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International Resource Panel

Metal Recycling

Opportunities, Limits, Infrastructure




United Nations Environment Programme

Acknowledgments

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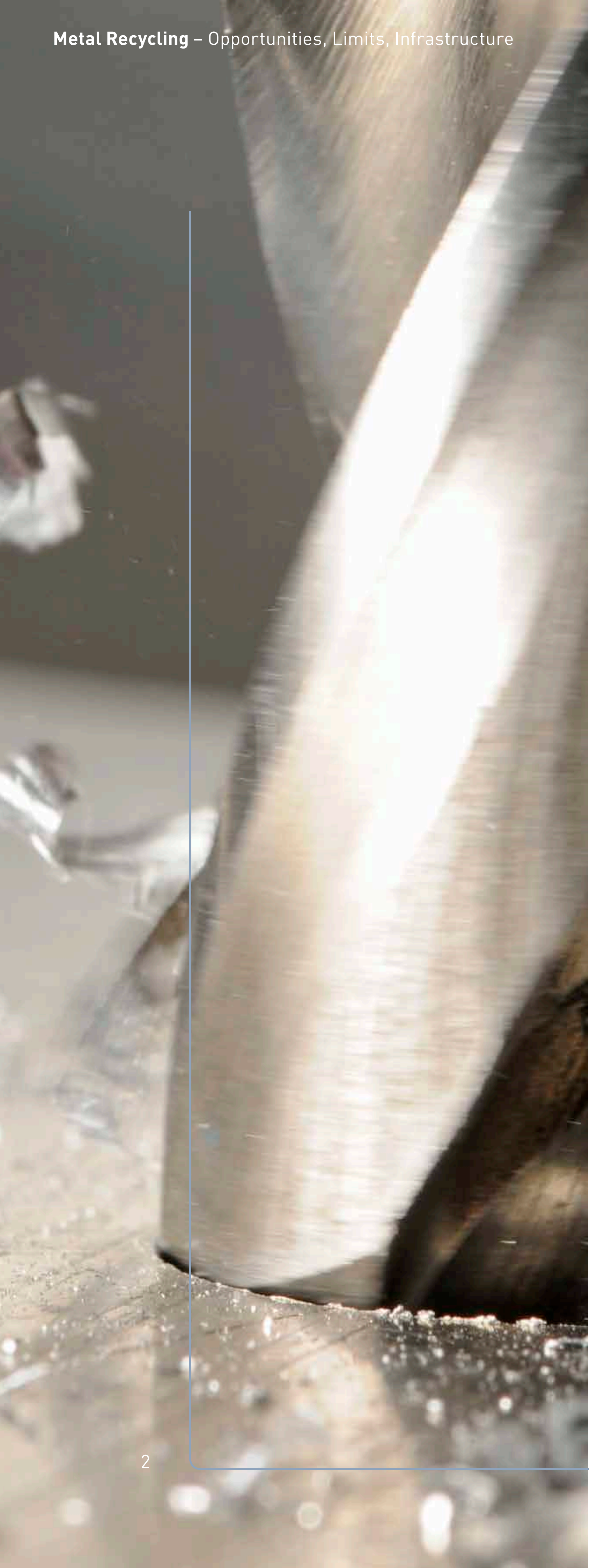
International Resource Panel

Metal Recycling

*Opportunities, Limits, Infrastructure**

* This is report 2b of the Global Metal Flows Working Group of the International Resource Panel of UNEP.



Foreword

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, Metal Recycling - Opportunities, Limits, Infrastructure, 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 thewhole 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.

While common commodity metals like steel, magnesium and copper can be recovered relatively easily, as these are often used in relatively simple applications, the small amounts of metals in, for example, electrical and electronic waste can be harder to recover because they are often just one among up to 50 elements. As an example, a mobile phone can contain more than 40 elements including base metals such as copper and tin, special metals such as cobalt, indium and antimony, and precious and platinum-group metals including silver, gold, palladium, tungsten and yttrium. Fluorescent lamps contain various materials and elements which include a range of Rare Earth elements, and other critical metal resources. And a modern car contains nearly all metals available, as it is a

product that integrates a broad range of other metal-containing products.

This is why thefocus 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. The global mainstreaming of a product-centric view on recycling will be a remarkable step towards efficient recycling systems, resource efficiency, and a green economy in the context of sustainable development and poverty eradication.

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. Industry can be the source of driving innovation that maximizes resource efficiency when policy makers draw on their expertise and tools. Experts from the extraction industry, for example, can make a crucial contribution through their knowledge of metal streams and Best Available Techniques (BATs) for the separation and recovery of different components of a product. Moreover, the manufacturing industry plays a key role in the design of products that facilitate recycling, leading to a substantial increase in recycling efficiency. However, making so-called "urban mines" valuable through recycling can only happen if consumers dispose waste products at collection points operated according to BAT and decide against informal or illegal disposal.

As populations in emerging economies adopt similar technologies and lifestyles as currently used in OECD countries, global metal needs will be 3 to 9 times larger than all the metals currently used in the world. This poses a significant call for increased secondary production of metals. Two former reports from the International Resource Panel on the quantity of metal stocks and on metal recycling rates outlined the so-far untapped

potential and necessity to enhance global metals recycling. This follow-up report analyses the current limitations of metals recycling and discusses how to increase metal-secondary production – and thus resource efficiency – from both quantity and quality viewpoints. The report emphasizes that only a wide, systemic view of recycling looking at the industrial and economic factors driving recycling can deal with the complexity of interactions between metals.

It acknowledges that recycling is primarily an economic industrial activity, driven by the value of the recovered metals and materials. An infrastructure for optimized recycling would therefore make use of economic incentives. Those 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. This is a challenging task for policy makers. A wide, systemic approach based on the solid understanding of the industrial and economic factors driving recycling will be needed. Such a knowledge base will allow to develop a coherent regulatory framework and powerful incentives for all stakeholders to participate in recycling and thus in our transition to a resource efficient society.

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UN Under-Secretary General and
Executive Director UNEP

Nairobi, Kenya

Preface

The increasing demand for metals in the course of the last century, putting permanent pressure on natural resources, has revealed that metals are a priority area for decoupling economic growth from resource use and environmental degradation. The imperative of decoupling will become even more pressing in the future with a global demand for metals on the rise: In developing countries due to rapid industrialization and in developed countries due to modern, metal intensive technologies that are crucial not only but especially for the transformation towards green technologies. Ensuring appropriate levels of supply while reducing the negative environmental footprints will therefore be essential on our way towards a global green economy.

In this regard, recycling and thus resource efficiency plays a crucial role, as it decreases the necessity to fulfil the demand by exploiting our natural resources further. Using secondary resources temporarily locked up in so-called "urban mines" hence decreases not only the environmental impacts associated with mining, but also decreases the release of – partly toxic – wastes into the environment. Taking into account that most modern technologies rely on 'critical' elements, which are not abundant in nature, it is of crucial importance to preserve and reuse them as much as possible.

The International Resource Panel's working group on Global Metal Flows contributes to the promotion of an international sound material-cycle society by providing a series of six scientific and authoritative assessment studies on the global flows of metals. To achieve best scientific results, it cooperates with a number of actors, including metal industry associations. The present, report builds on the findings of the two previously published assessments of metal stocks in society and recycling rates, which came to the conclusion that despite huge metal "mines above ground", recycling rates remain low. It aims at leveraging secondary production of metals through a close analysis of the necessary conditions and enablers of recycling.

The report identifies a number of shortcomings in current recycling policies but also shows ways for their improvement. It emanates from the report that recycling systems need to adjust to the fact that recycling has become increasingly difficult due to the rising complexity of products. Raising metal-recycling rates therefore needs realignment away from a material-centric towards a product-centric approach. A focus on products discloses the various trade-offs between for example achieving weight-based policy targets and the excessive energy consumed in efforts to meet these targets. Recycling objectives that go beyond what is thermodynamically possible, thus rather hinder than promote recycling. Appropriate recycling goals, which draw on the expertise and tools available within the recycling industry, are a better way to enhance recycling of metals.

The present report responds to the pressing need to optimize current recycling schemes with the help of a better understanding of the limits imposed by physics, chemistry, thermodynamics and kinetics, as well as by the technological, economic and social barriers and inefficiencies encountered. Much is at stake when thinking about how to improve recycling systems: closing loops, reducing related environmental impacts, safeguarding the availability of metals, minimizing metal prices, and promoting meaningful and safe jobs for poor people in developing countries.

We are very grateful to the lead author Markus Reuter and principal contributors Christian Hudson, Antoinette van Schaik, Kari Heiskanen, Christina Meskers and Christian Hagelüken for having generated such a thorough and valuable report.

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Emmendingen, Germany

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New Delhi, India

Co-Chairs, International Resource Panel

Preface

Metal recycling is increasingly promoted as an effective way to address resource scarcity and mitigate environment impacts associated with metal production and use, but there is little systemic information available regarding recycling performance, and still less on the true recycling rates that are possible and how to do better considering the system in its totality. The former topic was the subject of an earlier report from the International Resource Panel (Recycling Rates of Metals: A Status Report, 2011). In the present report, the second topic is addressed.

This new report discusses the benefits and necessity of approaching recycling from products, considering them as complex "designer minerals" with typical structures and joinings. This Product Centric approach therefore takes account of the complexities of modern products (which are 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. All contained metals in all streams can be tracked by revealing the "mineralogies" of the material particles, thereby allowing a more detailed and deeper understanding of these complex systems.

As the report argues, modern technology systems require not only efficient end-of-life collection of products, but also effective sorting after collection, and then the optimum suite of physical separation and metallurgical technologies for an economically viable recovery of metals from the sorted recyclates. The report shows how failure at any stage of the recycling chain limits recycling 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 especially those critical technology elements that were shown to have low recycling rates.

