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1. Introduction

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This publication includes all four of the International Resource Panel's publications to date on metals. The introduction summarizes the knowledge contained in these reports while making use of cross-references to the reports wherever possible, in order to allow the reader to gain a deeper understanding of the topic at hand. Much more extensive information and citations to the relevant literature are available within the reports themselves.

Metals and their compounds have been used in society for millennia because of their unique properties, such as conductivity, malleability, hardness, and lustre. In the 19th century, however, iron and steel became the material foundation of a new level of social progress, enabling bridges, stronger buildings, longer lasting industrial products, and the like. That development continues today, with most of the highly-valued products of modern technology, such as computers, medical scanners, aircraft engines, and weather satellites being inconceivable without the widespread use of metals. Metals are essential for most current and future technologies, e. g., renewable energy technologies. They have the potential to allow for sustainable global social and economic development, and constitute one of the key elements of a prospective Green Economy.

According to UNEP's Green Economy Report (UNEP 2011a), the main sources of economic development and growth in the future will be renewable energy technologies, resource and energy efficient buildings and equipment, low-carbon public transport systems, infrastructure for fuel-efficient and clean energy vehicles, and efficient waste management and recycling facilities. All of those rely heavily on metals. Hence, as outlined in § 4 of the Rio +20 Declaration[a] „promoting integrated and sustainable management of natural resources" – including metals – is a key necessity to achieve the transition to a resource efficient and green economy.

The understanding that a holistic approach that takes a life cycle perspective to resources management is needed to better identify their interlinkages and gaps in a systemic way led to the establishment of the International Resource Panel (IRP). Hosted at UNEP, the IRP was officially launched in November 2007 to provide the scientific impetus for decoupling, which means the use of fewer resources per unit of economic output while simultaneously reducing the environmental impact of any resources that are used (Figure 1).

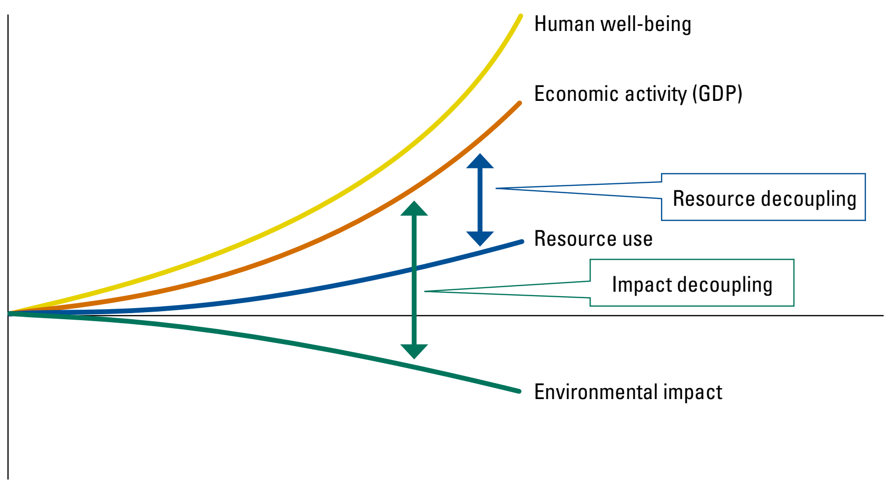


Figure 1: Stylized representation of resource decoupling and impact decoupling (UNEP 2011b).

a UNCSD 2012: The Future We Want; available at: http://www.uncsd2012.org/thefuturewewant.html

The IRP is composed of 23 distinguished experts, supported by a large group of collaborators. Among other areas of interest, the Global Metal Flows Working Group of the IRP was established to contribute to a better understanding of anthropogenic metals cycles. It seeks to foster the establishment of a global sound material-cycle society by providing scientific and authoritative assessment studies on the global flows of metals. Since its establishment, the Working Group has published four out of a planned series of six reports. These four are part of this publication and are cross-referenced as part of this introduction. As listed in Table 1, reports published so far have looked at various aspects of metals, including their stocks in society, their recycling rates and opportunities for increase, and the various environmental challenges associated with metals extraction and use. In addition to these reports, a working paper on long-term estimates of geological stocks of metals (UNEP 2011c) has been published, where some usable estimates are available. However, as the mineable quantities of metals in virgin ore deposits remain challenging to quantify, data are very limited. Hence, the working paper also makes use of estimates, derived from an expert workshop exercise.

Report 1 – **Metal Stocks in Society** – Scientific Synthesis (UNEP, 2010)

Report 2a – **Recycling Rates of Metals** – A Status Report (UNEP, 2011d)

Report 2b – **Metal Recycling** – Opportunities, Limits, Infrastructure (UNEP, 2013a)

Report 3 – **Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles** (UNEP, 2013b)

Report 4 – Future Demand Scenarios for Metals

Report 5 – Critical Metals and Policy Options

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

* As part of the series and to complement the existing reports, a working paper with the title "**Estimating Long-term Geological Stocks of Metals**" (UNEP 2011c) has been published. This working paper provides important data and estimates related to metal geological stocks. It has not, however, been subject to independent review by outside specialists, so should not be regarded as a final version of a report by the International Resource Panel.

Table 1:

Reports of the Global Metal Flows Working Group of the IRP

Within the aforementioned reports, the Global Metal Flows Working Group divides the 62 different metallic elements of the periodic table into the following four groups (Figure 2):

1. **Ferrous metals:** These are metals containing iron and other elements that are widely mined and used in large quantities for a variety of industrial and other purposes.

2. **Non-ferrous metals:** These are metals, including alloys, that do not contain iron in appreciable amounts.

3. **Precious metals:** These metals, including gold, silver, and platinum, have major uses in financial risk management and in personal adornment, but also see significant industrial use that takes advantage of their resistance to corrosion as well as other physical and chemical properties.

4. **Specialty or Technology metals:** These elements are used in small quantities, but in uses for which they are superbly adapted. High-technology applications in solar panels, electronics, magnets, and high-temperature performance are examples that illustrate the central role these often scarce materials play in modern society.

