B, metal A is considered an impurity or tramp element that may or may not compromise the quality of metal B.

Example 1 – Galvanized steel, coated with zinc

At end-of-life, the galvanized steel is recycled in an electric arc furnace (EAF) that produces carbon steel. The zinc is captured in the flue dust with most zinc being recycled to become a secondary input material in the zinc smelter.

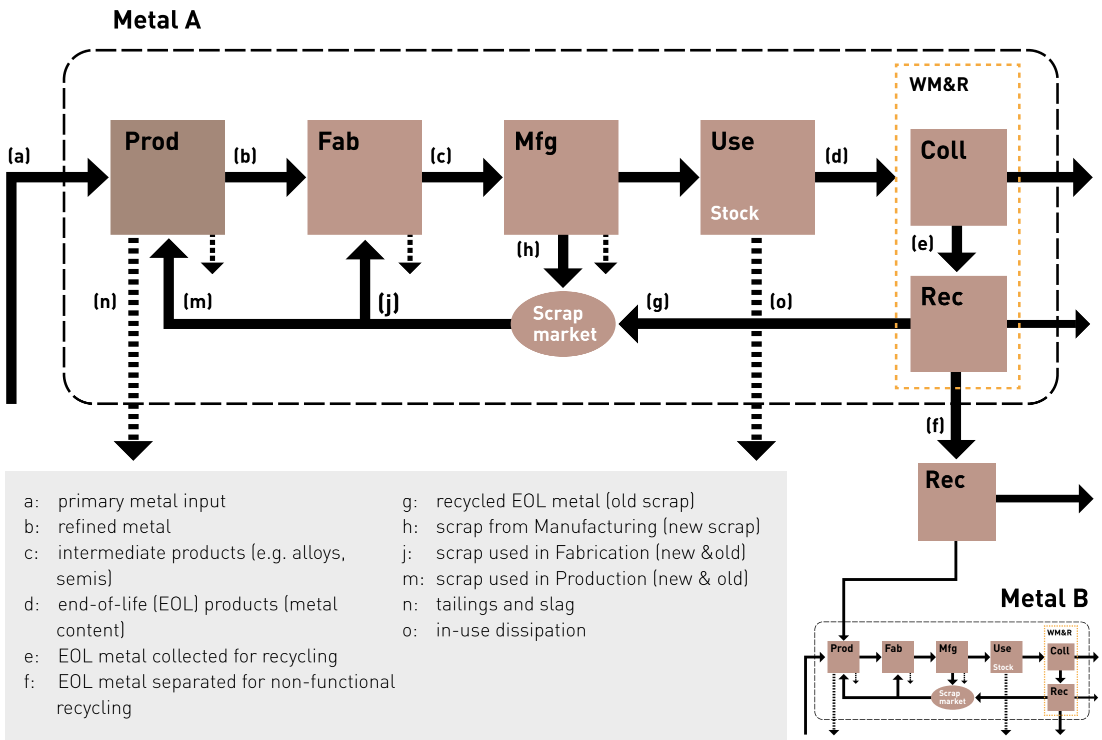


Figure 3. Flows related to a simplified life cycle of metals and the recycling of production scrap and end-of-life products. Boxes indicate the main processes (life stages): Prod, production; Fab, fabrication; Mfg manufacturing; WM&R, waste management and recycling; Coll, collection; Rec, recycling. Yield losses at all life stages are indicated through dashed lines (in WM referring to landfills). When material is discarded to WM, it may be recycled (e), lost into the cycle of another metal (f, as with copper wire mixed into steel scrap), or landfilled. The boundary indicates the global industrial system, not a geographical entity.

a) The zinc perspective (i. e., zinc is metal A):

The zinc fraction of the disposed of galvanized steel corresponds to flow d. The zinc entering the steel EAF corresponds to flow e. The processes EAF and flue dust recycling are located within the "recycling"-process box (part of WM&R). Functional recycling takes place when the zinc in the flue dust is recycled and becomes first flow g, and later becomes a part of flow m as secondary zinc input into the zinc smelter. Metal loss takes place when the zinc concentration in the flue dust is too low to justify zinc recycling and the zinc, together with the dust, is landfilled (shown as yield loss from the recycling process).

b) The carbon steel perspective (i. e., carbon steel is metal A):

The disposed of galvanized steel corresponds to flow d. After separation steps within the "recycling" process the old scrap flow (flow g) becomes part of the scrap input of the EAF (flow m). The EAF is located within the "production" process.