The report concludes with a number of tools that can aid decision-makers in arriving at improved recycling approaches. This provides a physics basis for performing Design for Recycling and Sustainability, Eco-labeling, and quantifying resource efficiency, as well as estimating the opportunities, limits, and infrastructure of recycling.

Prof. Thomas E. Graedel

Leader of the
Global Metal Flows Working Group

Prof. Markus Reuter

Lead Author

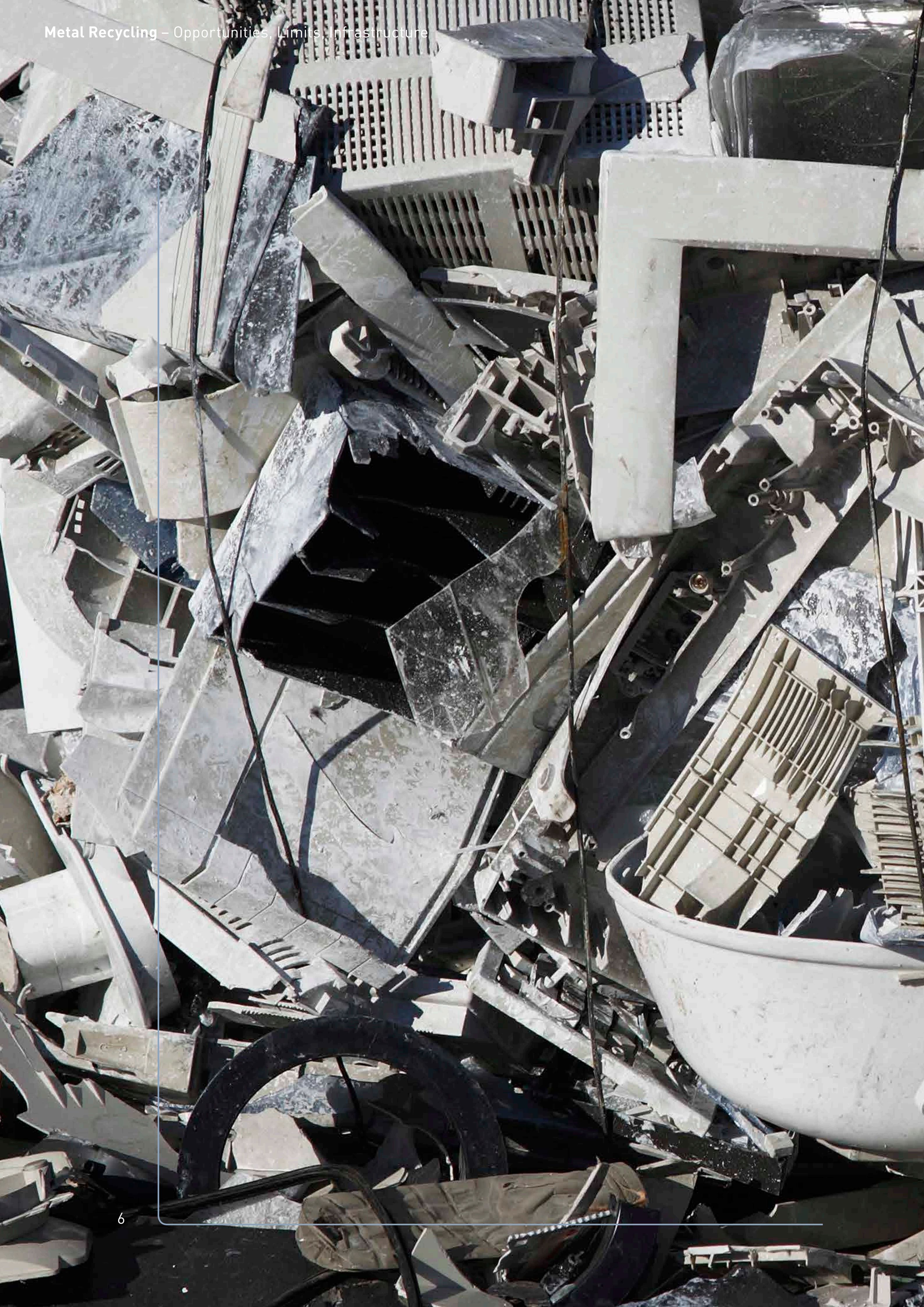

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Figure 1:

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.

Executive Summary

Metal recycling is a complex business that is becoming increasingly difficult! Recycling started long ago, when people realized that it was more resource- and cost-efficient than just throwing away the resources and starting all over again. Until recently, such relatively straightforward recycling concentrated on specific materials, including metals, as most products were relatively simple; this form of recycling follows the so-called **Material (& Metal)-Centric** (MMC) **approach**.

However, thanks to the increasingly sustainability enabling technological advancement of the 21st Centuries, products have become increasingly complex, mixing almost any imaginable metal or other material. Recycling these products became increasingly difficult as trying to recover one material would often destroy or scatter another, and it became clear that we needed a **Product-Centric approach**. Here, recycling targets the specific components of a product, devising ways to separate and recover them. To do this for metals, recyclers increasingly seek the help and expertise of metal miners, who extract mineral ores often containing several metals and have developed ways and means of recovering the metals of interest via complex methods that are based on physical and chemical principles.

Apart from the technological complexity, as always, the basic problem is whether it will pay. And, if not, and as we need the metal anyway, how can we make it pay?

In this report, we discuss how to increase metal-recycling rates – and thus resource efficiency – from both quantity and quality viewpoints. The discussion is based on data about recycling input, and the technological infrastructure and worldwide economic realities of recycling. Decision-makers set increasingly ambitious targets for recycling, but far too much valuable metal today is lost because of the imperfect collection of **end-of-life (EoL)** products, improper practices, or structural deficiencies within the recycling chain, which hinder achieving our goals of high **resource efficiency** and resource security, and of better recycling rates.

The report consists of **seven chapters** and **six appendices**. The chapters deal, successively, with:

1. A brief overview of the factors affecting recycling.

2. Recycling opportunities.

3. Limiting factors in recycling.

4. Consequences of limiting factors.

5. Infrastructure for optimizing recycling.

6. Tools to aid decision making.

7. Policy drivers and recommendations for recycling.

The appendices highlight some of these subjects, including a last section on the physics and thermodynamics underlying extractive metallurgy.

These practical considerations are the basis for recommendations to decision-makers, some of which turn existing policy approaches on their head. We particularly focus on the recycling of high-value, low-volume metals that are essential elements of existing and future high-tech products. Such metals are often scarce, but essential for sustainable growth, though typically lost in current recycling processes.

Factors affecting recycling

For many purposes, the above-mentioned **MMC** and **Product-Centric** approaches of recycling can be considered together. However, designing recycling systems from a purely Product-Centric viewpoint needs a good understanding of separation physics, thermodynamics and metallurgy, as well as of the as-

sociated economics, in order to innovate and optimize product design. Figure 2 illustrates this, describing some of the major factors that **increase resource efficiency by maximizing recycling rates**.

Increasing metal-recycling rates is possible when considering and applying a Product-Centric approach of which the MMC approach is a subset. A Product-Centric approach is far better in considering the complex interactions in a recycling system than just an MMC approach, as it contemplates how to improve the recycling of an entire EoL product. It also assesses what comes out of the system, in order to minimize the losses from each step, thus quantifying the economic feasibility of a potential recycling chain, and, ultimately, for awarding operating licences to the stakeholders involved. It takes its cue from classical extraction of metals from geological minerals; where the objective has always been to maximize recovery of all elements into economically valuable products, while maximizing energy recovery and minimizing the creation of residues.

Three interrelated factors determine the success of recycling and maximize resource efficiency:

1. The recycling processes and the major physical and chemical influences on the metals and other materials in the processing stream.

2. The collection and pre-sorting of waste.

3. The physical properties and design of the end-of-life products in the waste streams.

While reading this document consider the three points above and consider the technological and economic challenge of producing pure water, sugar, milk and coffee from a cup of coffee – a consumer product. This illustrates the complexity of recycling, the effect of dissolution of metals in each other and then separating them into pure or alloy products of economic value as shown by Figure 2.

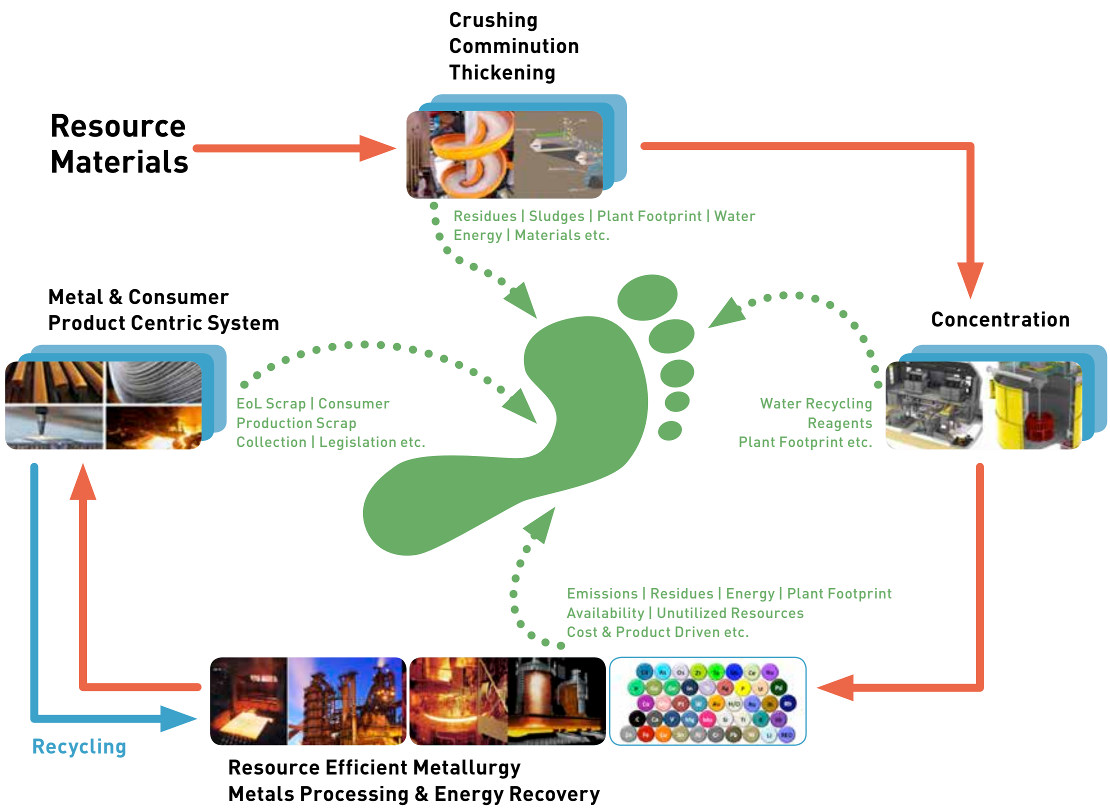


Figure 2:

The best footprint of sustainability and resource efficiency may be achieved by reducing losses during processing by bringing together the various stakeholders, thus minimizing the use of resources in their widest sense. No society can truly achieve a "closed-loop" status; there will always be some loss and economic growth implies more raw-material needs; therefore, Figure 2 shows how this footprint is affected by the various activities of transforming raw materials.

It is impossible to optimize one factor without considering the others. To get the best results out of recycling, product designers, collectors and processors must know what is happening in the other parts of the system, which requires a multi-faceted approach that considers all metals, compounds, and other materials.

Recycling saves resources, as it strengthens the primary supply from primary mining by using the resources temporarily locked up in "**urban mines**[a]". Especially 'critical' elements, not abundant in nature, must be preserved and reused as much as possible.

An added advantage is that the energy consumption of metal recovery from recycled sources is usually less than that of primary production, as recycling often "only" involves the re-melting of metals. In addition, a resource-efficient system minimizes water use and maximizes the quality of wastewater before discharge.

The basic assumption of recycling is that the value of the recovered (and other materials) has to pay for all collection, dismantling, sorting and other recycling activities. The economics of such recycling is based on estimating the true value of recyclates from the best recovery of refined metals, alloys and compounds.

Recycling is thus driven by the value of the recovered metal (and material). In any case, all metallurgical plants always try to recover all valuable elements. **If there is an economic incentive, recovery will happen.**

Another point of great importance is that modern **product design** should consider the complexity of recycling such products. If possible, the design should avoid incompatible metal mixtures, or joints between product parts 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.

In summary, we discuss how the environmental footprint of society is minimized by maximizing resource efficiency on an economic and technological basis.

Above, mention was made of the fact that many modern products are incredibly complex. Table 1, below, illustrates this fact for a few "household" objects.

---

a The word "urban mine" has been used for some years and has been registered since many years e.g.
Details for Australian Trademark No. 1371937.
Number Australian Trademark No. 1371937.
Mark URBAN MINE.
Owner RECUPYL SAS.
Service Refer to WIPO Address for Correspondence.
Filingdate in Australia 16 March 2010.
The applicant has advised that the English translation of the words appearing in the trade mark is URBAN MINE.

Table 1:

Compatibility matrix as a function of metallurgical recovery (van Schaik and Reuter, 2012; Reuter and van Schaik, 2012a&b) (PMs: precious metals; PGMs: platinum group metals).

Recoverability per application	PMs Ag	PMs Au	PGMs Pd	PGMs Pt	Rare Earth (Oxides) Y	Rare Earth (Oxides) Eu	Rare Earth (Oxides) Other	Other Sb	Other Co	Other In	Other Ga	Other W	Other Ta
Recovery possible – If separatly recovered and/or if there is appropriate technology and recovery available.													
Washing machine													
Large Hh Appliance													
Video recorder													
DVD player													
Hifi unit													
Radio set													
CRT TV									green+orange			green+red	
Mobile telephone	green	green	green	green					green	green+orange		green	
Fluorescent lamps													
LED										green+orange	green		
LCD screens										green+orange			
Batteries (NiMH)					green	green	green		green				
Limited recovery under certain conditions – If separatly recovered. Partial or substantial losses during separation and/or processing/metallurgy. Recovery if appropriate systems exist.													
Washing machine	orange+red	orange+red	orange+red										
Large Hh Appliance	orange+red	orange+red	orange+red										
Video recorder	orange	orange	orange				orange						orange+red
DVD player	orange	orange	orange				orange						orange+red
Hifi unit	orange	orange	orange										orange+red
Radio set	orange	orange	orange										orange+red
CRT TV	orange	orange	orange	orange	orange	orange	orange+red		orange+green				orange+red
Mobile telephone										orange+green			orange+red
Fluorescent lamps					orange	orange	orange						orange+red
LED					orange+red	orange+red	orange+red			orange+green			
LCD screens	orange	orange	orange							orange+green			
Batteries (NiMH)													
No separate Recovery – Pure recovery not possible. Lost in bulk recyclates during separation and/or during metallurgy into different non-valuable phases.													
Washing machine	red+orange	red+orange	red+orange										
Large Hh Appliance	red+orange	red+orange	red+orange										
Video recorder							red+orange	red					red+orange
DVD player							red+orange	red					red+orange
Hifi unit							red	red					red+orange
Radio set							red	red					red+orange
CRT TV							red+orange	red				red+green	red+orange
Mobile telephone					red	red	red						red+orange
Fluorescent lamps												red	red+orange
LED					red+orange	red+orange	red+orange					red	
LCD screens													
Batteries (NiMH)													

For a combination of colours, e.g. orange+red
Depending on the process route followed, high recovery rates as well as high losses are possible. Hence a careful attention to design, infrastructure, legislation etc. is necessary. This is especially possible for metals closely linked where one metal can be recovered while the other due to this selection of recovery then goes lost. This is driven by thermodynamics, technology, design etc.

Opportunities and limiting factors in recycling, and their consequences

If each product were made from a single substance, recycling would be relatively simple and its interactions linear, up and down the 'recycling chain'. However, the reality is that many products contain several metals, and their alloys and compounds. Several 'recycling chains' are thus necessary from end-of-life (EoL) product to metal, which will interact because of the functional connections of these materials. This creates a multi-dimensional system, whose level of complexity must be clear to stakeholders and policy makers.

Figure 3 shows these complex interactions, which are in fact partly bi-directional along the chain. It also shows that the metals and alloys arriving at recycling operations are almost always mixed with other materials and compounds, including plastics and other modern materials, such as composites, fillers and paints. These materials all have a monetary value that increases with their purity, affecting treatment charges incurred by custom smelters and processors of the recyclates. However, they can also negatively affect the processing in a physical and chemical sense.

In the recycling process, EoL products are usually broken (or cut, crushed etc.) up into small pieces, and a first attempt is made to liberate and sort the different mixed materials. However, this is generally only partly successful. For example, materials that are functionally attached to each other, as they often are built into a product for functionality reasons, will stay close together. Therefore, most metals enter metallurgical processing as a mix, often rather complex.

Physical and metallurgical recycling technologies and processes exist for the separation of many metals, but each process flowsheet will deal differently with metal mixes. When such metals and their compounds have compatible thermodynamic and physical properties, the metallurgical processing technology used will succeed in economically separating them. If not, mixed alloys, sludges, slimes and slags are produced, wasting the contained resources and creating an additional dumping or storage cost.

The degree to which metals can be separated thus affects the economics of recycling.

It is clear from Figure 3 that the elements within complex products are not recycled individually. Instead, they pass through one of a wide range of processes that has to be in place to optimally recover all metals in complex products and their "mineralogies". The choice of process is an economics- and physics-based technological optimization puzzle for the recycling operation, which is at least partly driven by the changing market value of the metal and its high-end alloy products.