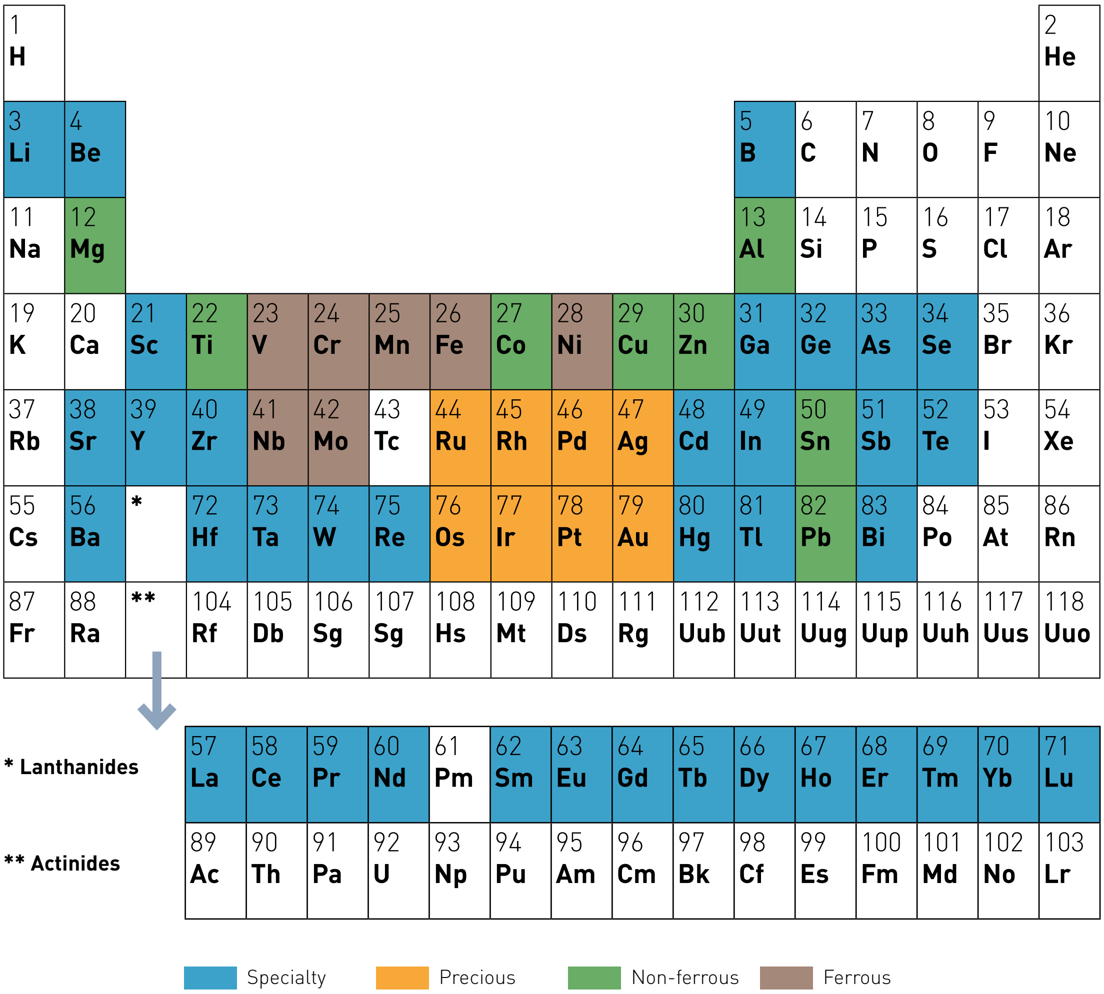


Figure 2: The major metal groupings addressed in this report (UNEP 2011d).

The rising demand for metals is likely to cause challenges for supply

Supplies of metals can be constrained by issues other than absolute geological abundance. Accessibility to metal resources can be limited by technological (depth, composition of ore), economical (infrastructure, size of deposit), environmental (natural habitats), and geopolitical (trade barriers) challenges.

These challenges are further fuelled by an accelerating demand for metals and elements. This is especially true for those used in new energy technologies (e. g., solar cells, batteries, etc.) and the production of complex electronic devices and networks. As a result of the increasing demand for magnets, for example, there is great interest in securing supplies of rare earth elements (Nd, Pd, Dy), nickel, cobalt, and lithium. The rising demand for specialty and critical metals is mainly linked to the application of high-technologies in developed countries. In contrast, the demand for base metals will rise due to developing countries' increasing efforts to build basic infrastructure.

Graedel and Cao (2010) demonstrate that all countries rely heavily on the supply of metals, regardless of their level of development. According to them, the "rate of use of the spectrum of metals stock is highly correlated to per capita gross domestic product, as well as to the Human Development Index and the Global Competitiveness Innovation Index" (Graedel & Cao 2010). Consequently, the demand for metals across the entire spectrum of metals will rise along with a global increase in wealth and technology.

The use of metals can have significant consequences for the environment

With rising metal demand, the pressures on the environment will also increase. Primary metal production can result in local environmental and health impacts. These are mainly due to the leaching of toxic substances into ground- and surface water. In addition, the improper treatment of mine wastes, the release of air emissions (greenhouse gases, sulphur dioxide etc.), and biodiversity loss are continuing challenges. Although mines will always be a manifestation in the local landscape, adverse impacts can be prevented to a large extent by using appropriate technologies, and can be remediated after closure of the mine, if done properly. Applying best-available-techniques (BAT) based systems and other measures can also help increase energy and entropy efficiency and can thus improve performance substantially.

While the demand for most metals is rising, for certain metals a reduced demand can lead to an oversupply. This oversupply also occurs for metals with a former high level of use, where old stocks entering the waste stage form an unwanted source of secondary material. Cadmium is a good example in which a highly toxic metal has been used for batteries in the past and is now less needed. Those final waste streams thus need to be immobilized in order to prevent them from interactions with the environment. A storage solution is hence necessary for environmental protection, as well as to allow future generations access to those metals.

