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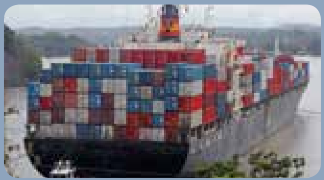
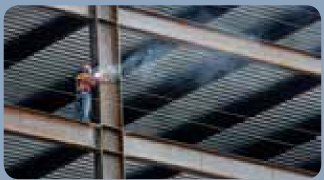
International Resource Panel





Assessing Mineral Resources in Society:

METAL RECYCLING

OPPORTUNITIES, LIMITS, INFRASTRUCTURE

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International
Resource
Panel

The following is an excerpt of the Report 2b of the Global Metal Flows Working Group

METAL RECYCLING

OPPORTUNITIES, LIMITS, INFRASTRUCTURE

The full Report is available on CD-ROM (available inside the back page of this summary booklet).

Preface

Preface

Increasing demand has revealed that metals are a priority for decoupling economic growth from resource use and environmental degradation. Metal recycling is increasingly promoted as an effective decoupling approach, but there is little systemic information available regarding recycling performance, and still less on the true recycling rates that are possible and on how to improve recycling systems. The former topic was the subject of an earlier report from the International Resource Panel. The present report addresses the second topic, discussing the benefits and necessity of approaching recycling from products by considering them as complex "designer minerals".

This Product-Centric approach therefore takes account of the complexities of modern products (often much more complex than geological minerals), and the ways in which non-traditional mixtures of elements are now common. The approach gains much useful perspective from experience in classical minerals and metallurgical processing.

Modern technology systems require not only efficient End-of-Life collection of products but also effective sorting after collection and an optimum suite of physical separation, modern metallurgical technologies, and integrated infrastructure for an economically viable recovery of metals from sorted recyclates. The report shows how failure at any stage of recycling limits performance, and shows as well that basic thermodynamic, technological, and economic limitations may prevent metallurgical metal recovery for some combinations of metals and materials.

The complementary Material-Centric recycling view point, as presented in the first report, has the capability to answer the question of how much is recycled, but does not pretend to answer why and what should be done to improve recycling of metals. This new report sheds light on how to improve the recovery of all metals, but especially those critical technology elements that were shown to have low recycling rates. It presents a physics-based approach to Design for Recycling and for Resource Efficiency, as well as for estimating opportunities and limits of recycling. These techniques can aid decision-makers in arriving at improved recycling approaches.

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Co-Chair of the
International Resource Panel

Prof. Thomas E. Graedel

Leader of the
Global Metal Flows Working Group

Prof. Markus Reuter

Lead Author

Preface

The challenge of sustainable development at the beginning of the 21st century has become a systemic one, with environmental, social and economic dimensions on an equal footing. UNEP and the UNEP-hosted International Resource Panel consider that our contributions also need to be systemic, for example through the promotion of resource efficiency, improved materials recycling and life-cycle thinking. This report from the Panel provides unrivalled science to inform policy makers about how the recycling of metals can be optimized on an economic and technological basis along product life cycles in the move towards sustainable metals management.

The report shows that sustainable metals management requires more than improving recycling rates of selected materials. We need to change the whole mindset on recycling of metals, moving away from a Material-Centric approach to a Product-Centric approach. Recycling has become increasingly difficult today and much value is lost due to the growing complexity of products and complex interactions within recycling systems.

This is why the focus needs to be on optimizing the recycling of entire products at their End-of-Life instead of focusing on the individual materials contained in them. Such a transition will depend on the mobilization of everyone in the value chain, from operators in the primary production of metals and metal-containing products to the recycling and collection industry to the consumers. As recycling is primarily an economic industrial activity, economic drivers must align with long-term economic goals, such as conserving critical metal resources for future applications, even if their recovery may be currently uneconomic.

Getting all stakeholders on board is crucial if we want to meet the increasing metal needs of the future in a sustainable way. A wide, systemic approach based on the solid understanding of the industrial and economic factors driving recycling will be needed. Such knowledge base will require coherent regulatory frameworks and powerful incentives for all stakeholders to participate as we move towards an inclusive, low carbon and resource efficient global Green Economy.

Achim Steiner

UN Under-Secretary General and
Executive Director UNEP

UNEP IRP's activities on metals

UNEP IRP's activities on metals

International Resource Panel (IRP)

The International Resource Panel was established in 2007 by UNEP to provide independent, coherent and authoritative scientific assessment on the sustainable use of natural resources and the environmental impacts of resource use over the full life cycle.

By providing up-to-date information and the best science available, the International Resource Panel contributes to a better understanding of how to decouple human development and economic growth from environmental degradation. The information contained in the International Resource Panel's reports is intended to be policy-relevant and support policy framing, policy and programme planning, and enable evaluation and monitoring of policy effectiveness.

Global Metal Flows Working Group

The International Resource Panel launched the Global Metal Flows Working Group in order to contribute to the promotion of the re-use and recycling of metals and the establishment of a sound, international recycling society. Therefore it is publishing a series of scientific and authoritative assessment reports on the global flows of metals. The expected results of these include identification of potentials for increased resource efficiency at national and international levels. The present booklet summarizes the findings of Report 2b: Metal Recycling – Opportunities, Limits, Infrastructure.

Relevance of metals for sustainable development

Economic development is deeply linked to the use of metals. The growing demand for metals puts permanent pressure on our resources. Metals are high-value resources and can in principle be easily re-used and recycled. Re-use and recycling activities of metals on a global scale can contribute to turning waste into resources, thus closing material loops. Expected benefits are reduced environmental impacts of primary metal production, securing of metal availability, as well as reduced metal prices, and promotion of jobs in the related economic sectors.


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Objectives of the Report

Motivation and objectives

Metal recycling has a long tradition, since people realized that it is more resource- and cost-efficient than throwing the resources away with the waste and starting all over again with mining and primary metals production. Until recently, recycling concentrated on few specific metals, mainly base metals like steel, copper or aluminum, as most products were relatively simple. Due to increasingly complex, multi-material products metal recycling in the 21st century is becoming a more challenging business.

Previous UNEP reports showed that far too much valuable metal today is lost because of imperfect collection of End-of-Life (EoL)products, improper recycling practices, or structural deficiencies within the recycling chain including the lack of proper recycling technologies for some metals embedded in certain EoLproducts.

Increase of metal-recycling rates

Report 2b of UNEP's International Resource Panel summarized in this booklet accentuates the current opportunities and limits of metal recycling and envisions the infrastructure needed in order to maximize the recovery of valuable resources from waste streams. For this purpose it promotes a Product-Centric approach which takes account of the multi-material composition of modern products and applies the available technological know-how of recovering metals from complex geological minerals to these new "designed minerals", i. e. the human-made products. The specific challenge of recycling designed minerals derives from the fact that they may contain more than 40 elements while geological minerals can be made up of, for example, one main metal and around 15 minor metals. These complex mixtures require a deep understanding of thermodynamics to separate modern products into economically viable metal, alloys, compounds etc. that flow back into products. It would be clear therefore that product designers also have a key role to play in efforts aimed at increasing metal-recycling rates.