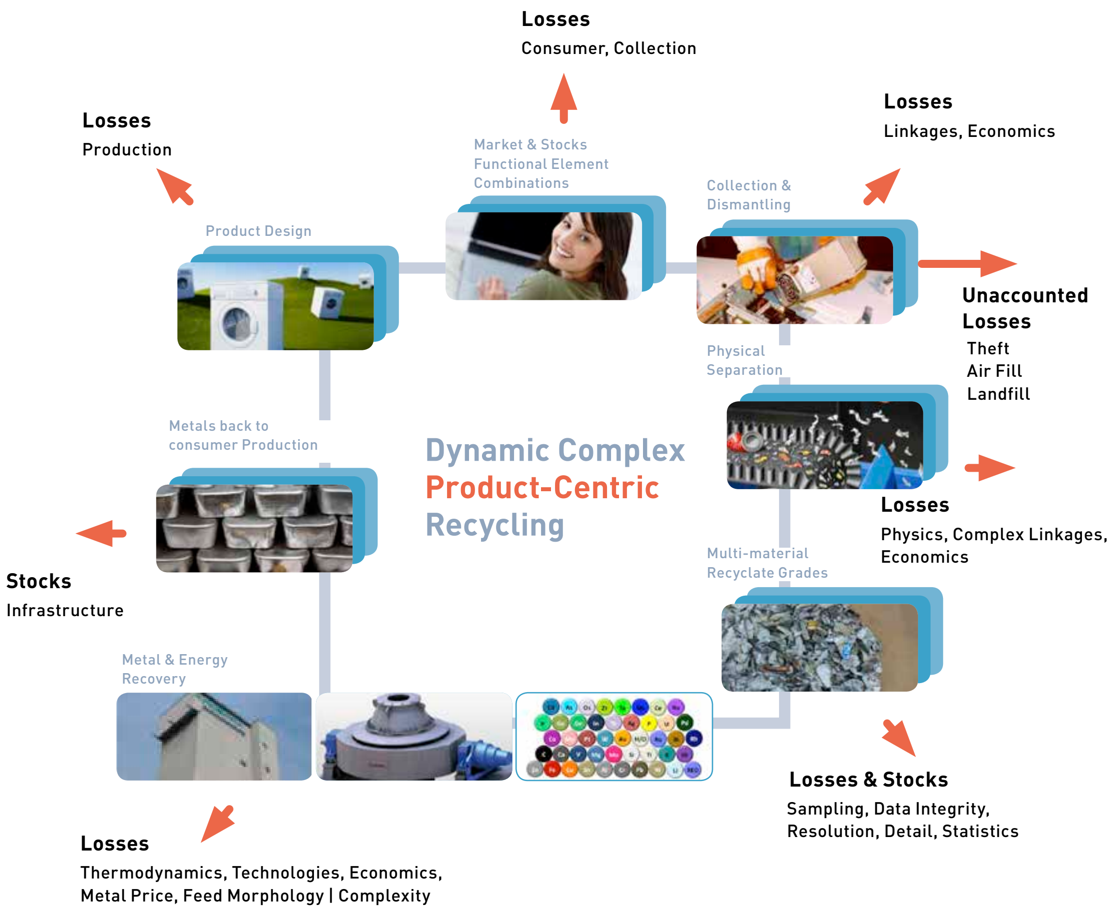


Figure 3: Product-Centric recycling – A schematic diagram of the life cycle of metal-containing products going through recycling, showing the inevitable losses. Design for resource efficiency covers all details of the figure in order to minimize losses

Zoom

Infrastructure for optimizing recycling

The Product-Centric approach (Figures 2 to 4) is an example of the practical application of several physics-based systems to a complex multi-dimensional issue, with strong implications for public recycling policy. It suggests that, for optimizing recycling, the following conditions and infrastructure have to exist:

- **BAT:** EoL, waste, and residue streams destined for recycling must be processed by Best Available Technique (BAT), according to specific performance standards and being mindful of environmental and social costs and benefits. These BATs can differ between products and regions, and do not need to be high technology per se. They may include hand sorting in the earlier steps of the recycling chain, thus creating jobs. Where waste streams enter uncontrolled flows or less suitable processes, value will be lost and the environmental impact may be severe.

- **POLICY: Targets** must align with the economic drivers of a complete system. With so many operators in the collection and recycling industry, enforcing regulations is unlikely to be sufficient for steering the destination of metal-containing waste streams. Policy must create the economic incentives for waste to be handled by registered BAT operations, rather than by 'grey' recycling, or even improper practice. Economic drivers must align with long-term economic goals, such as conserving **critical metal resources** for future applications, even if their recovery currently is uneconomic. **Policy targets** should consider the "loss" of metals due to a complex recyclate composition. Policies should neither exceed what is physically and thermodynamically possible, nor prioritize one or two metals at the inadvertent expense of other metals found in the input stream.

- **KNOWLEDGE:** The metallurgical recycling industry has the knowledge needed for **linking BAT processes** so that they separate a maximum of valuable metals and create a minimum of secondary residues. Successful and resource-efficient metal producers generally aim at producing a wide range of metals, rather than focusing on one or two metals as their production output.

- **INCENTIVES:** They exist for all participants in recycling – from product design to purchasing recycled metal – to work with the other participants in the system for improving the recycling performance of the system as a whole. Practical ways exist for improving information flow between the participants; for example, **producer-responsibility laws** motivate a product manufacturer to innovate in recycling-process technology for meeting recycling targets. Such incentives can be purely legislative or purely economic, but work best as a combination of policy and profit.

- **MODELLING:** Physics-based-modelling and simulation of how products recycle can help designing a product that facilitates recycling, based on how products and their constituents break up and separate in BAT recycling processes. Such design goes beyond "**design for disassembly**" and "**design for recycling**", to become "**design for resource efficiency**". Here disassembly breaks down complex products into components or subassemblies that then can be directed into more suitable recycling processes, such as the easy removal of a circuit board from a plastic, aluminium or steel housing.

The report discusses the facts behind these required conditions and their implications for policy.

Tools to aid decision-making

Various tools exist for supporting decision-making to maximize resource efficiency. What needs further development is a rigorous multiphysics basis that clearly links the stakeholders within the Product-Centric chain as shown in Figures 2 and 3. Existing physics-based tools cover separation physics as well as thermodynamics, various simulation approaches and life-cycle assessments. **Multiphysics** is a new concept, covering studies that **combine hitherto separate physics-based tools**, generating relational mathematical models and validating them experimentally to improve our understanding of natural systems.

A major new tool is the **Metal Wheel**, a simplified version of which is shown in Figure 4. The wheel is separated into slices, one for each basic metal used by society or **Carrier Metal**, and showing its main BAT processing route. The light-blue, white and green rings show the main potentially valuable elements associated with this Carrier Metal (CM). The first contains mostly metallic elements that dissolve in CM (generally using pyrometallurgy), the white ring contains compound elements mostly treated by hydrometallurgy, and the green ring shows associated elements that are generally lost in waste.

The available computer-based tools can be ranked in several classes. The most important are:

- **Liberation modelling**, when coupled with modelling of the thermodynamics of a specific processing plant, allows defining recyclate grades and thus the resulting economic value. **Design for Resource Efficiency (DfRE)**, of which **Design for Recycling (DfR)** is a sub-set, demands knowledge of liberation behaviour (particulate quality of recyclates; separation efficiency; compatibility and recovery and/or loss of material) as a function of design choice, connection type and connected materials.
- **Life Cycle Assessment** or LCA is a tool that facilitates understanding and quantification of the ecological and human-health impacts of a product or system over its complete life cycle. It must be linked to rigorous simulation tools to quantify resource efficiency.
- **Design for Sustainability** requires product designers to assess which material promises the best sustainability performance, for example with regard to energy efficiency combined with other factors like recyclability, durability, etc., by taking a life cycle perspective. Products must be designed such that compatible groupings of metals are easy to dismantle to be directed into the correct metallurgical processing infrastructure.
- **Life Cycle Management**, LCM, is a business approach that can help companies achieving sustainable development. It helps reducing, for instance, a products' carbon, material and water footprints, as well as improving its social and economic performance. LCM is about making life-cycle thinking and product sustainability operational for businesses that aim for continuous improvement.

Figure 4:

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. As there are so many different combinations of materials in End-of-Life products, only physics-based modelling can provide the basis for valid predictions. In essence, primary metallurgy is situated in a segment a complete processing plant, while the complexity of consumer product mineralogy requires an industrial ecological network of many metallurgical production infrastructure to maximize recovery of all elements in end-of-life products (Reuter and van Schaik, 2012a&b; Ullmann's Encyclopaedia, 2005).

Society's Essential Carrier Metals: Primary Product Extractive Metallurgy's Backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.

Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy) Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

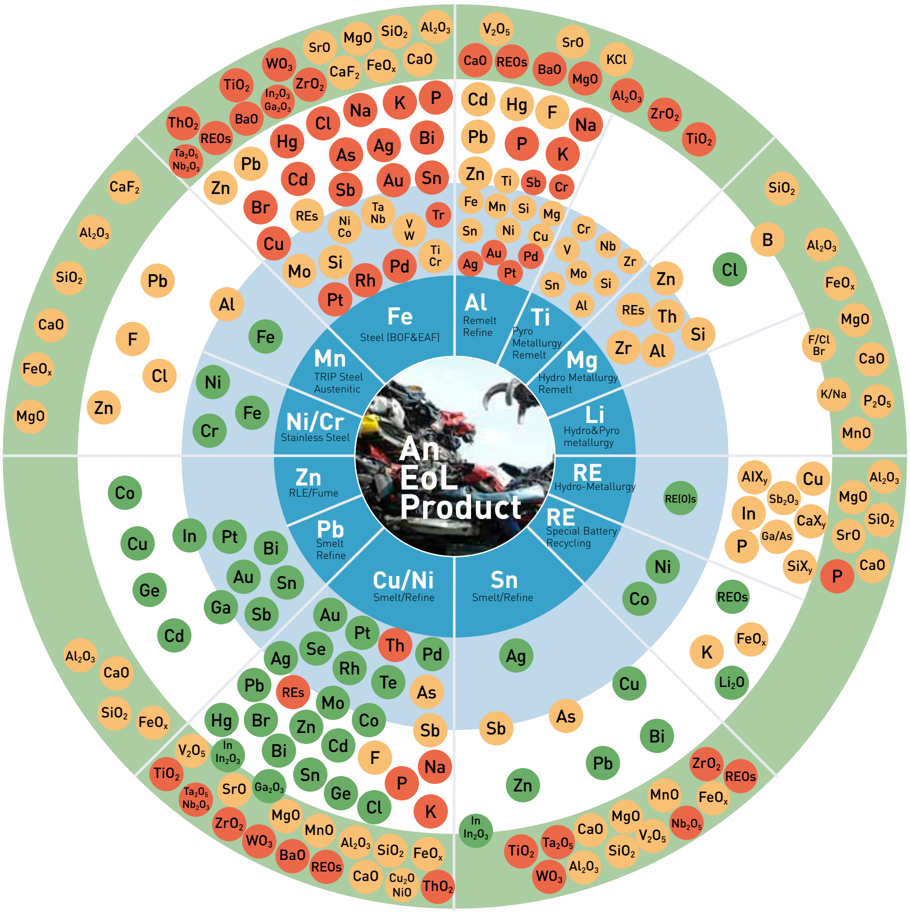
Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy) Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

Mainly to Benign Low Value Products Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

El **Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.

El **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).

El **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.