In most cases, anthropogenic metal cycles are orders of magnitude larger than natural metal cycles. Emissions to the environment, however, are roughly of the same order of magnitude as natural emissions from weathering and volcanism. Anthropogenic metal emissions to the environment are, however, increasingly dominated by non-metal sources (e. g., fossil fuels, phosphate fertilizers), reflecting the increasing global demand for fossil energy carriers and the growth of agricultural production. Metal emissions can occasionally lead to human and ecosystem health risks, as concentrations in the environment transgress no-effect levels.

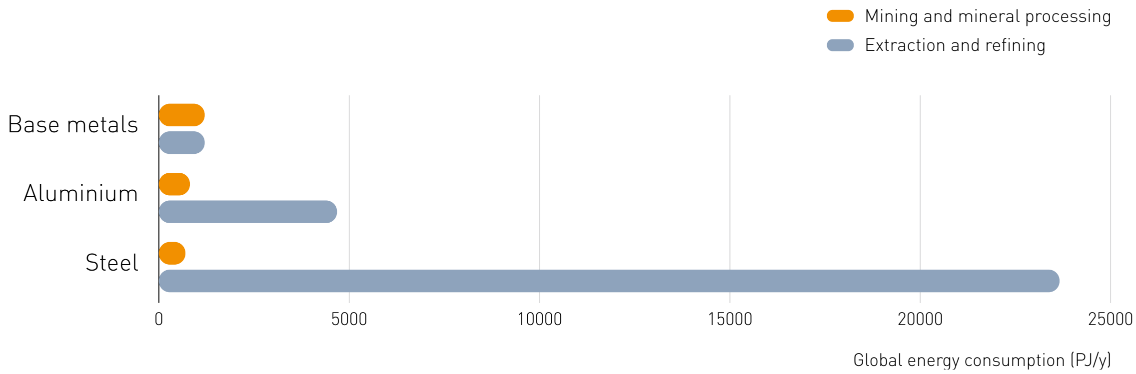


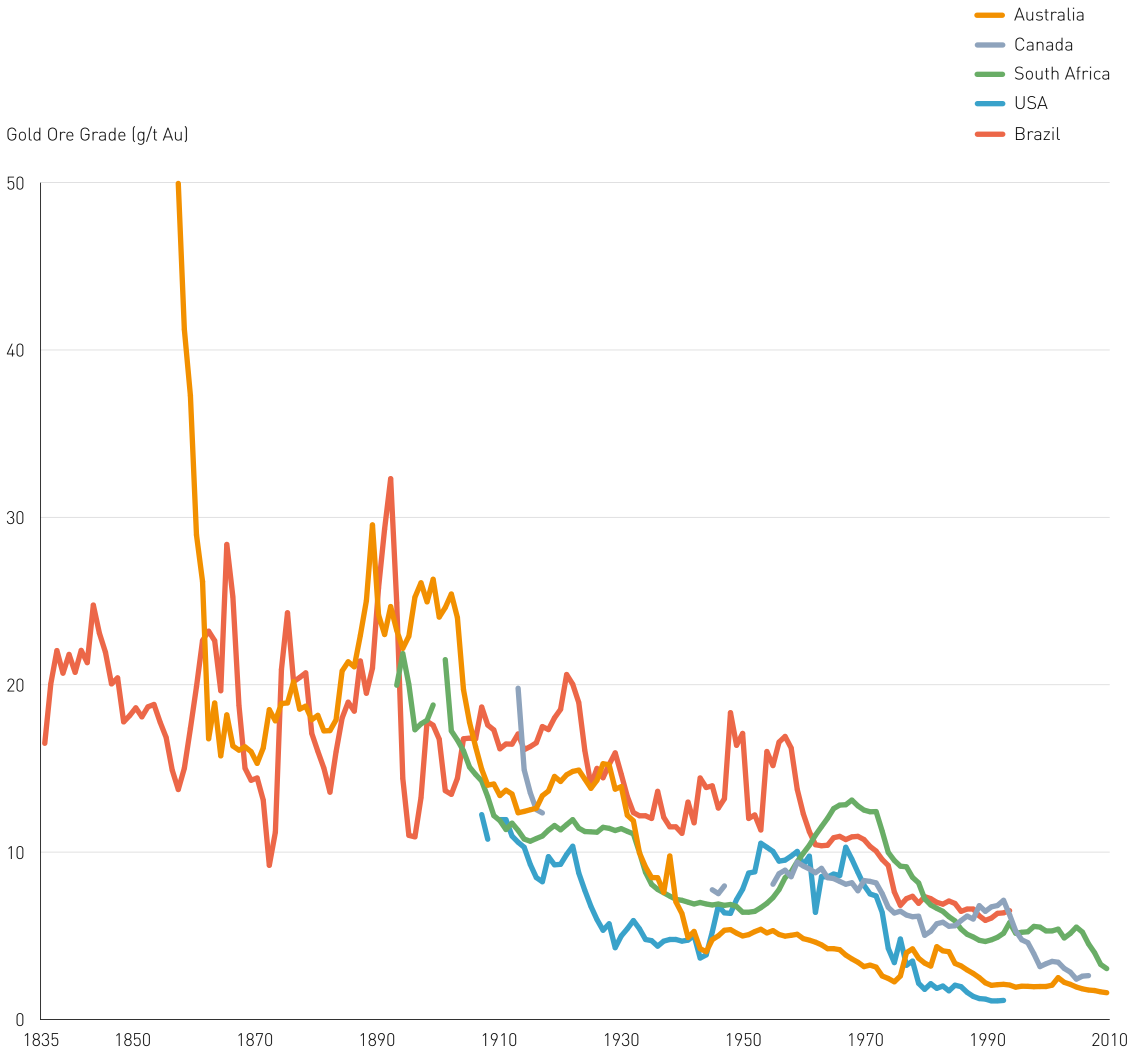
Figure 3: Global energy consumption for primary metal production (UNEP 2013b).

Primary metals production is responsible for 7–8% of global total energy use and thus for 7–8% of the energy related GHG emissions. The gross energy requirement varies significantly from metal to metal, from 20 MJ (steel) to 200,000 MJ (platinum) per kg of metal produced. Nevertheless, due to their large production volumes, steel and aluminium still constitute the largest share of the global energy use for primary metals production (Figure 3).