Giving answers on how to increase metal-recycling rates – and thus resource efficiency – from both quantity and quality viewpoints mean a real challenge. Critical questions revolve around the amount and composition of recycling inputs, the required technological infrastructure in a particular region, and worldwide economic realities of recycling.

The present summary booklet highlights the following main points:

- Economics of recycling and legislation
- Recycling and metallurgical infrastructure and technology
- Collection as part of the recycling system
- Design for Resource Efficiency (DfRE)
- Material and resource efficiency targets
- Education, information, R&D and system & process simulation

Geological

Copper Mineral
Chalcopyrite $CuFeS_2$

More than

15 Minors e.g.
Au, As, Pd, Se, etc.

Designed

Copper "Mineral"

More than

40 Elements
Complexly Linked as Alloys, Compounds etc. for Product Functionality Reasons

Geological Linkages → Product Design and Material Combinations Create New "Minerals" → Material Connections → Joined Materials

Product-Centric recycling: application of economically viable technology and methods throughout the recovery chain to extract metals from the complex interlinkages within designed "minerals" i.e. products, gleaning from the deep know-how of recovering metals from complex geological minerals.

Recycling economics, technology and legislation

Policy framework for environmentally sound recycling

Economics, technology and legislation are three core issues of metal recycling. They need to be designed in a way that promotes high recycling rates for many metals simultaneously so as not to limit the recycling of a metal while another one is maximized. This point is crucial because the lack of legislation and control leaves room for actors in the recycling chain to just extract the most valuable components from the waste and carelessly discard the rest. Often rooted in poverty and in a lack of understanding of the characteristics of recyclates this behavior causes considerable harm to man and environment as several of the non-valuable components contain hazardous substances which require adequate treatment and disposal.

Policy Messages

- → **Create a global level playing field** for all stakeholders
- → **Promote** an adequate **legislative framework** for BAT-based recycling
- → A **metallurgical infrastructure** is key to metal recycling

The minor metals challenge

Functional product requirements lead to complex material mixtures in design, making difficult the recovery of minor metals. Weight-only EoLrecycling targets in legislation further aggravate existing difficulties. Minor metals like palladium and indium are embedded in small concentrations in million or even billion units of End-of-Life devices like discarded mobile phones, notebooks or cars. Often ending in informal recycling chains, these metals are often lost. Therefore in the case of minor metals effective international arrangements will be required to facilitate transparent cross-border transportation to large central plants which fulfill the requirements of Best Available Techniques (BAT). Bulk material like steel or aluminium fractions dismantled from EoLproducts could be addressed at local level. This could foster for instance the steel and aluminium recycling industry in some African countries.

Very often complex EoLproducts are treated in an inappropriate way which poses risks to health and environment and loses relevant quantities of material. The main challenges are the global establishment of an efficient collection and dismantling/separation infrastructure, knowledge transfer to and appropriate collaboration with the informal recycling sectors in developing countries and the creation of new business models for international co-operations.


Creation of a level playing field

There is a need to create a level playing field within the recycling sector through the internalization of external costs. In some cases the support of promising recovery solutions is necessary even if they are currently not economic so as to prevent recycling practices which can harm human health and the environment.

Common international standards have to be defined and to be agreed upon for pre-treatment and refining processes/plants. This helps stakeholders in the recycling system to operate on a 'best practice' basis, along social, environmental, technological and economic considerations. In this regard, the design of policies and regulations aimed at improving recycling results must be supported by thermodynamics and realistic economics.

Policy Messages

→ **Policy and regulations must be supported** by thermodynamics and realistic economics

Promotion of best available techniques (BAT)

In the first place a much wider use of Best Available Techniques (BAT) is necessary to increase metal recovery rates. These BAT should be defined as the processes which promise the highest material efficiency with lower overall environmental impacts along each step of the recycling chain.

The technology required for each step (collection, pre-processing, recycling) can vary considerably: while for the pre-processing stage careful manual dismantling offers very high recovery rates, for the recovery of critical metals from special metal fractions high-tech and large-scale metallurgical refining plants may be the best solution. These plants are often operated by companies with large experience in metallurgy of primary as well as secondary material.

Concerning the collection of waste by private or public operators economic incentives are needed which guarantee that all components arriving in the waste streams are collected and processed to the next stages in the BAT recycling chain. Measures include extended producer responsibility, deposit schemes, and the fair distribution of the profits obtained from the recycling of the valuable fractions among all actors in the recycling chain.


Adaptive infrastructure and technology

Recycling infrastructure and technology

The nature of today´s products is becoming increasingly complex: to provide the multitude of ever new functionalities many different materials are closely combined. The challenge of recycling such products can be illustrated by the separation of a thoroughly mixed cup of coffee into its primary components: pure extracted coffee, water, milk and sugar crystals.

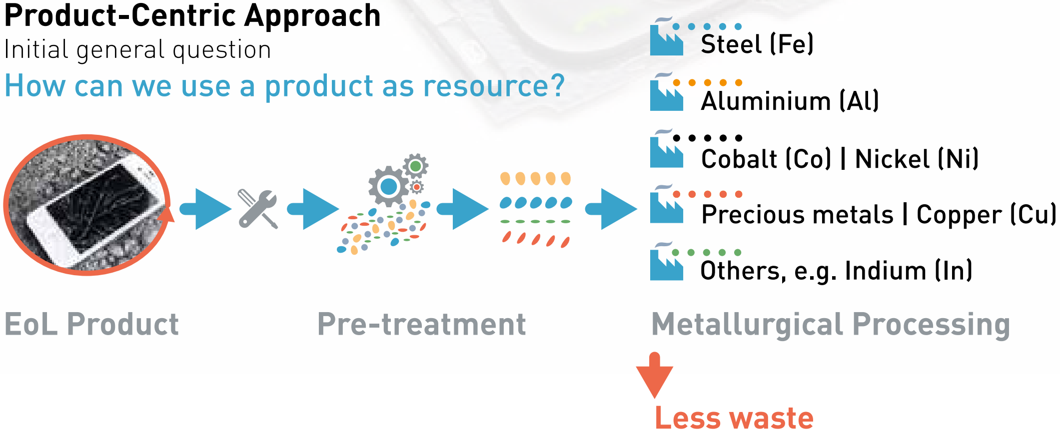
The general lines of the appropriate recycling system can be developed following the Product-Centric approach: based on the holistic view of all elements contained in an EoLproduct, it maintains and innovates a sophisticated physical and metallurgical processing infrastructure to produce high quality metals from complex multi-material recyclates. This requires all stakeholders in the recycling chain (product designers, collectors and processors) to understand the whole system and the respective infrastructure to be adaptive to the changing composition of the EoLproducts. Therefore, expert knowledge is needed to be able to deal with increasing complexity. Moreover, recycling technologies need to be flexible and optimally linked to simultaneously maximize the recovery of various and often vastly chemically different, metals and elements.

Taking the multi-material-composition of modern products into account, the Product-Centric approach answers the question of how to best recycle a product in order to achieve maximum resource efficiency.

Product-Centric Approach

Initial general question

How can we use a product as resource?



→ Create the right environment to **promote a Product-Centric approach-based recycling system**

→ Use physics depth to understand the metallurgical complexity to **create metals from recyclates**

In analogy to the geological minerals processed by primary metallurgy, EoL-products can be considered human-made designed minerals. Thus the recyclers of complex modern products increasingly need the expertise of metal miners.