The **usual basis for any bankable feasibility study** at the heart of all process design is a thorough description of the Product-Centric recycling system. This requires rigorous simulation, including closure of all mass balances of not only the bulk materials, but also of the elements contained in organic and inorganic compounds and alloys. The energy balance has to be closed as well, showing the details of all inflow and outflow for quantification of the streams. This detail is required to determine the environmental impact of all recycling streams. Nothing less rigorous will provide innovative solutions for a sustainable future.

Figure 5 shows how rigorous process simulation and design models for complex flowsheets are linked to environmental soft-

ware and have become a basis for calculating recycling rates. This link, discussed in detail in this report, helps quantifying resource efficiency, and can:

- **Standardize systems** on the basis of physics and economics, for discussing sustainability and CleanTech.
- Resolve **policy and legislation questions**.
- Provide rigorous **recyclate-rate calculations** that include physics and non-linear interactions.
- Establish **key performance indicators** based on BAT and not on the global averages generally used in environmental databases.
- Harmonize the input and language of, among others, engineers, policy specialists and environmentalists based on economic feasibility, technology and physics.

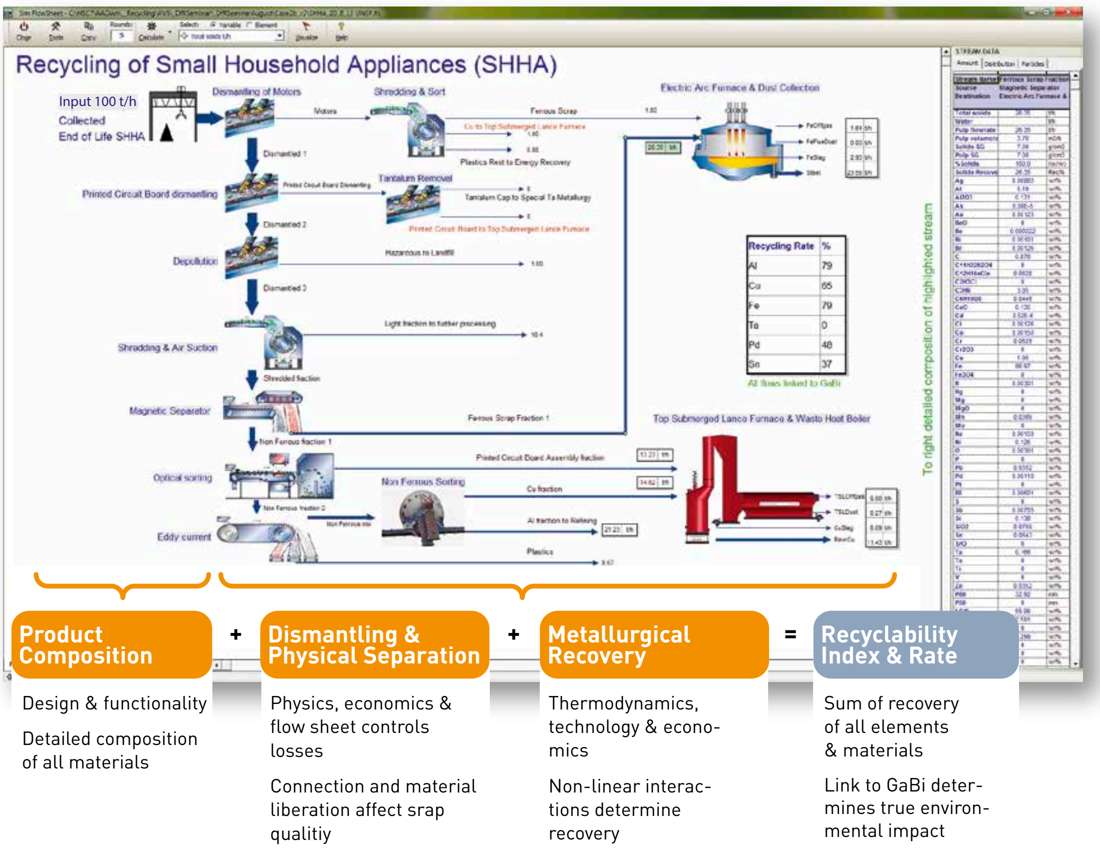


Figure 5: Example of existing software for flowsheet design, based on compositional data for a product, which lead to simulated resource efficiency data that, in turn, lead to a recyclability index based on environmental analysis – a metallurgical processing infrastructure is prerequisite (Reuter 1998).

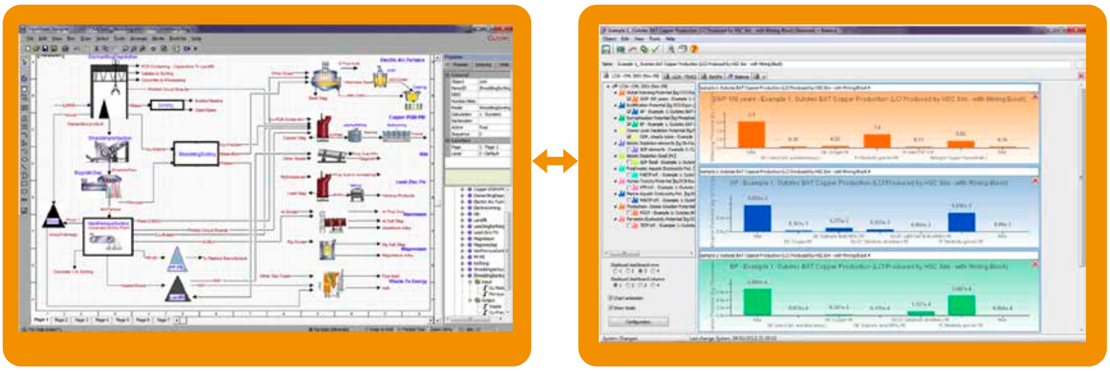
Zoom

In summary, a whole **set of tools is available to help decision-makers understand the recycling system**, assess how they can best increase recycling, and facilitate the information exchange between stakeholders. Each of these tools provides an easy way for decision-makers to access the detailed information usually held by industry-sector experts. Such tools enable the decision-makers in one part of the recycling system (designers or metal processors, for example) to arrive at better predicting the results of the system of any changes that they would make, such as investments in new technology.

A final observation: true **Design for Recycling** can only take place with tools that are based on a rigorous application of physics, thermodynamics and process technology, as reflected by, for example, Figure 6.[a]

Figure 6: Resource cycles are linked by flowsheeting and simulation tools (Reuter 1998 & 2011) based on rigorous physics before interactively linking them to environmental-impact assessment software (HSC Sim and GaBi).

Zoom



BAT, Flow Sheets & Recycling System Maximizing Resource Efficiency – Benchmarks

$US/t Product (CAPEX & OPEX)

Recyclability Index (based on system simulation of whole cycle)

- GJ&MWh/t Product (source specific) and Exergy
- kg CO_2/tProduct
- kg SO_2/tProduct
- g NO_2/tProduct
- m^3 Water/t Product (including ions in solution)
- kg Residue/t Product (including composition)
- kg Fugitive Emissions/t Product
- kg Particulate Emissions/t Product
- Etc.

Environmental Indicators based on BAT Driving Benchmarks of Industry

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Eutrification Potential (EP)
- Human Toxicity Potential (HTP)
- Ozone Layer Depletion Potential (ODP)
- Photochemical Ozone Creation Potential (POCP)
- Aquatic Ecotoxicity Potential (AETP)
- Abiotic Depletion (ADP)
- Etc.

a 7th Principle of the Earth Charter (www.earthcharterinaction.org): Adopt patterns of production, consumption, and reproduction that safeguard Earth's regenerative capacities, human rights, and community well-being.

1. Reduce, reuse, and recycle the materials used in production and consumption systems, and ensure that residual waste can be assimilated by ecological systems.
2. Act with restraint and efficiency when using energy, and rely increasingly on renewable energy sources such as solar and wind.
3. Promote the development, adoption, and equitable transfer of environmentally sound technologies.
4. Internalize the full environmental and social costs of goods and services in the selling price, and enable consumers to identify products that meet the highest social and environmental standards.
5. Ensure universal access to health care that fosters reproductive health and responsible reproduction.
6. Adopt lifestyles that emphasize the quality of life and material sufficiency in a finite world.

Policy recommendations

Many of the world's existing recycling policies have grown out of environmental policy, and are often still under the jurisdiction of environmental ministries. This duly reflects the potential environmental benefits from increased recycling as well as the potential harm from insufficient waste treatment. However, it can also obscure the fact that **recycling is primarily an economic industrial activity with a strong environmental and social implication**, and is strongly affected, for better and for worse, by all policies that influence the costs and benefits of recycling. Waste- and recycling policies directly affect the cost of recycling processes (e. g. where environmental requirements change such processes) as well as the cost of alternatives to recycling, such as waste disposal. These policies also influence the availability and composition of waste streams for recycling. Relevant, too, are trade restrictions on waste or metals, and all policies regulating industrial activity such as taxation, labour regulation and energy costs. Governments should be conscious, in crafting and implementing such policies, of their impact on sustainable development.

Defining the system boundaries for which targets are stipulated is of critical importance. Furthermore, **weight-based targets hinder rather than promote recycling** of the many critical elements in complex products, usually present in very low concentrations. In addition, priorities have to be set for different metals, such as base metals, special metals, critical-technology metals, etc. This further highlights the dilemma of defining recycling targets for metals that are present in small quantities in products. **Targets that go beyond what is thermodynamically possible for recycling are likely to fail** and might lead to **excessive energy consumption** in efforts to meet the recycling target. Policy makers can set appropriate targets from a life cycle perspective and by drawing on the expertise and tools available within the recycling industry.

A **Product-Centric view helps understanding the tradeoffs** between achieving high recycling targets and natural-resource depletion. If this product complexity is fully understood, this will improve the recycling of valuable critical and scarce elements, and the recycling rates of the commodity metals. Including a Product-Centric view of recycling into the discussion requires thorough rethinking of policies to ensure that resource efficiency is maximized.