Example 2 – Nickel use in superalloys, at End-of-Life recycling as input material for stainless steel production

Metal A is nickel. Refined nickel (flow b) is used in alloy and stainless steel production, both located in the fabrication process. Superalloys are used in high-temperature applications such as turbines that are mainly produced from primary materials in order to meet their stringent specifications. Stainless steels comprise a family of many grades with varying nickel concentrations and typically have a scrap content of more than 40 % (nickel content).

The end-of-life superalloy (a subflow of flow d) will be collected for recycling to become a secondary input material either in the superalloy or stainless steel production, both located in the Fabrication process. In the case of use for stainless steel, the old superalloy scrap (a subflow of flow g) becomes part of the scrap input in stainless steel production (a subflow of flow j). Both processes, superalloy- and stainless steel production, are located within the system boundary of nickel (metal A), which is why also the recycling of superalloys to stainless steels corresponds to functional recycling.

If, instead, some of the end-of-life superalloys were recycled as, for example, cobalt alloys that nickel content would be considered as non-functional recycling (flow f to Metal B). In this case, metal B would be cobalt.

Applying recycling metrics at the material- or product level:

The metal recycling rates presented in this study (Figures 4–6) only refer to the material level, i.e., they present global averages across all product applications of a metal, not distinguishing between different forms of metals (pure or alloyed) or different end use applications (e.g., buildings, transportation, machinery). A further breakdown of recycling metrics to product groups is generally not possible due to a lack of available data.

However, applying these recycling metrics to product groups is possible. For example, once a generic collection rate (CR) for end-of-life vehicles (ELV) has been determined, the information can be used to directly compare the end-of-life recycling rate of the different materials used in vehicles (e.g., aluminum, steel, copper) by combining the CR with the material-specific recycling process efficiency of ELVs.

Appendix H. Scrap use in metal production: Recycling Input Rate vs. Recycled Content

(Lead Author: B. Reck)

Two terms can be found that describe the share of secondary metal (scrap) in a product, with 'product' referring to either the elementary metal, a metal alloy, or a manufactured product: 'Recycled Content' (RC) and 'Recycling Input Rate' (RIR). Without consensus across stakeholders, some use the two terms interchangeably while others distinguish them by using 'Recycling Input Rate' at the material level (e.g., scrap content in a sheet of alloy) and 'Recycled Content' at the finished product level (e.g., scrap content in a car, as average over all materials). In our opinion, such a distinction in terminology would likely be confusing to practitioners and policymakers alike. Instead, we use one term only, Recycled Content, as it is well-established, while using the same calculations as for the RIR.

The **calculation methods** for this metric often differ in the reference flow used ('the product', 'metal produced', 'total metal input') when determining the scrap share (the following flow annotations all refer to Figure 4). Reference flows used include

1. "metal produced", interpreted either as primary refined metal (flow b) or fabricated metal (flow c), and
2. "primary plus secondary metal input", with primary input interpreted either as metal-content in the extracted ore (flow a), mine production (flow a*), or primary refined metal (flow b).

The selection of the reference flow is often driven by practical reasons such as data availability.