Pre-treatment

Pre-treatment breaks down complex products into components that can be directed into the appropriate recycling streams. Therefore, the EoLproducts are separated and sorted mechanically. Already at this stage the degree of separation and sorting determines the possible future qualities of the recyclate. Suitable dismantling, sorting and robust, adaptive and high-tech extractive metallurgical (both hydro- and pyrometallurgy) infrastructure are hence needed to deal with two major developments in product design: miniaturization and the variability of products and their composition. Highly adaptive manual dismantling and sorting is also an example of the requirements needed to ensure the needed flexibility in recycling systems.

Recycling and refining

The metal fractions leaving pre-treatment are supplied to the secondary metals industry which recovers the different metal elements or alloys of economic value. In order to maximize the recovery care has to be taken that the metal mixes entering a specific recycling route have compatible characteristics. Only then metallurgical processing will succeed in economically separating them. As the characteristics of metals are determined by their physicochemical properties, knowledge of primary metallurgy is an equally important requirement for improved recycling processes.

The Metal Wheel

The primary metallurgy-derived Metal Wheel offers valuable lessons on how to design recycling systems in order to achieve maximum recovery of the different metals. Centered on the EoL-product at first the main metal components, the so-called carrier metals, are differentiated (see Figure "Metal Wheel"). Each corresponding slice in the Metal Wheel represents the complete infrastructure for carrier metal production and refining. During refining operations the carrier metals are recovered while accompanying metals (in the form of alloys, compounds and imperfectly sorted and liberated materials) undergo different fates: in the best case (green circles) they are compatible with the carrier metal and can be recovered alongside or they are recoverable from other output streams (e.g. dust, slag) in subsequent processing. In the other cases, depicted with yellow and red circles, the accompanying metals are mainly lost or only recovered for low-quality products like cement. As a critical example, the processing of copper and precious metals like platinum group metals, gold and silver in the iron processing route has to be avoided by proper sorting as far as possible because there these valuable elements are lost. On the other hand, the processing of precious metals with copper as a carrier allows their recovery with high rates.

Examples of carrier metal routes

Carrier Metal
Steel (Fe)

Fe

W Mn Nb Mo Si

~~Au~~ ~~Ag~~ ~~Pt~~ ~~Pd~~ ~~Rh~~ ~~Cu~~

Steel recycling route

Steel, which predominantly consists of iron along with some other alloying elements, is the metal with the largest global volumes and its recycling infrastructure has been established for centuries. Today up to 90 % of the steel reaching its End-of-Life is recycled. However, various steel incompatible metals through incomplete liberation, mixed recyclates, complex product designs etc., which enter the steel recycling route are not recoverable. While in some cases they still contribute to the functionality of the recycled steel as alloying elements (e. g. silicon, molybdenum, niobium, manganese and tungsten, if they dissolve and do not oxidize to slag or volatilize) other elements (e. g. copper or platinum-group metals (PGMs)) are lost and even detrimental to the quality of the recycled product.

In very specific PM and PGM recycling processes iron can serve as a solvent and then be sent to the copper route in which the precious metals are recovered and the small quantity of iron used is lost to slag.

Carrier Metal
Copper (Cu)