The overall amount of energy used for metals production is expected to increase steeply during the next few decades. The process efficiencies of mining and refining are also increasing, lowering thereby the energy requirement. On the other hand, the increased processing of lower grades of ore (e. g., copper, nickel, or gold as depicted in Figure 6) to meet increasing demand leads to a higher energy requirement per kg of metal. According to a the IRP's Decoupling report, *"today, depending on the metal concerned, about three times as much material needs to be moved for the same ore extraction as a century ago, with concomitant increases in land disruption, groundwater implications and energy use"* (UNEP 2011b).

Figure 4:

Long-term trends in processed gold ore grades for select countries (UNEP 2013b).



In addition to the increasing demand for metals for infrastructure and new technologies, the growing use of renewable energy technologies will also lead to a rising demand for specialty metals and their compounds/alloys Still, while the demand and thus the overall energy requirement for metal production will rise, applying these metals in renewable energy and other smart and sustainability-enabling technologies will assist in lowering overall global energy related GHG emissions (Figure 5).

Available Stocks of Metals in Society need to be identified and used

Secondary production of metals has enormous benefits, both with regards to resource availability and to reducing impacts related to energy use and mining. Increasing recycling rates and making use of stocks that are available in our societies therefore must be a key component of any sustainable metals management. According to UNEP's Decoupling Report, "waste recycling represents one of the most immediate, tangible and low-cost

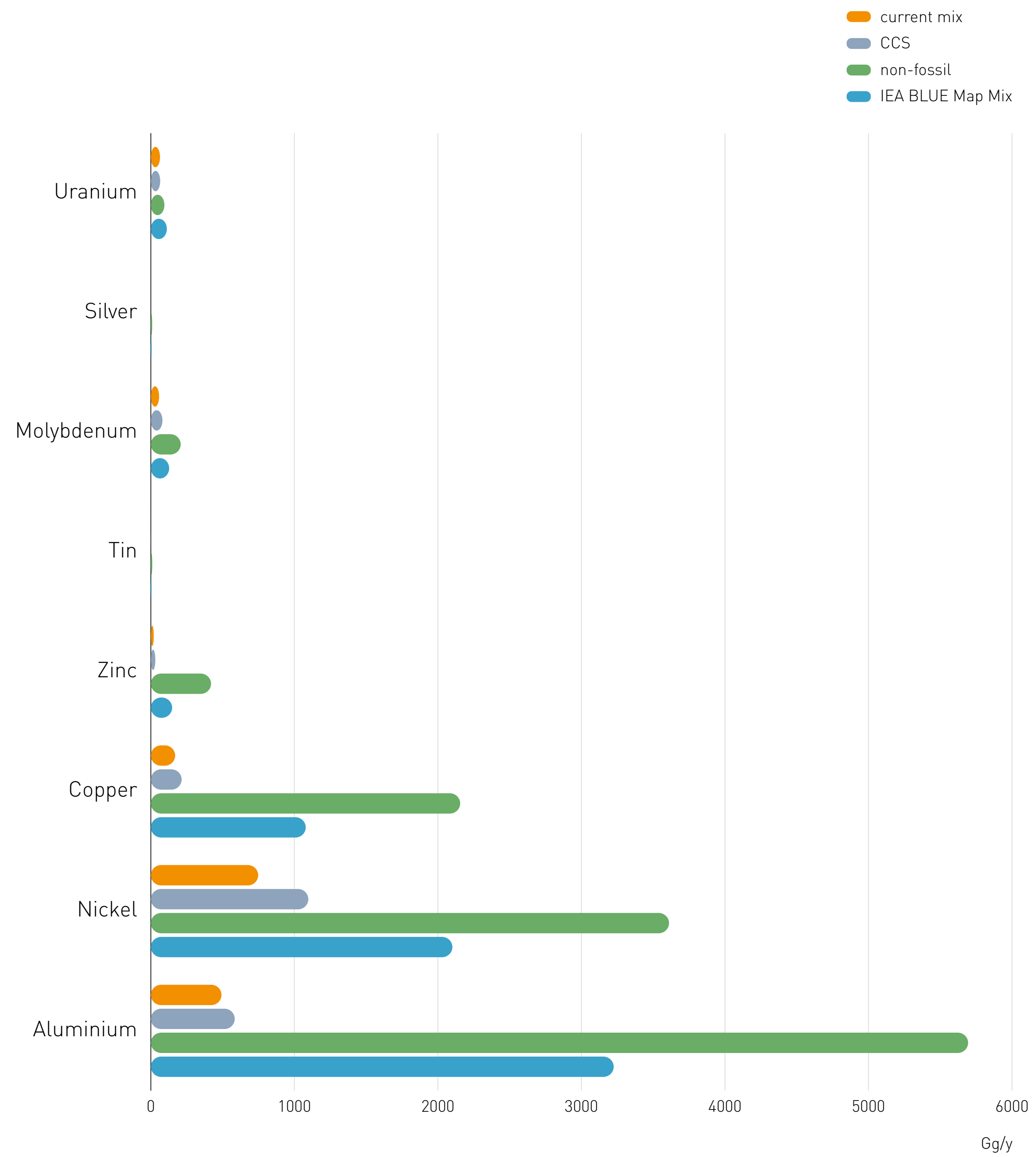


Figure 5:

Demand for metals for the global electricity system under various scenario assumptions (UNEP 2013b).

investments in dematerialization available. It saves on capital costs, creates jobs, and forces the middle classes to take greater responsibility for the resources they throw away" (UNEP 2011b).

In order to develop targeted and effective recycling strategies, an overview and understanding of metal stocks in society is important. However, assessing stocks in society is highly complex. By applying a Material-Centric perspective (i.e., a focus on a particular material, which may exist in different forms and in many products), a number of estimates have been developed. Such estimates are essential to have insight into the magnitude of societal stocks, so as to determine whether they can be a significant source of future supply. Reliable estimates of in-use stocks and in-use lifetimes have been developed only for the following five metals: aluminium, copper, iron, lead, and zinc (Figure 6).

Figure 6: Extant In-Use Stock Estimations for the Major Engineering Metals (UNEP 2010).