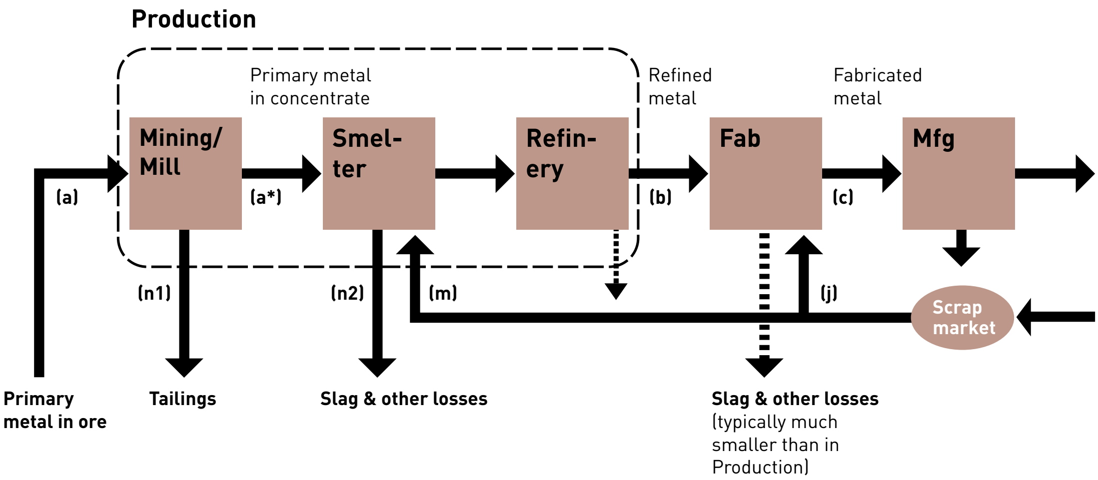


Figure H1. The main subprocesses of metal production are mining/milling, smelting, and refining. The flow annotations follow Figure 2 in the main article, with n being the sum of the flows n1 and n2. Examples for fabricated metal (flow c) include steel or brass sheets, aluminum foil, and cast alloys. The share to which scrap is used in either production (flow m) or fabrication (flow j) varies greatly from metal to metal.

From a resource perspective we are interested in how much primary mining has been avoided by using secondary metal. In this study, we therefore select "primary plus secondary metal input" as the reference flow, with primary input being the metal content in the extracted ore (flow a). This leads to the following definition of the Recycling Input Rate (RIR):

$$RIR = (j + m) / (a + j + m) \qquad (1)$$

The RC of the fabricated metal (e.g., brass) considers the scrap use at all previous metal processing steps (e.g., scrap use in the primary copper smelter, flow m, and scrap use in the brass mill, flow j). In this paper, all Recycled Content values are based on (1), leading to identical results for Recycled Content and Reycling Input Rate (RIR).

Earlier definitions and terminology:

We note that an earlier, slightly different definition of the RIR in (1) was introduced by the metal industry in 2007 (Sempels 2007). In that definition, the scrap share in metal production was referred to the amount of "metal produced" (flow c) instead of to the total metal input (a + j + m):

$$RIR_{old} = (j + m) / c \quad \text{(outdated)} \qquad (2)$$

The result was a slightly higher RIR value than the one resulting from (1), as all the losses from metal production (mainly slag, flow n2) were only assigned to the primary metal input. This led to the unintended consequence that with increasing metal losses the value of the RIR increased as well. The current definition was proposed by Reck and Lifset (2008b), and has since been adopted by Eurometaux's Recycling Project Team (Mistry 2010).

References of Appendices

1. Amey, E.B. 2004. Gold recycling in the United States in 2000, USGS Circular 1196-A.

2. Birat, J.-P. 2001. Le cycle du fer ou le recyclage durable de l'acier, 18ème Congrès Francophone en Gé-nie des Procédés, Palais des Congrès de Nancy, Récents progrès en génie des procédés, vol. 15 (2001) no.88, pp. 3–24.

3. Blossom, J.W. 2004. Molybdenum recycling in the United States in 1998, USGS Circular 1196-L.

4. Brooks, W.E. and Matos, G.R. 2005. Mercury recycling in the United States in 2000, USGS Circular 1196-U.

5. Buchert, M. 2009. Critical Metals for Future Sustainable Technologies and Their Recycling Potential, Darmstadt: Öko-Institut e.V. (UNEP DTI/1202/PA).

6. Carlin, J.F. Jr. 2004. Tin recycling in the United States in 1998, USGS Circular 1196-K.

7. Carlin, J.F. Jr. 2006. Antimony recycling in the United States in 2000, USGS Circular 1196-Q.

8. Chancerel, P., C.E.M. Meskers, C. Hagelüken, and S. Rotter. 2009. Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. Journal of Industrial Ecology 13(5): 791–810.

9. Civic, T. 2009. Brush Wellman Co., Private communication.

10. Cunningham, L.D. 2004a. Columbium (niobium) recycling in the United States in 1998, USGS Circular 1196-I.

11. Cunningham, L.D. 2004b. Tantalum recycling in the United States in 1998, USGS Circular 1196-Z.

12. Cunningham, L.D. 2004c. Beryllium recycling in the United States in 2000, USGS Circular 1196-P.

13. Fenton, M.D. 2004. Iron and steel recycling in the United States in 1998, USGS Circular 1196-G.

14. GFMS. 2009a. Gold 2008, London.

15. GFMS. 2009b. Silver 2008, London.

16. GFMS. 2009c. Platinum and Palladium 2008, London.

17. Goonan, T.G. 2009. Nickel recycling in the United States in 2004, USGS Circular 1196-Z.

18. Goonan, T.G. 2010. Copper recycling in the United States in 2004, USGS Circular 1196-X.

19. Goonan, T.G. 2010. Titanium recycling in the United States in 2004, USGS Circular 1196-Y.

20. Graedel, T.E., D. van Beers, M. Bertram, K. Fuse, R.B. Gordon, A. Gritsinin, A. Kapur, R. Klee, R. Lifset, L. Memon, H. Rechberger, S. Spatari, and D. Vexler. 2004. The multilevel cycle of anthropogenic copper, Environmental Science & Technology, 38: 1253–1261.