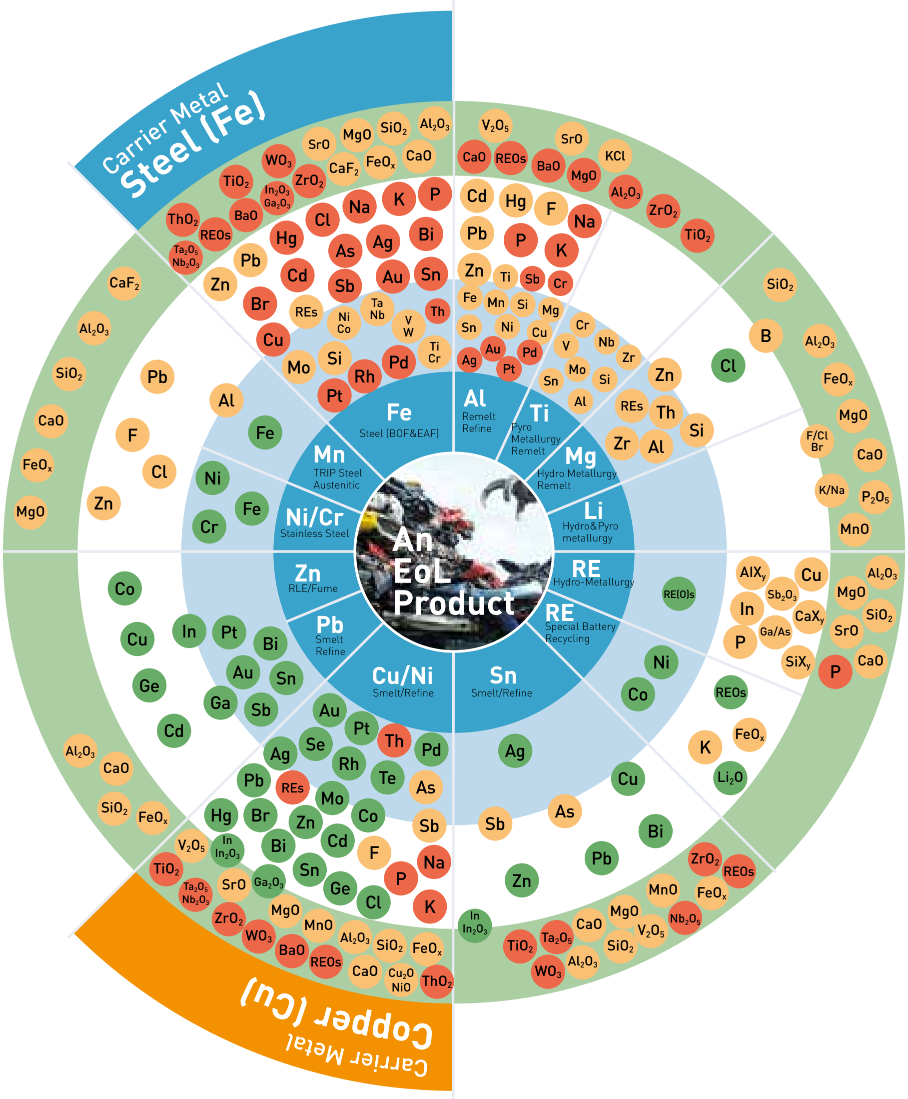
Cu

Au Ag Pt Pd Rh FeO_x

Copper recycling route

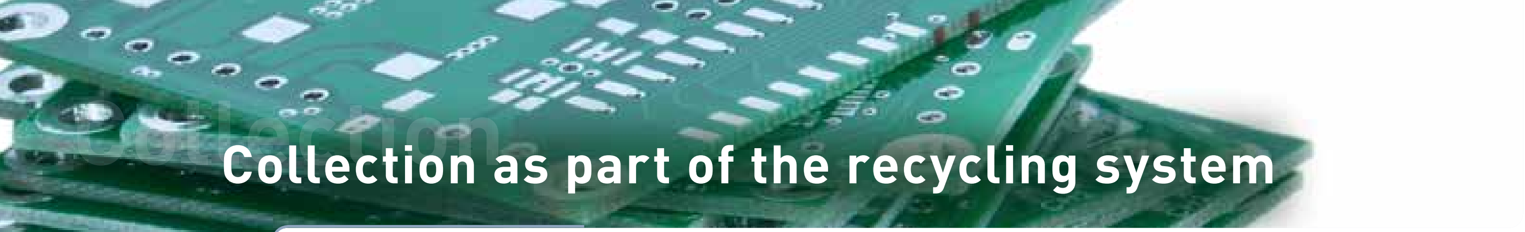
The physico-chemical properties of copper make it act as a collector for many precious metals (e. g. gold, silver, platinum, palladium, rhodium) during pyro-metallurgical processing (metal smelting). These metals, e. g. present in complex products and recyclates such as printed wiring boards and electronic components, which have high value but in commercial products generally occur in trace quantities only, are concentrated in the copper phase during smelting and can subsequently be recovered through further hudro- and pyrometallurgical technology. Also nickel can be won back this way after dissolving in the copper and recovered through hydrometallurgical methods. Aluminium, rare earths or lithium accumulate as oxides in the slag and are generally not recovered due to the high related effort. Slags are generated in pyro-metallurgical processes in large volumes and today are mainly used as low-grade products e. g. in road construction. Copper metallurgy is a key for the recycling of various metal mixtures occurring in complex recyclates. Its infrastructure and deep know-how are therefore a prerequiste for a sustainable society, as it has the robustness to take care of the recyclates shown on page 9.

The "**Metal Wheel**", based on primary metallurgy but equally valid for metals recycling reflects the destination of different elements in base-metal minerals as a function of interlinked metallurgical process technology. Each slice represents the complete infrastructure for base or carrier metal refining.



- **Essential Carrier Metals**.
- **Metal phase: Dissolves mainly in Carrier Metal** if Metallic (Mainly to Pyrometallurgy).
- **Compounds mainly recovered** from Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy).
- **Compounds not recovered** from Dust, Slime, Speiss, Slag, but mainly to Benign Low Value Products.

- El **Mainly Recovered Element**.
- El **Mainly element** in Alloy or Compound in Oxidic Product, **not recovered separately**, but not detrimental and even possible functionality.
- El **Mainly Element Lost**, not always compatible with Carrier Metal or Product.



Collection as part of the recycling system

All steps are relevant

Recycling is a chain of activities: collection, pre-processing (separation & sorting), and final processing (recycling & refining). The overall recovery efficiency for each material results as the product of the efficiencies of each step. Thus, its optimization requires the combination of the respective best-performing technologies, both in terms of recovery efficiency and environmental soundness.

Collection is key

As collection stands at the beginning of the recycling chain it is a prerequisite in order to enable any subsequent activity. Moreover, especially in industrialized countries, it often constitutes a weak link in the overall recycling chain. Collection is hence a crucial issue in order to improve resource efficiency but the establishment of a suitable collection infrastructure still poses challenges, mainly from an economic point of view. Additionally, consumer acceptance plays an important role.

The main metal-containing resources for post-consumer waste are cars, electronic appliances, packaging and diverse small metal products, e. g. toys or bikes. The main collection options for these goods are collective municipal or commercial collection, individual producer and retailer collection, and collection by the informal sector. Charity initiatives, small-scale pilot projects, or event-based collection can also contribute to the collection of electrical and electronic equipment waste (WEEE), which in terms of metal recovery constitutes a high-value stream (depending of precious metal content).

System	Collection	Pre-processing	Final processing	Net yield
Formal (Europe, UNU 2008, Chancerel et al. 2009)	60 % formal take-back system	25 % mainly mechanical processes	95 % integrated smelter	15 %
Informal (India, Keller 2006)	80 % individual collectors	50 % manual sorting and dismantling	50 % backyard leaching	20 %

Material-Centric-Recycling-Chain All steps in the recycling chain are relevant for the overall recovery efficiency – illustration based on the example of gold recycling from printed wiring boards by a formal system in Europe and the informal sector in India.

Collection as part of the recycling system

The balance between these collection routes depends on the policies and economics of the different countries. Thus, in OECD-countries in general the formal sector prevails while developing countries have a strong informal sector. As an example, in Europe, the consumers pay for collection, whereas in developing countries usually the waste collectors pay consumers for their obsolete appliances and metal scrap. In the latter case often impressive collection rates are reached because poor people rely on the income generated from the valorization of the waste. This shows how strong economic stimulus for collection is a key factor.

Qualitative aspects of collection

A large variation in the properties of the collected waste will adversely affect product quality and recovery, thus increasing losses, during the subsequent processing steps. The streams may even become economically unviable for processing when incompatible materials and compounds are mixed. In general products to be recycled must be separated, liberated, sorted etc. into recyclates streams that can be treated economically in appropriate BAT metallurgical infrastructure. Thus source-segregated collection offers the quality that is best suited for the subsequent steps if the recyclate mixtures are compatible with Carrier Metal process metallurgy with a Product-Centric context. However, it is constrained by stream values and collecting costs and effort and can, in general, be economically and environmentally feasible. The optimal ranges for segregation are affected by policies and collection schemes as well as recycling technology, economics and metallurgical infrastructure.
In any case, the identification of the suitable waste stream for an EoLproduct requires data on its compositional structure. To date, information on product composition is still incomplete, but it is indispensable for optimizing recycling systems with suitable process simulation tools that map the complete recycling chain.

Quantitative aspects of collection

The economics of recycling depend on the available quantities reaching the pre-processing and recycling facilities. The supplies, which need to be assured by the appropriate collection systems, have to be sufficient in volume and stable in order to provide economic reliability.
In many developing countries the establishment of a formal sector is hampered by the fact that collectable waste volumes are insufficient for economic operation because they are recovered by the informal sector at higher prices.

Policy Messages

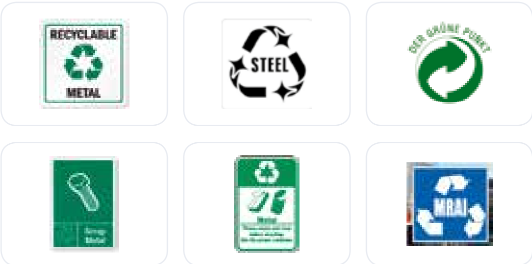
→ **Enhance** availability of information on **material composition of products**

→ **Process metallurgy** must be understood by all actors

Collection as part of the recycling system

This is possible due to the fact that informal recycling practices tend to avoid costs by just extracting the valuable components from the waste. However, the leftovers could cause considerable harm to human beings and environment if they are not treated properly. This is why formal recyclers are obliged to comply with partially costly environmental standards.
Some critical metals, e. g. present in WEEE, are recoverable at high rates in high-tech industrial plants. With a view to material efficiency it is hence desirable that corresponding fractions reach these plants which offer BAT for the recycling of low-concentrated critical metals. However, in order to offset high initial investment costs, these plants are often large-scale so that their supplies need to be sourced from a large pool of countries requiring a concentration to a few global facilities.