Metal	Number of estimates	Percent of all estimates	Global per capita stock	MDC per capita stock[b]	LDC per capita stock[c]
Aluminum	9	7.4	80	350 – 500	35
Copper	34	27.0	35 – 55	140 – 300	30 – 40
Iron	13	10.7	2200	7000 – 14000	2000
Lead	20	16.4	8	20 – 150	1 – 4
Steel	1	0.8		7085	
Stainless steel	5	4.1		80 – 180	15
Zinc	14	11.5		80 – 200	20 – 40

a The years of the determinations in Tables 1 – 3 vary, but most are for the period 2000 – 2006. The units of per capita stock are kg of metal in most cases, but g of metal for cadmium, gold, mercury, palladium, platinum, rhodium, and silver. The total number of estimates is 124.

b The more-developed countries (MDC) used in this calculation are Australia, Canada, the European Union EU15, Norway, Switzerland, Japan, New Zealand, and the United States (altogether about 860 million people in 2005).

c The less-developed countries (LDC) used in this calculation consist of all countries except those in the "more-developed" category (altogether about 5620 million people in 2005).

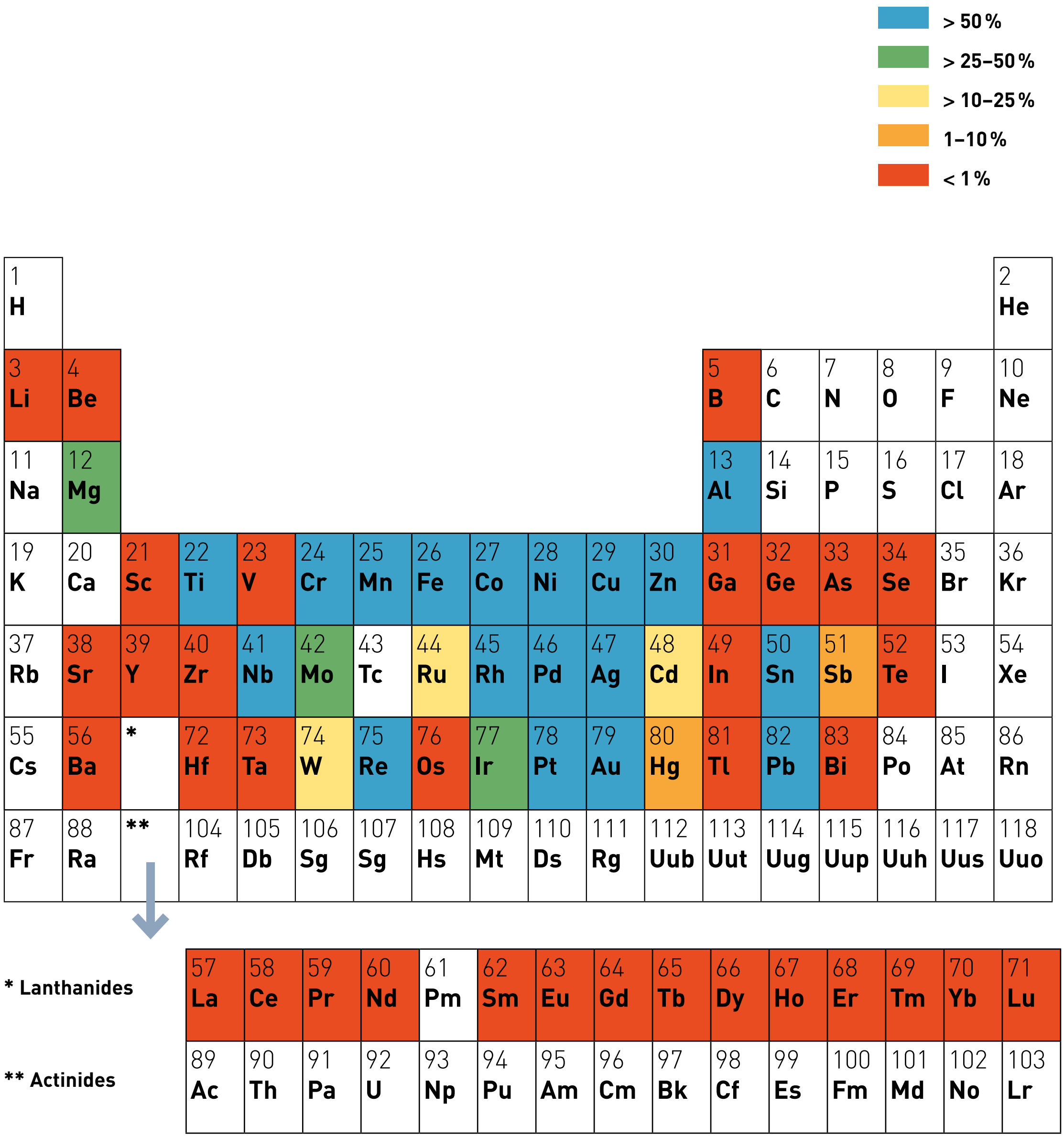
The available limited data suggest that per capita in-use stocks in more-developed countries typically exceed those in less-developed countries by factors of five to ten. Sparse but potentially useful in-use stock information exists for nineteen other metals. Very little information is available on stocks in government repositories, and on stocks in "hibernation" (no longer in use, but not yet discarded, as in obsolete bridges or mobile phones, for example). The same holds true for stocks in tailings repositories, in industrial stockpiles, and in landfills. Information on typical in-use lifetimes for almost the entire periodic table of the elements is also missing. Outflows from in-use stocks, potentially useful for determining future reuse, can currently be reliably estimated only for aluminium, copper, iron, lead, and zinc. Enhancing the knowledge on available stocks thus remains a crucial step to enable the development of reliable scenarios with regards to the future availability of metals.

Recycling of metals is highly complex, yet a crucial part of the solution

The estimated current global recycling rates leave ample room for improvement. Most End of Life-Recycling Rates (EoL-RR) are very low: for only 18 metals are they above 50 %. More importantly, for half of the metals assessed an EoL-RR of below one per cent has been estimated (Figure 7).