21. Graedel, T.E., D. van Beers, M. Bertram, K. Fuse, R.B. Gordon, A. Gritsinin, E. Harper, A. Kapur, R.J. Klee, R.J. Lifset, and S. Spatari. 2005. The multilevel cycle of anthropogenic zinc, Journal of Industrial Ecology, 9 (3): 67–90.

22. Hagelüken, C., M. Buchert, P. Ryan. 2005. Material flows of platinum group metals. GFMS. London.

23. Hilliard, H.E. 2003. Silver recycling in the United States in 2000, USGS Circular 1196-N.

24. Hilliard, H.E. 2004. Platinum recycling in the United States in 1998, USGS Circular 1196-B.

25. IAI (International Aluminium Institute), 2009. Sustainability update 2009. London: IAI.

26. Johnson, J., J. Jirikowic, M. Bertram D. van Beers, R.B. Gordon, K. Henderson, R. J. Klee, T. Lanzano, R.J. Lifset, L. Oetjen, and T.E. Graedel. 2005. Contemporary anthropogenic silver cycle: A multilevel analysis, Environmental Science & Technology, 39: 4655–4665.

27. Johnson, J., L. Schewel, and T.E. Graedel. 2006. The contemporary anthropogenic chromium cycle, Environmental Science & Technology, 40, 7060 –7069.

28. Johnson Matthey Co. 2009. Platinum 2009, New York.

29. Jones, T.S. 2004. Manganese recycling in the United States in 1998, USGS Circular 1196-H.

30. Jorgenson, J.D. 2006. Germanium recycling in the United States in 2000, USGS Circular.

31. 1196-V.

32. Kramer, D.A. 2004. Magnesium recycling in the United States in 1998, USGS Circular 1196-E.

33. Mao, J.S., J. Dong, and T.E. Graedel 2008. The multilevel cycle of anthropogenic lead. II. Results and discussion, Resources, Conservation, and Recycling, 52: 1050 –1057.

34. Meskers, C.E.M. and C. Hagelüken. 2009. The impact of pre-processing routes on precious metal recovery from PCs. In Proceedings of the European Metallurgical Conference, GDMB, Clausthal-Zellerfeld, Germany, pp. 527– 540.

35. Mistry, M. 2010. Personal Communication with M. Mistry, Chairman, Recycling Project Team, Eurometaux. Brussels, 18 April 2010.

36. Morrow, H. 2009. International Cadmium Association, Private communication.

37. Papp, J.F. 2004. Chromium recycling in the United States in 1998, USGS Circular 1196-C.

38. Plachy, J. 2003. Cadmium recycling in the United States in 2000, USGS Circular 1196-O.

39. Plachy, J. 2004. Zinc recycling in the United States in 1998, USGS Circular 1196-D.

40. Plunkert, P.A. 2006. Aluminum recycling in the United States in 2000, USGS Circular 1196-W.

41. Reck, B.K., D.B. Müller, K. Rostkowski, and T.E. Graedel 2008a. The anthropogenic nickel cycle: Insights into use, trade, and recycling, Environmental Science & Technology, 42: 3394 –3400.

42. Reck, B.K. and Graedel, T.E. 2010. The global nickel cycle in 2005. Unpublished material.

43. Reck, B.K. and R. Lifset. 2008b. Resource efficiency, recycling rates, and metal losses: pitfalls in terminology and implications. Paper presented at ConAccount Workshop, 11–12 September. Prague, Czech Republic.

44. Risopatron, C.R. 2009. The case of copper, Paper presented at Eurometaux Workshop on Metal Recycling Data, Brussels, June 4.

45. Rochat, D., C. Hagelüken, M. Keller, and R. Widmer. 2007. Optimal recycling for printed wiring boards (PWBs) in India. In R'07World Conference: Recovery of Materials and Energy for Resource Efficiency, L.M. Hilty, X. Edelmann, and A. Ruf (Eds.), ISBN 978-3-905594-49-2.