Collection systems need to be designed in a way which channels all components in the collected waste streams into the right pre-processing and consequently recycling routes, ensuring increased material recovery rates as well as ecological harmlessness.



Collection infrastructure

Collection infrastructure can be set up by the authorities, by product manufacturers and retailers (corresponding to their enhanced producer responsibility) or by companies, individuals or charities wishing to earn money from the value in the waste or to reduce environmental impact. One crucial part for setting up that infrastructure is the knowledge base, the motivation and the availability of physical infrastructure for dealing with separate streams of collected waste. Another part is the incentive structure: some collectors may act out of ethical or environmental considerations, but nearly all work because they earn money from collection, or face penalties for failing to collect.

Policy Messages

- → **Promote** the right **incentives to collect**
- → Benefit from existing distribution structures for consumer goods to **design collection schemes**

Consumer behaviour

The collection of consumer waste (as opposed to e. g. industrial waste) forms an especially difficult logistical challenge. While there are the collectors on the side where the waste streams enter the recycling chain, there are billions of consumers where products leave their use phase and become waste. One aspect to facilitate increased collection is to improve the performance of this interface: educating and changing the behaviour of individuals can lead to better recycling.

The keys are convenience and awareness. The opportunities and infrastructure of the system need to be transparent and accessible. As an example, to enable the consumer to contribute to source segregation, clear guidance is needed concerning the composition of End-of-Life products and the corresponding adequate fate in the (separated) waste streams. Marketing and social media can be used to influence personal attitudes and motivate individuals towards recycling.

In different countries different ways of communicating, providing incentives and motivating consumers are established. Thus, even if recycling is a global issue it needs local execution.

Policy Messages

- → **Increase consumer awareness** towards recycling
- → **Guarantee convenient collection,** e. g. by easy access to collection points

Design for Resource Efficiency (DfRE)

Recycling starts with product design

Design for Resource Efficiency (DfRE) describes a holistic technology- and economy-driven concept which aims at utilizing the combined capabilities of the production and the complete recycling chain in order to maximize resource efficiency. It requires a Product-Centric approach which takes into account the complexity of products to allow for the optimized recovery of all elements contained within. As it is impossible to optimize one factor without considering the others a lifecycle perspective is required: product designers, as well as collectors and processors of End-of-Life products must be aware of the whole system. Modern product design should consider the complexity of recycling multi-material products, and avoid designs that hinder recycling. This is not always possible because the primary function of the product will always prevail but, if necessary, policy should reinforce this point. Moreover, product designers should scrutinize their designs within realistic boundaries of product functional demands.

Design for Dismantling

As one sub-aspect of DfRE Design for Dismantling aims at designing products so that compatible groupings of metals are easy to dismantle so that they can be directed into the correct metallurgical processes. This means, for example, constructing bondings or joints between components in a way that they can be opened during mechanical pre-processing. Apart from technical design, economic realities play a crucial role here: if careful dismantling becomes too costly, e. g. because labour costs exceed the value that can be recovered for the extracted components, the lack of economic incentives becomes critical/counter-productive to increased recycling.

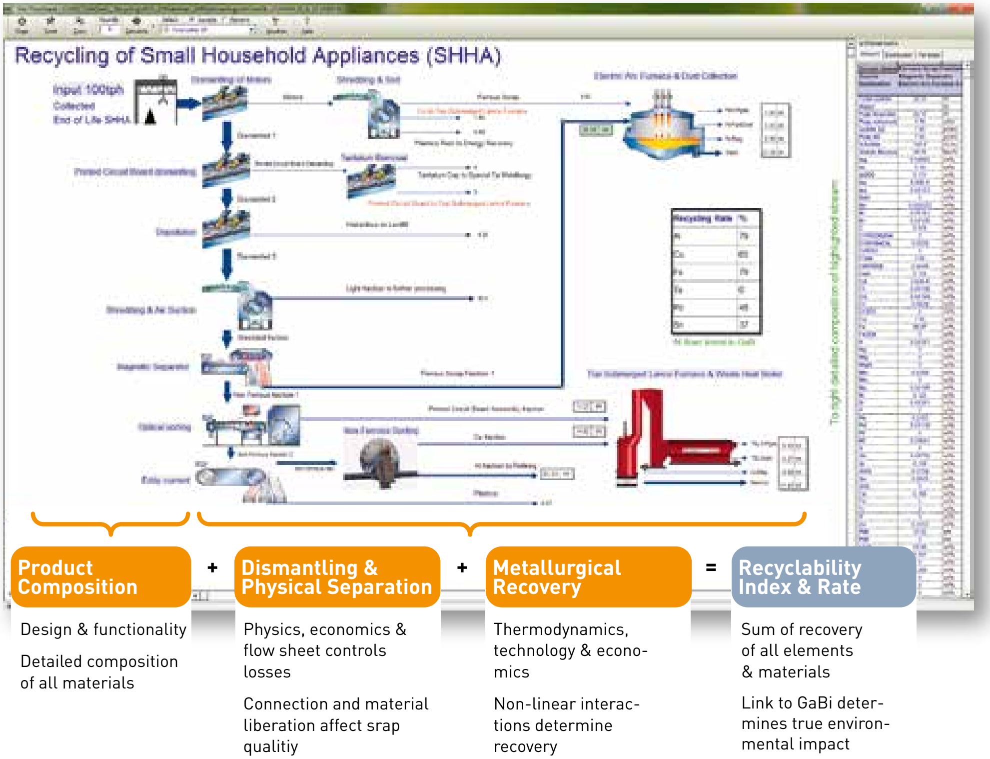
Design for Recycling

Design for Recycling takes into account the physical and chemical realities of metallurgy as well as the technological and economic possibilities of recycling and refining operations. Based thereon it tries to avoiding incompatible material mixes so that the elements contained in the different metal streams can be recovered as pure metals or in alloys by BAT practices to a maximum extent. Of course, this approach is equally limited by the functionality demands of a product which might dictate that certain metals and materials must be combined. Joints/constructs affect dismantle-ability and therefore material liberation. Linked materials in turn affect their respective recovery during process metallurgy.

Tools to aid decision making

Metallurgical realities are concisely reflected by the Metal Wheel, which indicates the possibilities of combined metal recycling, refining and recovery for various metallic elements. Physics-based recycling simulation tools capture the ef-

Example of existing **software for flowsheet design**, based on compositional data for a product, which lead to simulated resource efficiency data that, in turn, lead to a recyclability index based on environmental analysis – a metallurgical processing infrastructure is prerequisite.



fects of design/material choices and linkages on recycling, based on how products break up and separate in recycling processes. Pinpointing critical issues and providing the information in an understandable format, these tools should hence be used to assist product design. For a given product, these tools identify recycling solutions and achievable recycling rates based on data on its compositional structure. In order to identify BAT operations they need to be coupled interactively with ecological (LCA) and economic assessments tools which evaluate the proposed processes from a lifecycle perspective. Thus DfRE should drive the creation of a BAT-based recycling system.