Product design strongly affects the physical properties of the waste stream, as do collection methods. Optimal recycling can only succeed through increased physics-based **Design for Recycling** (DfR) or **Design for Sustainability** (DfS). This is better covered by the term **Design for Resource Efficiency** that is more economics based with links to Product-Centric recycling. Here, product design is based on, or at least cognisant of, recycling BAT (as concisely reflected by the Metal Wheel).

Optimal design for recycling and recycling systems demands good understanding of the limits imposed by physics, chemistry, thermodynamics and kinetics, as well as by the technological, economic and social barriers and inefficiencies encountered. Functionality demands mean that this optimal design is not always possible; it might dictate that certain metals and materials must be combined, rendering Design for Recycling inefficient.

The information in this document leads to the following points that are relevant for policy formulation:

General perspectives

- **A wider, systemic, view of recycling must look at the environmental, industrial and economic factors driving recycling**. Simplified approaches to recycling – specifying desired recycling outputs – will not adequately support a drive for resource efficiency. A linear, one-dimensional, approach cannot deal with the complexity of interactions between metals, mixing of waste streams, and the economics behind processes.

- For maximizing resource efficiency, a **Product-Centric approach** to recycling must be based on a good understanding of the physics of materials in products. This allows simultaneous consideration of the interactions, why and when they dynamically vary, and the economic value of the resulting recyclates, as well as the impact on resource conservation and environmental sustainability.

- **Stimulating the use of BAT by certified operators raises the overall level of recycling**. Quantitative computer models, based on the physics and economics of recycling with BAT, can be used for resolving complexity and guiding policy, thus replacing simple material-flow analysis.

- As dictated by **the Second Law of Thermodynamics**, there will always be losses from a recycling system. Concepts such as 'Closing the loop', 'Circular Economy' and 'Cradle-to-Cradle' represent unattainable ideal conditions, but they bring systemic thinking into material-efficiency discussions, and provide an upper limit to the potential economic benefits.

Economics of recycling and legislation

- Policy and legislation play a key role in shaping the economic incentives and guiding conditions for overall system performance. Where the economic incentives for collection of waste by private or public operators are not aligned with policy goals, significant resource volumes can be lost to illegal or informal recycling, or are simply unaccounted for, sometimes through 'cherry picking'. This often leads to environmental problems, damaging health impacts and impacts on water or climate, as regulatory standards are ignored.

- The best policy and legislative results are achieved by creating **a level playing field that internalizes external costs**. This helps stakeholders in the recycling system to operate on a 'best practice' basis, along social, environmental, technological and economic considerations.

- **Policy and legislation** can improve results if it focuses on promoting BAT in recycling systems, setting up the framework for innovative business models. In some cases, this will mean providing incentives for coping with negative revenues from parts of the treatment process for EoL products. Actions increasing the willingness of product manufacturers and their customers to recycle EoL products and use recycled materials produced with BAT, can also drive the recycling market.

- For some minor elements, the required economies of scale will only be reached through processing at a sufficiently large "central" facility. However, in order to achieve this, effective international arrangements would be required to facilitate **cross-border transportation** in a transparent and sustainable manner.

Industrial infrastructure and technology are essential

- The infrastructure and knowledge for the processing of waste into recycled metal is often the same as that used for primary metal production. Therefore, the health of such production is vitally important for recycling, as a **healthy balance between primary and recycled metal production** fosters metallurgical systems knowledge. This balance also mitigates the cyclical nature of the primary metals industry.

- **Technology and expert knowledge of the academic communities and industries of society** should be adaptive and able to deal with changing complexity. We can revitalize the significance of these industries for sustainability with a suitably inspiring explanation of the sometimes dry and difficult physics underpinning recycling. For instance, current pre-processing technology is inappropriate for increasingly miniaturized technology or complex products, such as today's cars. A recycling system needs suitable dismantling, cutting, sorting and whole-product-smelting technologies. As product change is much faster than the change in processing equipment, processing must use flexible technology, such as the highly adaptive manual sorting, and some physical separation and sorting equipment may be moved to where scrap is being generated.

Collection as part of the recycling system

- Optimized recycling requires secure and large volumes of waste, collected (or sorted) in ways that assist its metallurgical processing. Two essential factors for successful waste collection are: (i) a suitable infrastructure for collection, and (ii) economic incentives for the delivery of waste to BAT operators, rather than to informal or illegal operators.

- Where economic incentives exist, private operators often set up collection infrastructures. In some cases, public-policy intervention must help the creation or capacity building of such infrastructure, for example when setting up recycling systems for mobile phones. Where waste ends up in areas with no or poor-quality recycling, the resources are often lost. Responsibility for collection can be shared between all stakeholders in ways that best finance and increase the capability of collection systems in such areas.

Design for Resource Efficiency (DfRE)

- For optimal recycling, the industrial-waste and End-of-Life-product streams that enter processing should be **economically and physically compatible** with the metal-production system. Both product design and collection methods strongly affect the physical properties of a waste stream. Optimal recycling can only succeed by better physics-based **Design for Resource Efficiency (DfRE)**. Design can then try to avoid putting metals together in a stream that cannot be separated by the BAT. Nevertheless, material linkages can make any DfRE useless, as the consumer primarily purchases product functionality.

- **Computer models** can facilitate DfRE, which includes Design for Recycling. These, like any engineering-process design model, should have enough detail that captures the physics of recycling, for predicting recycling-output quality and economic value. To be effective, they must be based on thermodynamics and the recycling techniques used. **Detailed data** must be collected for the materials chain to optimize the system, as **too simple data** collection makes Design for Recycling and Resource Efficiency impossible.

- Design changes can do much to improve recycling, though many **"critical" elements** may be **intertwined in products to ensure their complex functions**. Here, better design for disassembling the relevant – in terms of critical/valuable metals – subassemblies is an evident necessity. Design for Resource Efficiency is based on a perspective that looks at the **impact of products over their life cycle (life cycle management**, or LCM), and policy should assist the adoption of LCM by manufacturers.

- Digitalization of all aspects of the recycling chain with suitable tools such as ID tags in materials, sensors, simulation models, design tools, scrap contract payment etc. as discussed in this document is paramount to optimize it.

Technologically feasible policy objectives must be set to reflect product complexity

- Recycling rates as currently defined in EU waste legislation, such as the ELV and WEEE directives, do not refer to the actual recycling of individual metals in the recycling chain. Current system boundaries are the output of pre-processing steps and their resulting fractions, which again are a mix of different substances. The final smelting and refining step is not considered in the recycling rates.

- **Legal recycling-rate targets** have two implicit weaknesses:

  (i) They do not differ between individual substances, but are calculated solely by weight based on an entire fraction. Hence, to achieve the targets, recovery of mass substances such as plastics, glass or steel becomes much more important than recovery of precious and special metals, which are usually only present in small amounts.

  (ii) As the targets do not consider metallurgical steps, the high legal recycling targets pretend a recycling quality that in reality is not obtained. For instance, the EU's ELV directive requires a 85 % recycling rate (material and energy recovery), to be increased to 95 % by 2015. If smelting and refining are included, real recycling rates will be much lower, especially for precious and special metals.

- Due to product complexity and the inherently random separation of metals in the recycling process, there are **no single optimal recycling rates for metals** in End-of-Life products. The same product, put through BAT, can produce different amounts of recycled metal, with a differing quality depending on the system and market conditions.

- It may be **counter-productive to use material-based recycling-performance output** standards, such as mass or percentage of a single metal in a waste stream. They can ignore the complexity of recycling and its **inherent trade-off** between outputs of different recycled metals from mixed waste streams. This may lead to wasting of valuable metals. For example, a system focused on increasing recycled iron output may lose valuable metals with complex links to iron, such as vanadium.

- We must **reconsider** the current practice of using recycling rates of single metals, or of percentages of product mass, as the **Key Performance Indicator (KPI)** of a recycling system. Approaches based on the understanding of recycling physics can improve MMC indicators to render them more Product-Centric, especially if they include economics-based indicators.

- **Economics-based and environmentally benign KPI** processes should be considered as a BAT. Rather than industry having to achieve a mandated performance target, policy and industry need to create the conditions and incentives that facilitate high performance. This, however, requires policy actions across the system to overcome the bottlenecks that currently hold back optimized recycling.

Education and information – High-quality people and training

- **Research and education** is critically important for preserving expert knowledge, especially of the processing of key metals, and for driving innovation that maximizes resource efficiency. Moreover, much knowledge is **tacit** – held and transmitted by vitally important experts who cannot be traded like a commodity – and that is lost when industry sectors are too cyclical. There is a need for disseminating the **physics-based systems approach** to recycling, as described in this report.

- Market operations are significantly helped when recycling operators can estimate future needs for recycling infrastructure by quantifying the "**urban orebody**", its location and waste flows. Policy can stimulate or assist towards estimating the **metals in market products**.

- Teaching of Digitalization techniques and its physics basis is if utmost importance to drive innovation and R&D.

1. Brief Overview of Factors affecting Recycling

The Green Economy Initiative set up by United Nations Environmental Programme (UNEP), spearheads the transformations needed to create a viable future for generations to come. Its aim is to shape an economy "that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. In its simplest expression, a green economy can be thought of as one which is low carbon, resource efficient and socially inclusive" (UNEP, 2011a).

This is one reason why metals and metal recycling are central in the work of UNEP's International Resource Panel (IRP) and its Global Metal Flows Working Group. Another reason is that, while some studies exist on the local impact of mining, the environmental effects of recycling, or geological and anthropogenic metal stocks, no global and comprehensive overview of scientific data existed until now. To fill this gap, the Metal Flows Working Group commissioned several Status Reports of which this report is one.

We prepared the present report, following the one on Recycling Rates, as a response to several significant trends in society's ever more complex use of metals. We briefly discuss some aspects of anthropogenic metal flows and cycles, covering issues around

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.