Figure 7:

End of Life Recycling Rates for Sixty Metals (UNEP 2011d).

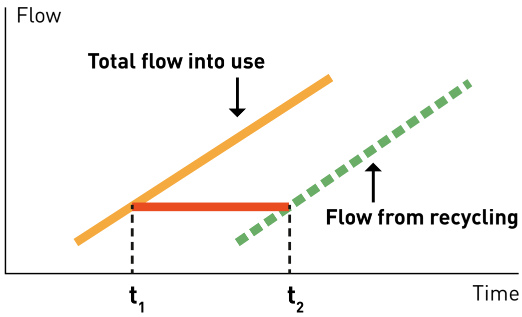


EoL-RR for sixty metals: The periodic table of global average End-of-Life (post-consumer) functional recycling (EoL-RR) for sixty metals. Functional recycling is recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use. 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.

This situation occurs because of increases in metal use over time as well as long metal in-use lifetimes. In addition, due to the unavoidable losses of material, the flow from recycling is not only delayed in time, but is also less than that entering use (Figure 8).

Figure 8:

The time delay in the recycling of metals in products (Revised version of Figure 7 from UNEP 2011d).



The low recycling rates are caused in part by product designs that make disassembly and material separation difficult or impossible for many products. From a technological and economical point of view, the effect of the combination of metals with each other and within products, and the necessity to then separate them into usable metals or alloys of economic value, is the challenge that needs to be overcome (Figure 9). In this regard a Product-Centric approach (i. e., a focus on a particular product, which may contain many different materials) can provide more detailed answers and allow a better simulation of reality in order to understand systems' complexity. Such an approach considers a product as a "designed mineral" and is hence far better at taking into account the complex interactions in a recycling system than is a Material-Centric approach. It also assesses what comes out of the system, in order to minimize the losses from each step.

Figure 9:

The cause and effect of various activities that maximize the resource efficiency of a Product Centric approach to recycling (UNEP 2013a).

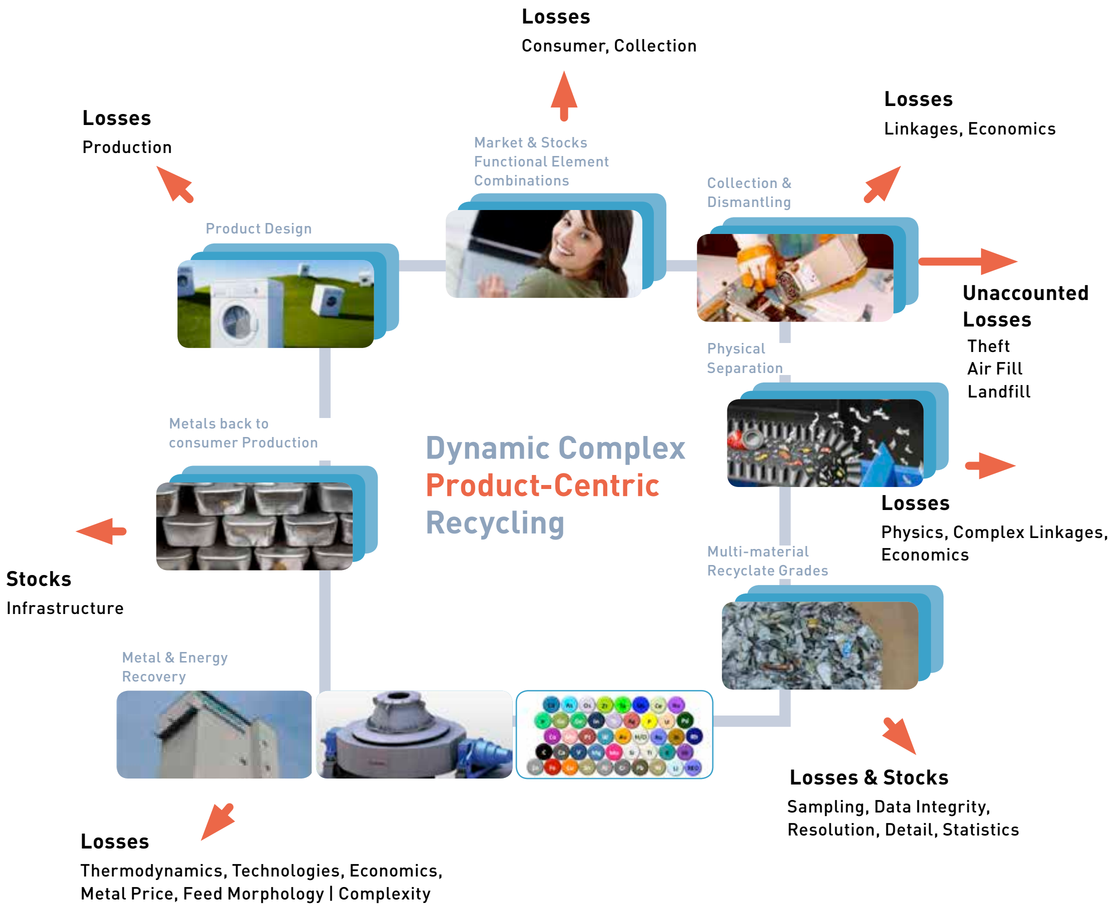
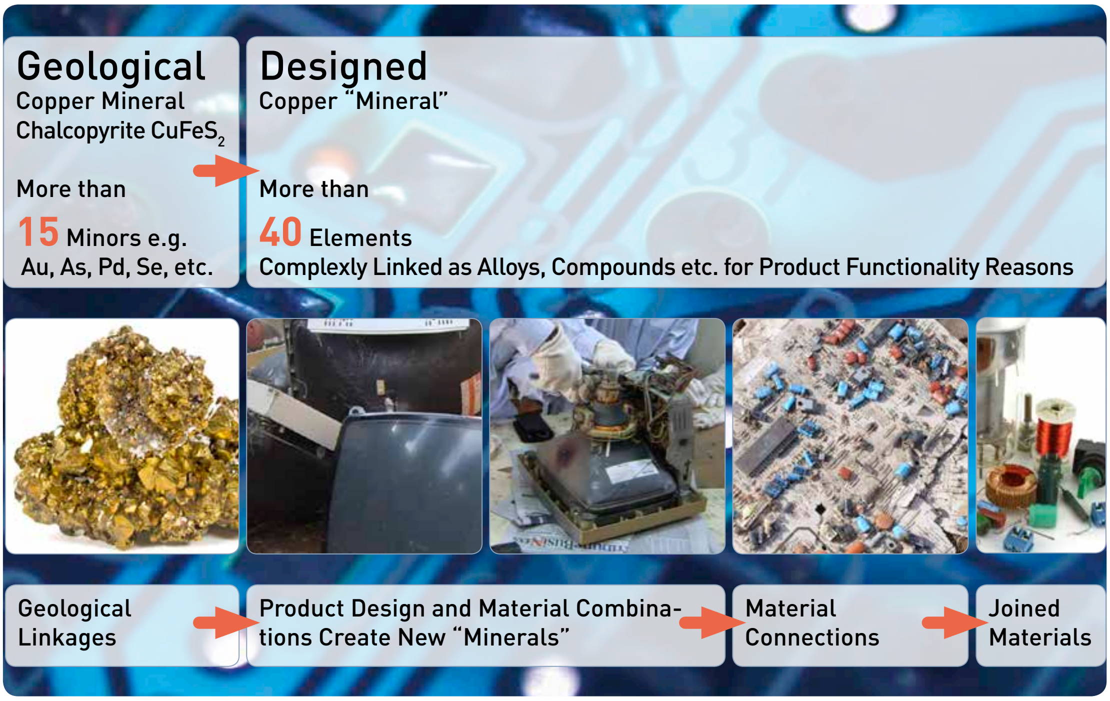