Policy Messages

- → **Support recycling friendly product design** using suitable Computer Aided Design (CAD) and linked process simulation tools
- → Assist the **adoption of lifecycle management** by manufacturers
- → **Set realistic recycling targets** based on the interactive physics-based simulation of production and recycling systems

Bulk materials

(Steel, stainless steel, plastics, glass, copper)

Electronic components

(Special and precious metals)

Steel, stainless steel, copper, glass, and plastics make up over 95 % of the mass of EoL devices like washing machines. Electronic components amount to less than 5 %. Thus under existing, mass-based recycling targets their recycling is often neglected. However, they contain specialty and precious metals, the recovery of which should be increased. The definition of the recycling targets should hence be refined using a Product-Centric approach.

Systemic material efficiency targets

Material efficiency targets

Policy tries to improve the recovery of valuable resources from End-of-Life products by setting physics and economics based material efficiency targets. These targets oblige the responsible industries to ensure that certain quantities of materials (metals and others) are recovered. However, their effectiveness is under debate.

Mass-based rates and critical metals

Existing mass-based End-of-Life recycling targets are often counterproductive concerning critical metals embedded in complex products. Due to their generally low quantities in many End-of-Life flows their contribution to mass based End-of-Life recycling rates for entire End-of-Life products is marginal while the recycling of mass materials like steel, aluminium or copper quickly increases the rates. Stakeholders in the recycling chain get the clear message to focus on the recovery of bulk materials to fulfil the minimum End-of-Life recycling rates and the recycling of critical metals like indium, gallium, rare earths etc. is often neglected.

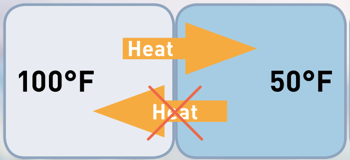
Key performance indicators

To overcome this bottleneck the establishment of economics-based and environmentally benign key performance indicators (KPI) is suggested. These should adopt a Product-Centric perspective and provide additional incentives for the recovery of critical metals by taking into account their criticality and relevance despite their low volumes. The KPI could be calculated based on interactive simulation tools which model the proposed recycling processes from technical, economic and environmental points of view. Subsequently they should be used to define BAT processes.

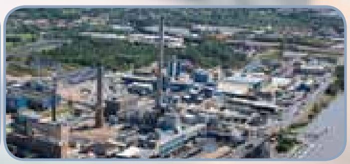
Policy Messages

- → **Define key performance indicators** on the basis of physics, technology and economics
- → **Adapt the legislative framework** accordingly

Metal & Energy Recovery



Thermodynamics



Technologies

Metallurgy

Economics

Education, Information and R&D

The basis for recycling

Better education, information and R & D are global key challenges to enhance the overall recycling rates of metals. Multidisciplinary systemic education approaches, improved research as well as activities to quantify the metal potential embedded in the techno-sphere are essential building blocks to achieve this objective.

Multidisciplinary education

Following the Product-Centric approach multidisciplinary systemic education must be applied that is based on a thorough understanding of thermodynamics, process engineering, physics, chemistry as well as social sciences, economics and law. Existing tools and knowledge from primary metallurgy have to be used consistently to close the recycling loops. This ambitious approach will be a key challenge to gain success with optimized metal recycling in the future which could address the increasing complexity of EoLproducts composition. The effect of metal substitution and future material combinations must be continually evaluated with rigorous simulation tools.

Improved research

For the processing of key metals and for driving innovation, improved research is critically important. It must be nurtured to preserve know-how, especially of the processing of the key metals, and for driving innovation that maximizes resource efficiency. Dissemination of the physics-based system simulation approach to recycling is a need to identify the true crucial needs for R&D, product design and system innovation.

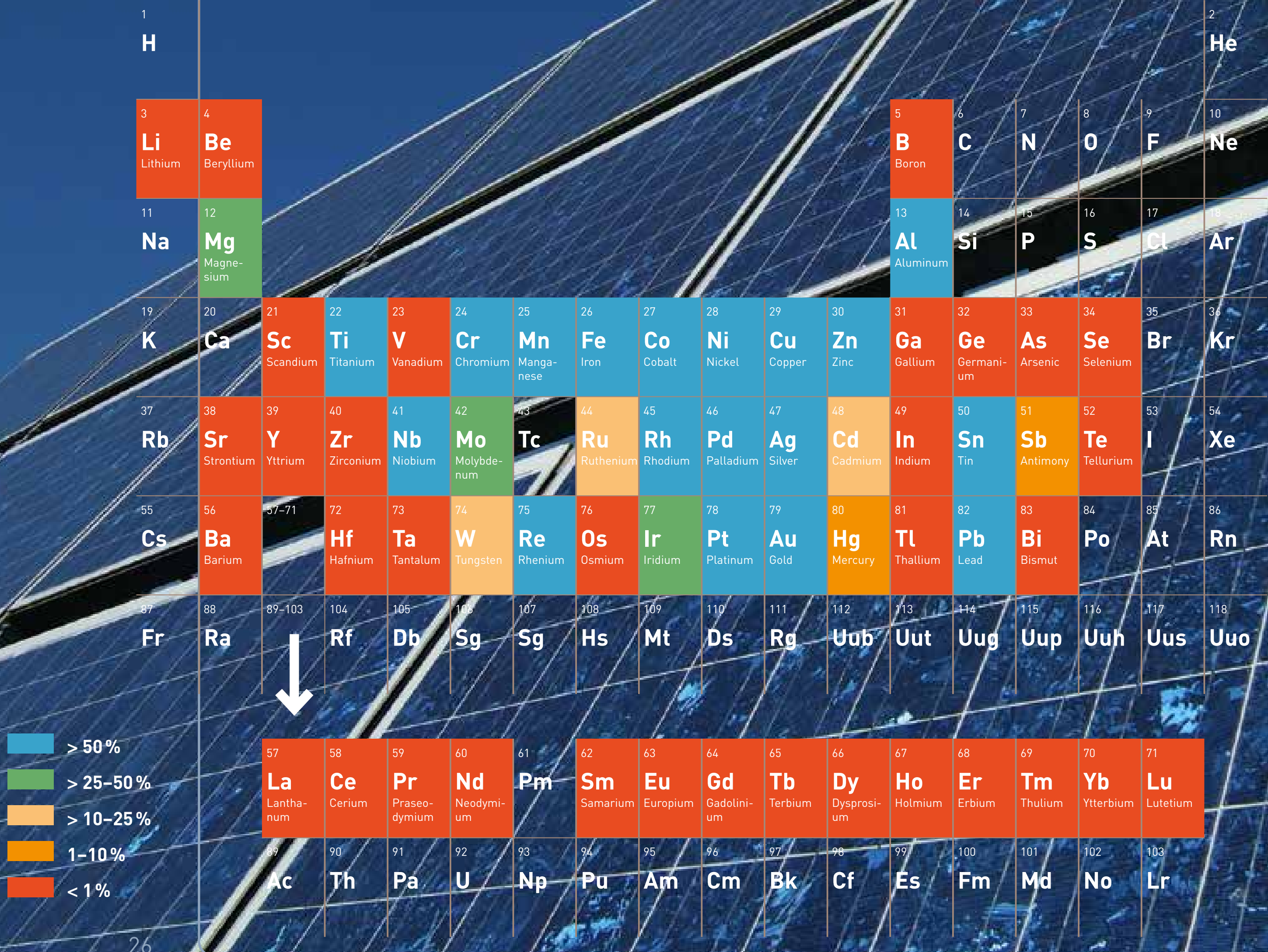
Quantification of the urban orebody

The stock of products in society - the designed minerals - constitutes an "urban orebody". The quantification of the metals contained in this stock, their locations and fate in waste flows is crucial to allow for high recovery rates and a prerequisite to support decisions on R&D activities and investments in metal recycling infrastructure and technologies. In this context policies should be developed based on geological approaches known from primary metallurgy. Databases must include similar structures as used for processing of minerals enabling rigorous process simulation.