The production and use of metals plays a crucial role in creating that future economy. According to the Green Economy Initiative Report, the main sources of future economic development and growth 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 waste management and recycling facilities (UNEP, 2011b). All of these rely heavily on metals.

the local impact of mining, energy use of the metal life cycle, the effect of metal emissions from non-metal sources such as fossil fuels and phosphate fertilizer, as well as the effect of final metal sinks and residues. This aspects are all covered in more detail in the Global Metal Flows Working Group's third report on "Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles" (UNEP, 2013).

The 1987 Brundtland report is as relevant as ever and is one of the bases of this document, especially its section on sustainable development of which the following paragraph (p. 24) is reproduced here:

"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits – not absolute limits but limitations imposed by the present state of technology and social organizations on environmental resources and by the ability of the biosphere to absorb the effects of human activity. But technology and social organization can be both managed and improved to make way for a new era of economic growth."

Of importance in this regard also is the 'Factor 5' discussion of von Weizsäcker et al., (2009) in which it is argued that sustainable development can be achieved by increasing resource productivity by 80 %. The availability of a Factor of 5 in efficiency improvements in entire sectors of the economy is possible without losing the quality of service or well-being. One of the objectives of the present report is to explore the opportunities and limitations with reference to recycling and resource efficiency.

The real quest is to use fewer materials in delivering social progress and prosperity. Recycling is part of this quest, and can mitigate part of the increased demand for metals and the related consumption of energy and other resources for their production. Recycling is in fact one of the most immediate, tangible and low-cost investments available for decoupling economic growth from environmental degradation and escalating resource use.

1.1 Increasing worldwide use of metals and energy constraints

The use of metals strongly correlates with per capita gross domestic product (GDP), though it levels off at higher GDP levels. If populations in emerging economies adopt similar technologies and lifestyles as currently used in OECD countries, global metal needs would be 3 to 9 times larger than all the metal currently used in the world. If long-term growth trends in population and prosperity are factored in, the global stock of metals in-use by 2050 could be equivalent to 5 to 10 times today's level, permitting supplies (Graedel, 2011).

The growth of demand for some metals is much faster than for others. As society changes, its product and infrastructure requirements also change, along with the demand for a particular metal depending on its use in new, or future products. The annual production involved is already so large that it is hard to imagine. For example, the total crude steel production for 2011 was 1.5 billion tonnes. If this were converted into a 1-mm-thick plate of a specific density of 7.85 kg/dm^3, it would cover a 5-km-wide strip along the Earth's equator.

Despite the vast reserves of several industrially important metals, it is clear that the growing world population – recently welcoming our 7 billionth citizen – cannot keep consuming metals at the rate that is now standard for western industrialized society, without going far beyond what is likely to be sustainable. For instance, the Climate Change impact of the energy used in current annual steel production is estimated to be the equivalent of 3.6 billion tonnes of CO_2.[a]

Altogether, metal production today represents about 8 per cent of the total global energy consumption, and a similar percentage of fossil-fuel-related CO_2 emissions. Obviously, recycling will help decreasing this "footprint" as it usually requires less energy "merely" to re-melt End-of-Life (EoL) prod-

a At 2.3 kg CO_2-equivalent/kg (this number includes recycling).

ucts containing metals such as steel, aluminium, copper etc., a point that is addressed in the following pages.

Due to the scale of their use, iron, steel and aluminium are included in the lists of materials that the International Resource Panel has prioritized for the decoupling of global prosperity from environmental depletion. However, many of the other metals used in smaller quantities have much higher energy and environmental impacts per kilogramme produced (UNEP, 2010a, p.12). A tonne of gold, for example, has a typical CO_2 footprint more than 5,000 times larger than the footprint of a tonne of copper; however, as much more copper is produced, in the end the copper industry emits about 1.3 times more CO_2 per annum than gold production (Hagelüken, 2012). A recent report discussed the economic benefits of recycling, putting forward a clear positive economic case for a Circular economy (Ellen McArthur Foundation, 2012).

While water recycling is not the topic of this report, its relationship to metal production is briefly mentioned as well. After all, when considering the metal cycle, the associated water cycle must also be considered, especially water quality and how it is affected by recycling.

1.2 Accelerated demand for and potential scarcity of some elements and resources

There is an accelerating demand for metals and elements used in new energy technologies (e.g. solar cells, batteries, etc.) and the production of complex electronic devices and networks enabling sustainability. For example, battery technology is of extreme importance today, which may well continue into the near future. Figure 7 shows the exponential growth in battery demand over the past four decades. As a result, there is great interest in securing supplies of the metals and compounds used in batteries, including rare earth elements (REE, specifically La), nickel, cobalt, and lithium and their compounds.

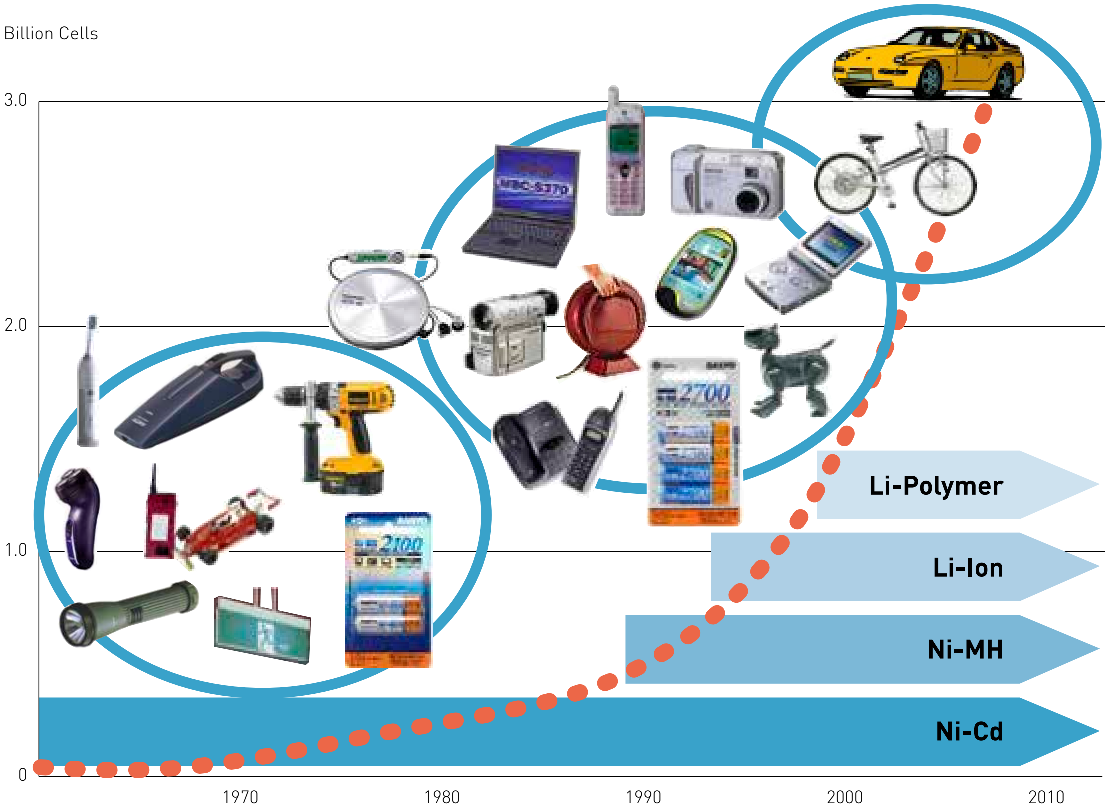


Figure 7: Past exponential growth of different battery technologies (Eurometaux, 2010).

Table 2 shows projected short-term growth of the REE group, indicating that demand already exceeds supply for some metals.

Table 3 sets out some estimates of demand for various scarce and valuable technology metals and their compounds used in emerging (sustainable) technologies; its final column shows how 2030 demand for such metals compares to 2006 demand and 2006 production for all uses.

Table 2:

Rare Earth Elements, their estimated supply and demand in 2016, and projected shortfalls (Lynas Corporation, 2011).

Rare Earth Oxide Group	Demand: Tonnes REO		Production: Tonnes REO	
	Global	ROW @ 35 %	Global	ROW
Light Rare Earths (La, Ce, Pr & Nd)	145,000 t	50,000 t	165,000 t	52,500 t 60,000 t
Medium Rare Earths (Sm, Eu & Gd)	4,250 t	1,500 t	6,000 t	1,000 t 1,350 t
Heavy Rare Earths (Tb, Dy, Er & Y)	14,500 t	5,000 t	7,000 t	300 t 750 t

Black/Red is committed; Blue is Possible

ROW = Rest of the World

Table 3:

Growth in element use projected to 2030. The 2006 and 2030 indicators show the proportion of ETRD compared to 2006 production, e. g. Ga: Indicator 2006 = 28/152 = 0.18 and Indicator 2030 = 603/152 = 3.97) (EU, 2010; BGR, 2010).