46. Roskill Information Services. 2007. Antimony, London.

47. Sempels, R. 2007. Recovery and recycling – vital to metal's sustainability. In Recycling Seminar. Lisbon, Portugal: International Study Groups for copper, lead and zinc, and nickel. http://www.insg.org/presents/Mr_Sempels_Oct07.pdf

48. Sempels, R. 2009. International Zinc Association, Private Communication.

49. Shedd, K.B. 2004. Cobalt recycling in the United States in 1998, USGS Circular 1196-M.

50. Shedd, K.B. 2005. Tungsten recycling in the United States in 2000, USGS Open File Report OFR-2005-1028.

51. Silver Institute. 2009. World Silver Survey 2009, Washington, DC.

52. Smith, G.R. 2004. Lead recycling in the United States in 1998, USGS Circular 1196-F.

53. Steel Recycling Institute. 2008. The Inherent Recycled Content of Today's Steel, Pittsburgh, PA.

54. US Geological Survey. 2009. Mineral Commodity Summaries 2009, Reston, VA.

55. US Geological Survey. 2010. Mineral Commodity Summaries 2010, Reston, VA.

56. van Oss, H. 2009. US Geological Survey, Private communication.

57. Wang, T., D. Müller and T.E. Graedel. 2007. Forging the anthropogenic iron cycle, Environmental Science & Technology, 41: 5120–5129.

58. Wilson, D., and P. White. 2009. Recycling ratios for lead, Paper presented at Eurometaux Workshop on Metal Recycling Data, Brussels, June 4.

59. Worldsteel. 2009. Worldsteel Model (unpublished), Brussels.

60. Zheng, L. 2009. Organisation of European Aluminium Refiners and Remelters, Private communication

About the UNEP Division of Technology, Industry and Economics

The UNEP Division of Technology, Industry and Economics (DTIE) helps governments, local authorities and decision-makers in business and industry to develop and implement policies and practices focusing on sustainable development.

The Division works to promote:

> sustainable consumption and production,
> the efficient use of renewable energy,
> adequate management of chemicals,
> the integration of environmental costs in development policies.

The Office of the Director, located in Paris, coordinates activities through:

- **The International Environmental Technology Centre** - IETC (Osaka, Shiga), which implements integrated waste, water and disaster management programmes, focusing in particular on Asia.
- **Sustainable Consumption and Production** (Paris), which promotes sustainable consumption and production patterns as a contribution to human development through global markets.
- **Chemicals** (Geneva), which catalyzes global actions to bring about the sound management of chemicals and the improvement of chemical safety worldwide.
- **Energy** (Paris and Nairobi), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.
- **OzonAction** (Paris), which supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.
- **Economics and Trade** (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies.

UNEP DTIE activities focus on raising awareness, improving the transfer of knowledge and information, fostering technological cooperation and partnerships, and implementing international conventions and agreements.

For more information, see **www.unep.fr**

A key question that relates to the very broad and intensive use of metals is whether society needs to be concerned about long-term supplies of any or many of them. This is a many-faceted question that cannot be answered quickly or unequivocally. To address it, the Resource Panel's Working Group on Global Metal Flows envisions a series of six reports, of which this is the second one addressing recycling rates of metals.

In this report compiled by a group of experts from industry, academia, and government evaluate recycling rate information for sixty different metals – essentially all the metals of the periodic table of elements. In this effort, recycling rates are carefully and clearly defined, and results then presented for all the metals for three important but different recycling rates. For many of these metals, this is the first time such estimates have ever been presented.

Many end-of-life recycling rates (EOL-RRs) are very low: for only eighteen of the sixty metals is the very important EOL-RR above 50 % at present. The results of this study indicate a tremendous challenge for circular economy.

Published in May 2011

www.unep.org

United Nations Environment Programme
P.O. Box 30552 Nairobi, Kenya
Tel.: ++254-(0)20-762 1234
Fax: ++254-(0)20-762 3927
E-mail: uneppub@unep.org

UNEP

For more information, contact:
Resource Panel Secretariat
UNEP DTIE
Sustainable Consumption
and Production Branch
15 rue de Milan
75441 Paris CEDEX 09
France
Tel: +33 1 44 37 14 50
Fax: +33 1 44 37 14 74
E-mail: resourcepanel@unep.org
www.unep.org/resourcepanel

International Resource Panel

ISBN: 978-92-807-3161-3
DTI/1381/PA