Policy Messages

- → Apply multi-disciplinary systemic **engineering education**
- → **Quantify the metals** and their "mineralogy" in market products
- → **Deep process metallurgy and technology knowledge** is critical for recycling and a sustainable society

The figure presents information for the metals in whatever form (pure, alloy, etc.) recycling occurs. To reflect the reliability of the data or the estimates, data are divided into five bins: > 50 %, > 25 – 50 %, > 10 – 25 %, 1 – 10 % and < 1 %. It is noteworthy that for only eighteen of the sixty metals the experts estimate the End-of-Life recycling rate 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 today. To increase these Material-Centric determined recycling rates, an in-depth understanding of physical separation, process metallurgy, metallurgical infrastructure, product design and composition/mineralogy and economics is required. The Product-Centric approach discussed in this report shows how to increase recycling rates using process simulation and other deep technological know-how.



Outlook

Resource efficiency: a joint mission of industry, science and policy

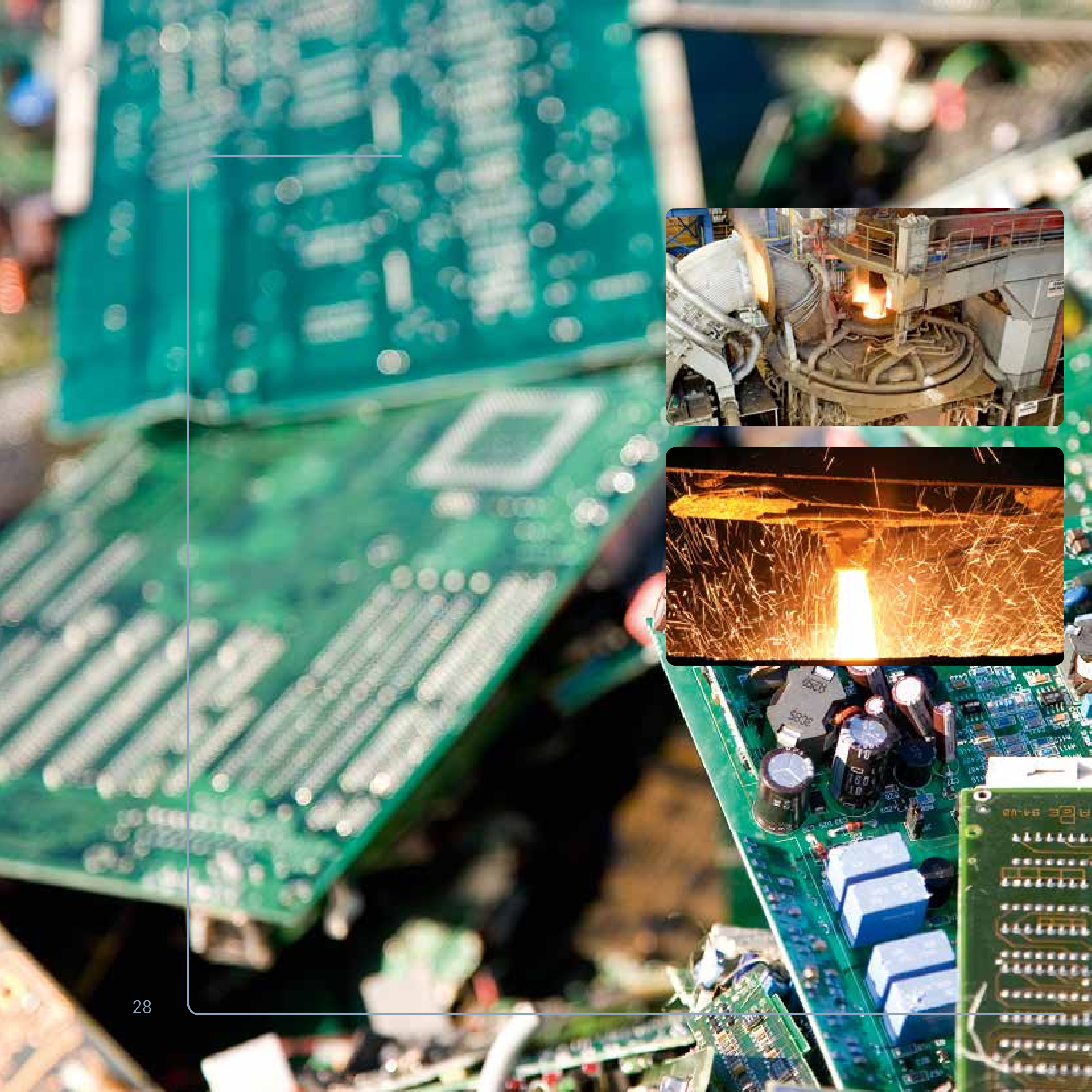
Increasingly complex products in the 21st century need to be addressed by a Product-Centric approach to foster recycling results for many metals. The previous UNEP Report 2a: Recycling Rates of Metals has confirmed that mainly for many specialty metals the current Material-Centric EoLrecycling rates are very poor or almost zero. The Report 2b: Metal Recycling – Opportunities, Limits, Infrastructure also shows that recycling rates of different metals are product-dependent and that a Product-Centric approach is required to increase recycling rates above their, in some cases, low values. Deep metallurgical knowledge and associated realistic product design will – among other interventions – help to increase these values to acceptable levels. Even in the case of base metals and precious metals there is still considerable room for improvement.

The current pre-treatment of complex products which can contain many different base, specialty and precious metals (more than 40 different elements) can fail Best Available Techniques (BAT) requirements if there is a mismatch between recyclate and carrier metal process metallurgy. The recycling challenges posed by increasingly complex products need to be jointly addressed by combined efforts from policy and legislation, research and education, and the metallurgical industry.

The role of the metallurgical industry

The role of the metallurgical industry to enhance the overall recycling rates of many metals in the future is two-fold. First, based on the comprehensive experience of the sector dealing with complex natural orebodies since many decades, this essential knowledge should be used and transferred to other stakeholders within the recycling chain so as to build their capacity to take the right decisions regarding collecting and sorting procedures of increasingly complex EoL-products (or "designed minerals"). Taking the lessons from the metal wheel into account, the knowledge about the relevance of carrier metals and other important metallurgical issues should be disseminated to promote optimized recycling infrastructure for metals.

Second, the metallurgical industry could contribute to better EoLrecycling rates of many metals – especially critical metals – in the future by fostering R & D and subsequently investment decisions regarding new metallurgical processes which could deal with new material compositions. Interesting examples are for instance the recycling of rare earths from discarded neodymium-iron-boron magnets or the recycling of cobalt, lithium and other metals from lithium-ion batteries.