Figure 10:

Geological and technological "minerals" (UNEP 2013a).



If all products were made from a single substance, recycling would be relatively simple and its interactions linear, up and down the recycling chain. This case, however, holds true only for a limited number of products. Instead, most products contain a number of metals and their alloys and compounds. Several recycling chains in these cases are necessary to extract metals from End-of-Life (EoL) products, and those chains interact because of the functional connections of these materials.

This level of complexity is reflected in Figure 10, which shows that, for example, a copper mineral might contain at least 15 minor constituents such as gold or arsenic. A complex product, however, might contain more than 40. This means that the recycling of the product will likely require the use of a number of different technologies, and even then there is a high probability that some metals will be lost. This situation emphasizes the degree to which a product designer controls the recyclability of a product, but also the availability of a suitable sophisticated networked metallurgical infrastructure.

In order to address these challenges, a variety of tools are available that could be used to enhance the understanding of the most resource efficient recycling processes. One such tool is the metal wheel, which is described in detail in the latest IRP report on Metal Recycling (UNEP 2013a) or rigorous process simulation to capture the complete flow of materials through modern recycling processes. It shows that recycling processes are always based on the technology of many 'carrier metals', which then determine which metals, compounds, and alloys can be retrieved by applying that process. Depending on factors such as temperature, slag formation, thermodynamics, and hydro- and pyrometallurgy, certain elements in a mixture within a product can be captured, while others are irreversibly lost. Hence it becomes obvious that losses are systemic in nature, that is, the total available infrastructure and know-how determines the recovery. A well designed metallurgical infrastructure can optimize the recovery of many elements by recognizing that each carrier metal has its own unique physics and technology challenges. The choice of process is hence an economics- and physics-based technological optimization challenge for the recycling operation.

Another challenging issue is the high spatial mobility of products, which are often used and eventually discarded in societies not technologically equipped to recycle their constituent metals. This challenge is perhaps most important for consumer products, as closed cycles are typical for many industrial goods such as industrial machinery, tools, and process catalysts. Although the required recycling technology for industrial discards does not differ much from that for consumer goods, the recycling efficiencies are usually much higher due to the high awareness of the involved stakeholders, economic recycling incentives, transparent and professional handling throughout the product lifecycle, and the often limited changes of ownership and location of use.

Especially with consumer goods, a generally low awareness about the loss of resources and the absence of economic recycling incentives due to the low intrinsic value per unit are significant obstacles. In addition, the lack of an appropriate collection and recycling infrastructure that applies Best Available Techniques for End-of-Life management of complex products in many countries results in efficiency losses.

Multiple factors determine success in metal recycling

Taking all these challenges and complexities into account, a variety of interrelated factors determine the success of recycling and the potential to maximize resource efficiency:

1. The net intrinsic value of the discarded materials.
2. The recycling processes and the major physical and chemical influences on the metals and other materials in the metallurgical processing infrastructure.
3. The collection and pre-sorting of waste.
4. The availability of a diverse and robust metallurgical industry.
5. The physical properties and design of the End-of-Life products in the waste streams.
6. The societal acceptance and understanding that support recycling systems.
7. The knowledge and education of relevant stakeholders about the metallurgical opportunities and limitations of metal recycling.

As metal recycling is driven to a large extent by economics, it is key to ensure that economically viable, adaptive, and robust recycling and metallurgical infrastructure is available along with the needed metallurgical process knowledge. Economic incentives should be provided by policy and legislation to promote the use of Best-Available-Techniques as well as innovating and maintaining a robust metallurgical infrastructure. This will require the creation of a global level playing field through the internalization of external costs (e. g., fighting illegal waste shipment). For some scarce metals, effective international arrangements will be required to facilitate transparent cross-border transportation to large central plants, which operate according to BAT standards.

Another key factor in fostering End-of-Life recycling rates is to achieve higher collection rates. Suitable collection infrastructure is absolutely necessary in order to secure sufficient volumes of EoL products to facilitate economic recycling. Fostering economic incentives for the delivery of waste to BAT operators (e. g., for discarded mobile phones) could be regarded as a key policy focus.

A Product-Centric view needs to be applied throughout the value chain to enable tackling complex design for resource efficiency issues. This approach requires product designers to take a life cycle perspective and to use comprehensive engineering process design models and system simulation tools that map the complete system. Product designers should also assess the substitutability of metals in products, selecting a material based on an understanding of the different environmental life cycle impacts associated with the use of one material or another. Policy should assist the adoption of life cycle management by manufacturers to promote design for resource efficiency.