Outlook

Outlook

The role of research and education

Research and education are key for addressing the increasing variability and complexity of products and hence (metals) recycling in the future. Quantification of the "urban orebody" and its "mineralogy" in products needs to be simulated on the basis of rigorous simulation as used in the metallurgical processing industry. This should be consequently linked to the design of recycling tools that provide physics based recyclability indexes. Rigorous understanding of thermodynamics, kinetics, metallurgical process engineering as well as physical separation physics and process economics is a pre-requisite to increase recycling rates.

The role of policy and legislation

Policy and legislation have to create a global level playing field for all stakeholders and have to promote the use of Best Available Techniques (BAT) on a Product-Centric basis (equivalent to geological minerals based processing), multi-material/metal system economics, and efficient collection systems. In addition, Design for Resource Efficiency capturing all inherent material and metal connections and non-linearities (e. g. by adoption of life cycle management) and definition of suitable key performance indicators for recycling capturing the multi-material interconnections that maximize resource efficiency, is essential.

Policy actions across the global system are necessary to overcome the bottlenecks that currently hold back optimized recycling. That means that the existing legislative systems for waste management and recycling have to be monitored regarding room for improvement to enhance the End-of-Life recycling for many metals, namely critical metals like rare earths which show significant environmental impacts in the primary production routes by the generation of radioactive waste streams and by hazardous emissions into air, soil and groundwater.

This includes enhancing the availability of information on material composition of products. Recycling-friendly product design has to be supported as well as the setting of realistic recycling targets based on the interactive physics-based simulation of production and recycling systems. A better quantification of the metals contained in market products is a necessary policy action to promote recycling.

Policy should apply multidisciplinary systemic education and should promote a robust systemically linked metallurgical infrastructure without which no metal recycling is possible.

Policy Messages

→ **Maintaining deep process metallurgy and technology knowledge** at engineering faculties is critical for recycling and a sustainable society

Categories of Metals

Categories of Metals

Ferrous Metals

V – Vanadium
Cr – Chromium
Mn – Manganese
Fe – Iron
Ni – Nickel
Nb – Niobium
Mo – Molybdenum

Non-Ferrous Metals

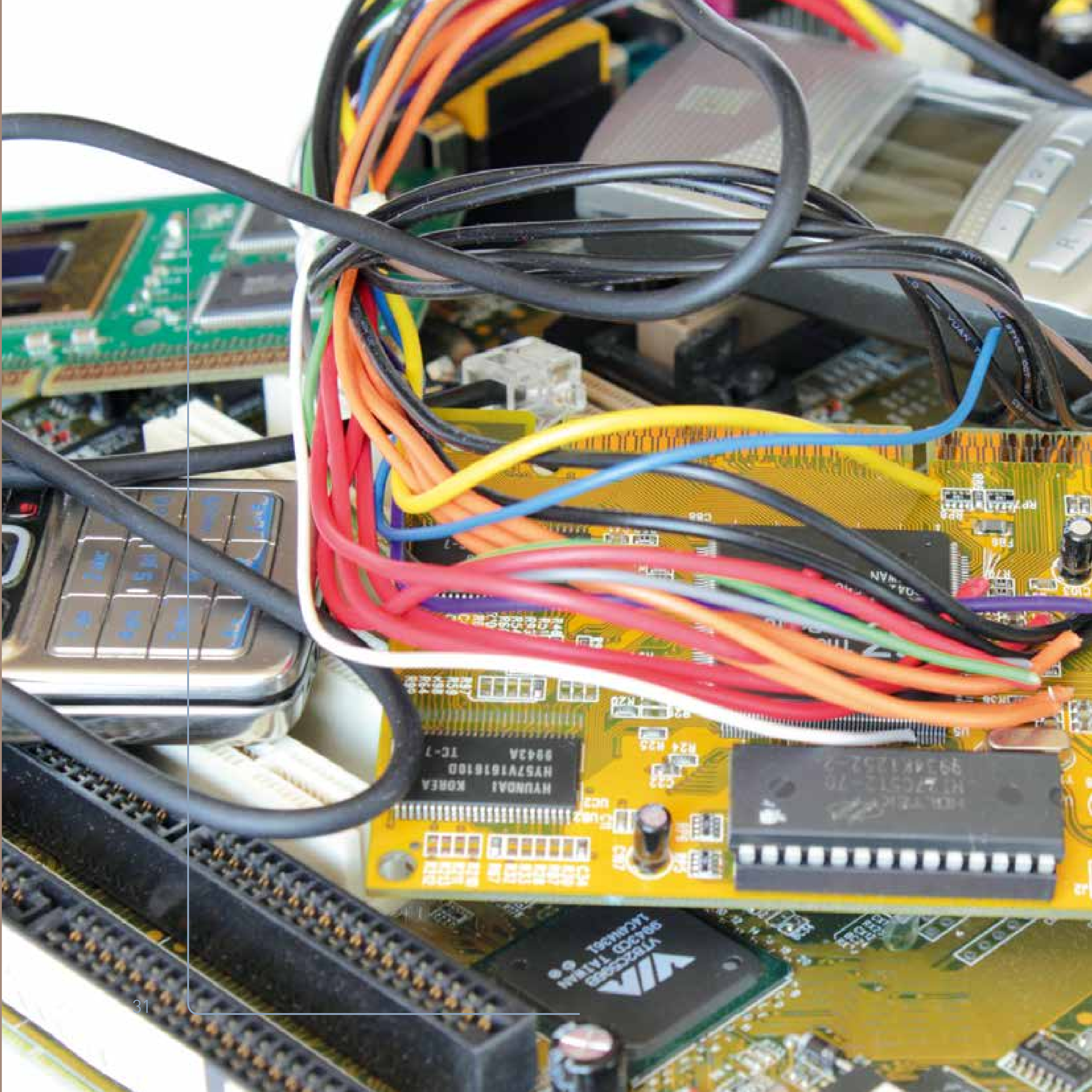
Mg – Magnesium
Al – Aluminum
Ti – Titanium
Co – Cobalt
Cu – Copper
Zn – Zinc
Sn – Tin
Pb – Lead

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



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THIS BOOKLET SUMMARIZES Report 2b: Metal Recycling – Opportunities, Limits, Infrastructure of the Global Metal Flows Working Group. The full report is available on CD-Rom (see page 31 of this summary booklet). UNEP's International Ressource Panel addresses the metals recycling challenge comprehensively.

A Product-Centric approach is necessary to promote metals recycling in the 21st century. This means the application of economically viable technology and methods throughout the recovery chain to extract metals from the complex interlinkages within designed "minerals", i. e. products, derived from the thorough know-how of recovering metals from complex geological minerals. These products can be regarded as designed "minerals", which provide the basis for recycling as geological minerals provide the basis for extracting metals from minerals. Adaptive and robust recycling and metallurgical infrastructure, systems and technology as well as thorough knowledge are essential to gain economic success and the required resource efficiency. It is therefore essential to use and evolve existing thorough economically viable metallurgical process knowledge and infrastructure. Both are available in the primary and secondary metals processing industry, which thus needs to be preserved in order to allow for the most resource efficient recycling of increasingly complex End-of-Life products.