In addition, systemic material efficiency targets are a must for the future. Existing mass-based End-of-Life recycling policies are often counterproductive concerning critical metals embedded in complex products. Economics-based and environmentally benign key performance indicators generated by rigorous simulation design tools should be used to define BAT processes that guarantee better overall resource efficiency.

Finally, enhancing education, information, and R & D is a key global challenge that needs to be overcome. Multidisciplinary systemic educational approaches based on a thorough understanding of engineering, physics, and chemistry as well as social sciences, economics, and law must be applied. Disseminating and providing an easy approach towards physics-based system simulation tools is another essential aspect of to be considered in both, education and R & D. In general, for the processing of key metals and for driving innovation, improved research and education is critically important. Teaching in recycling should include rigorous physics- and engineering-based tools.

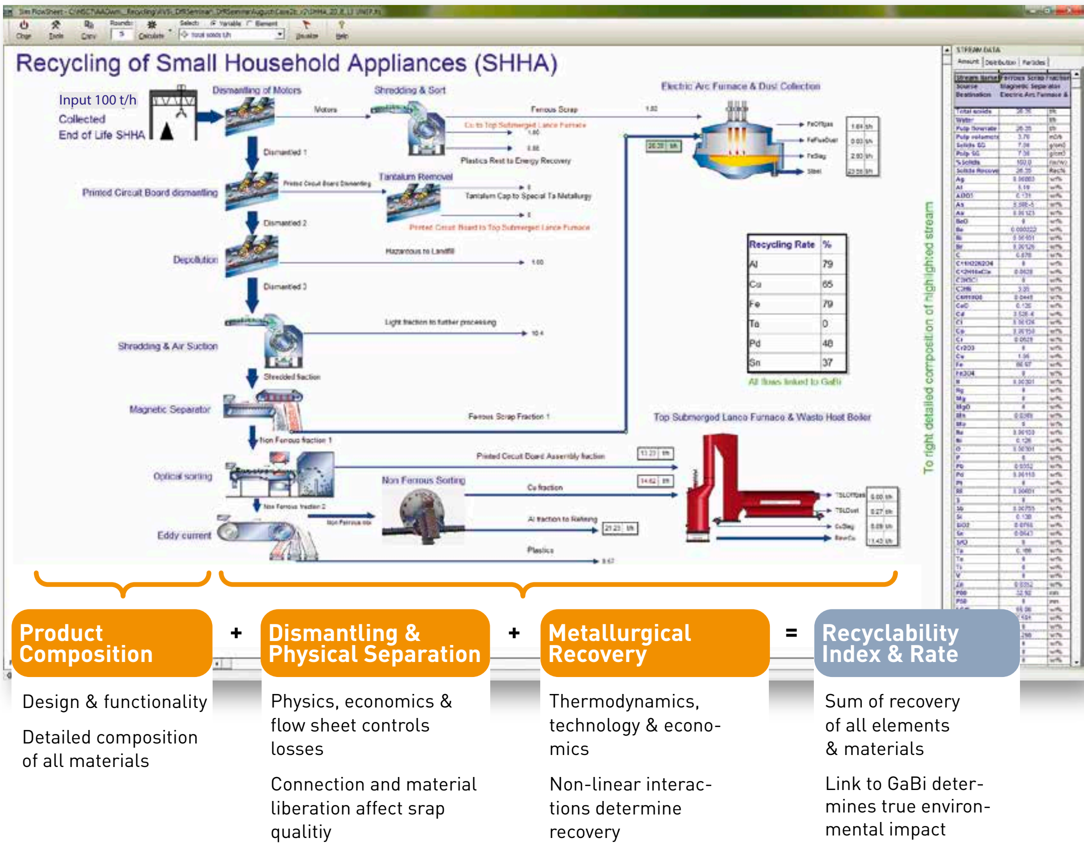


Figure 11: Physics based Design for Recycling and Simulation tools will permit the rigorous analysis of resource efficiency (UNEP 2013a).

Only the cooperation of all stakeholders involved will lead to success

As outlined throughout this introduction, sustainable metals management requires a wide range of actions. Demand for metals will continue to grow for the foreseeable future. As secondary production will, for the time being, not be a significant source in metals supply, it is crucial to apply BAT during mining and production, but equally during recycling processes, so as to ensure that environmental impacts are limited as much as possible. In order to avoid long-term environmental challenges, a comprehensive mine rehabilitation and closure management plan and process is crucial as well. In addition non-metal sources will need to be addressed as part of sustainable metals management, as their share is growing in significance, and a final sink must be developed for unavoidable metal waste streams in order to prevent emissions.

Manufacturers should strive to use metals that have been mined under sustainable conditions from geological or urban mines. They also need to manufacture products that have been designed for resource efficiency. This requires them to work closely together with their suppliers as well as their recyclers.

In addition to industry actors, retailers and consumers need to be educated and enabled to make informed decisions with regard to the sustainability aspects of products. Introducing systems that allow consumers to identify products that use metals sourced under sustainable conditions would help in this regard.

Secondary production can help to reduce the energy intensity of metal production, as it is significantly less energy intensive than primary production. It also helps to decrease the environmental impacts associated with primary production. And, while recycling is generally environmentally beneficial, recovering metals can lead to other problems if the recovered metals are not needed. Hence, a storage solution, a final sink, is required to prevent them from influencing the environment.

As outlined throughout this introduction, detailed knowledge relies heavily on the availability of accurate and reliable data. Due to the many data gaps, a large research and data collection effort is needed in order to locate missing information on geological and urban stocks, as well as on recycling rates. These data should be collected in a format that can easily be applied in simulation tools. First principles-based simulation can help to fill the gaps if measured data are not present.

In conclusion, the knowledge contained in the four reports summarized in this introduction provides a great overview of a variety of opportunities to take a step in the right direction. Tangible results will be possible by considering sustainable metals management from a life cycle perspective and building on the knowledge derived from both Material-Centric and Product-Centric approaches.

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