Raw material	Production [1] (t)	ETRD 2006 (t)	ETRD 2030 (t)	Indicator 2006	Indicator 2030
Gallium	152 [5]	28	603	0,18 [1]	**3,97** [1]
Indium	581	234	1.911	0,40 [1]	**3,29** [1]
Germanium	100	28	220	0,28 [1]	**2,20** [1]
Neodymium [6]	16.800	4.00	27.900	0,23 [1]	**1,66** [1]
Platinum [7]	255	very small	345	0	1,35 [1]
Tantalum	1.384	551	1.410	0,40 [1]	**1,02** [1]
Silver	19.051	5.342	15.823	0,28 [1]	0,83 [1]
Cobalt	62.279	12.820	26.860	0,21 [1]	0,43 [1]
Palladium [7]	267	23	77	0,09 [1]	0,29 [1]
Titanium	7.211.000 [3]	15.397	58.148	0,08	0,29
Copper	15.093.00	1.410.000	3.696.070	0,09	0,24
Ruthenium [7]	29 [4]	0	1	0	0,03
Niobium	44.531	288	1.410	0,01	0,03
Antimony	172.223	28	71	<0,01	<0,01
Chromium	19.825.713 [2]	11.250	41.900	<0,01	<0,01

ETRD = Emerging Technologies Raw Material Demand

[1]Data updated by the BGR based on new information [2]Chromite [3]Ore concentrate [4]Consumption [5]Estimation of full production in China and Russia [6]rare earth [7]platinum group metals

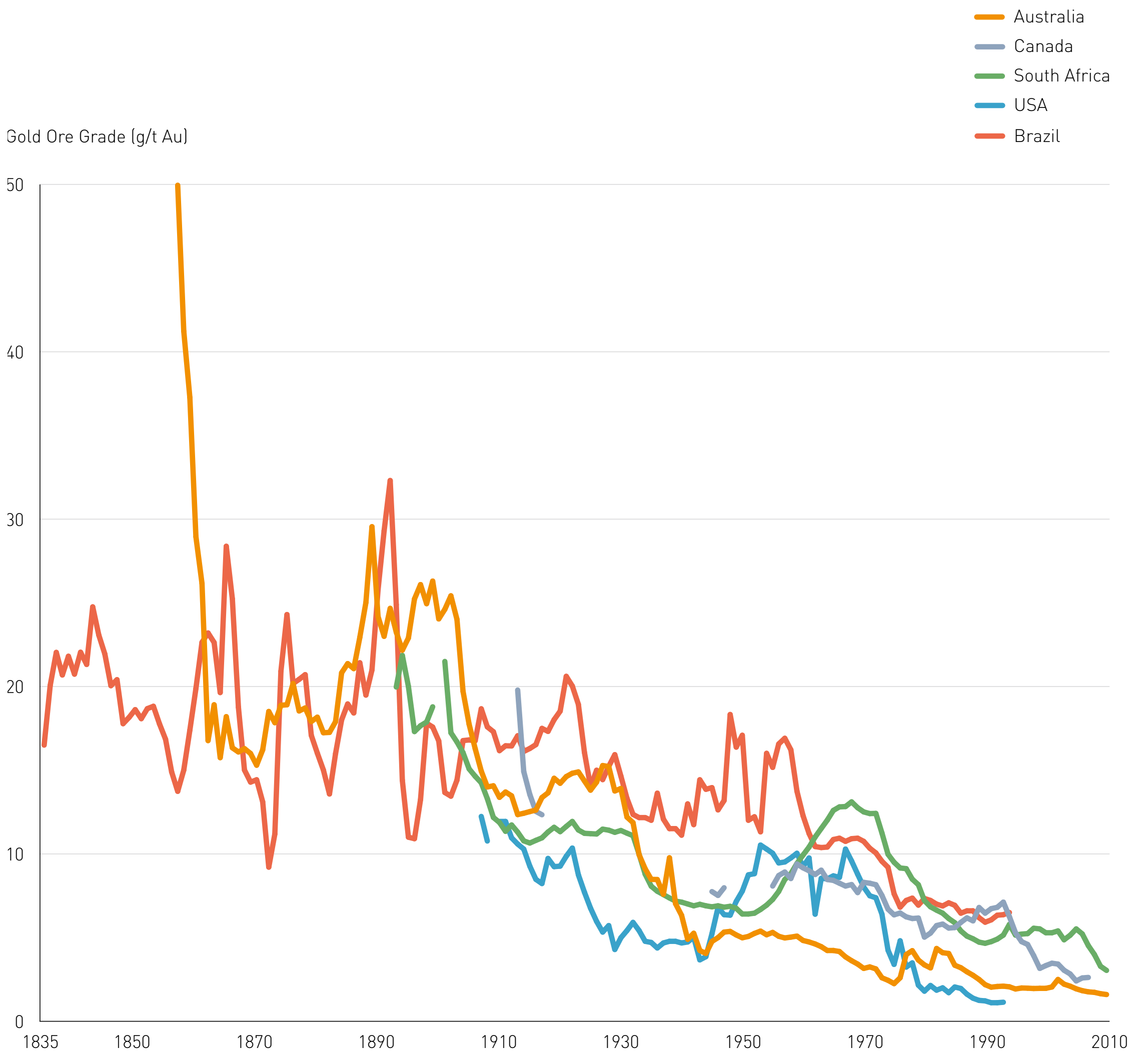
As many of these emerging technologies are essential for the smooth transition to a green economy, meeting the demand for these metals appears to be an essential part of our move to a sustainable, prosperous economy (see Appendix B: Details on Metals found in WEEE, Appendix C: Details on Battery Recycling, Appendix D: Mobile Phone Collection).

1.3 Declining ore grades and the consequences

As global demand for many metals continues to rise, more low-quality ores are mined, leading to an overall decrease in ore grades. Figure 8 shows this decrease in ore grades for gold over time, representative of a trend seen in many metals. The mining of lower-grade ore causes increased energy use and thus rising GHG emissions, even with improved extraction methods. 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, water use and pollution, and energy use (UNEP, 2011c).

Figure 8:

Gold ore grades between 1830 and 2010 (Source: UNEP 2011c, p. 24).



1.4 Increasing stocks in society – importance of their collection

On average, the metal stocks used in more-developed countries equate to between ten and fifteen metric tonnes per citizen. Of this amount, five metals – iron, aluminium, copper, zinc, and manganese – make up more than 98 %. UNEP's report on "Metals Stocks in Society" (UNEP, 2010b) reviewed 54 studies on metal stocks, finding that reliable estimates for in-use stocks exist for only four of those metals: aluminium, copper, iron and lead.

Trends in the production and use of metals show that worldwide stocks of metals in use by society are increasing. At the end of its use, this metal stock is an increasingly valuable resource. Therefore, future metal production must not only focus on ore mining, but also on recycling and the "urban mine", the stock of metals in use above ground. In other words, recycling is a key factor in the future use of metals. However, the "geology" of the "urban mine" is complex and unpredictable and makes economic predictions difficult.

An important point for recycling is that the residence times for these stocks vary substantially. The average residence time for iron in construction steel is several decades, while for indium in electronic appliances it is a few years or less. The effects of product innovation further affect such varying residence times. The steel types added to the stock today contain alloying elements not used decades ago. This is very marked in electronic appliances, where new product generations rapidly follow each other, causing a huge variation in stock properties. Another major point in recycling is the ever-increasing interconnectedness of stocks. The iron stock is getting more connected to REE stock via the addition of high-performance super-alloy steels.

The stocks have different availabilities at the end of their service life. Stocks of industrial-investment and infrastructure goods are more readily available and collectable for recycling than those in private hands.

"Mining" the valuable recycling sources of many technologically valuable elements requires extreme attention to collection, to ensure that End-of-Life (EoL) goods, especially privately owned, do not disappear into landfill or into systems and processes that cannot fully recover the most valuable elements.

1.5 Economics of recycling

"An annual net material cost savings opportunity of up to USD 380 billion in a transition scenario and of up to USD 630 billion in an advanced scenario, looking only at a subset of EU manufacturing sectors." is a conclusion of a recent report by the Ellen McArthur Foundation (2012). Physics primarily determine the potential and limits for metal recycling, thus affecting the economics of recycling. The value of the contained metal (and other materials) has to pay for this physical process as well as for collection, dismantling and other recycling activities. The simple economics of such recycling is based on estimating the true value of recyclates from the maximal recovery into refined metals, alloys and compounds. Recycling is thus driven by the value of the recovered metal (and material). As an example, the approximate recycling revenue achievable for office equipment is given by Table 4, with a detailed cost breakdown for a PC given in the right three columns. Without this material value, recycling will not happen.

Simply said, if EoL recyclates have sufficient economic value, they will be recycled when the appropriate technological infrastructure exists for recovering their contained elements, but not all EoL goods have a high value. Therefore, an economics- and physics-based policy should be careful to provide a framework and business model that breathes life into recycling systems. This will balance their performance in a system that sometimes has to cope with negative costs, due to the low value of some EoL goods.

While economics drive the system (Edwards and Pearce, 1978), local and global policy should promote the use of certified Best Available Techniques (BAT) in the global recycling system, to ensure that resource efficiency is driven to a maximum.

Table 4: The scrap value of office equipment and a simplified cost breakdown for a PC with value of about 1100 €/tonne, including the weight and value of various parts, in 2012 (Hieronymi, 2012).

WEEE Item	Value (€/t)
Desktop PC	~1100
Laptop	~1800
Printer (consumer)	~120
Printer/Copier (commercial)	~330
Flatscreen	~900

Cost Breakdown for Desktop PC	Weight (g)	Revenue (€)
Steel & aluminium	5241	1.41
High grade PC-boards	448	4.03
Low grade PC-boards	397	1.39
Chips and processors	68	2.55
Hard-disk drive	598	0.45
Cables	198	0.28
Other valuable items	444	0.27
Plastics w/o flame retardants	122	0.03
Plastics for energy recovery	226	-0.02
Other fractions with cost	0	-0.00
Labour	3 min	-1.50
Net Revenue for PC	**7742**	**8.61**

1.6 Recycling Rates and their Distribution

Given the predicted growth of metal demand, metal recycling can only mitigate a part of future demand. This is: a) Because of the delay between the initial sale of products and them becoming available as scrap; b) Because the amount of metals put into the market several years ago was lower than today; and c) Because of metal losses during recycling.

Recycling was already referred to in 1556 by the German Agricola, when commenting on forms of metal production in the oldest metallurgical textbook written (Agricola, 1556). For metals in simple products such as steel in cans, or even for steel from EoL vehicles, the recycling rate can be very high (Table 5).

Table 5:

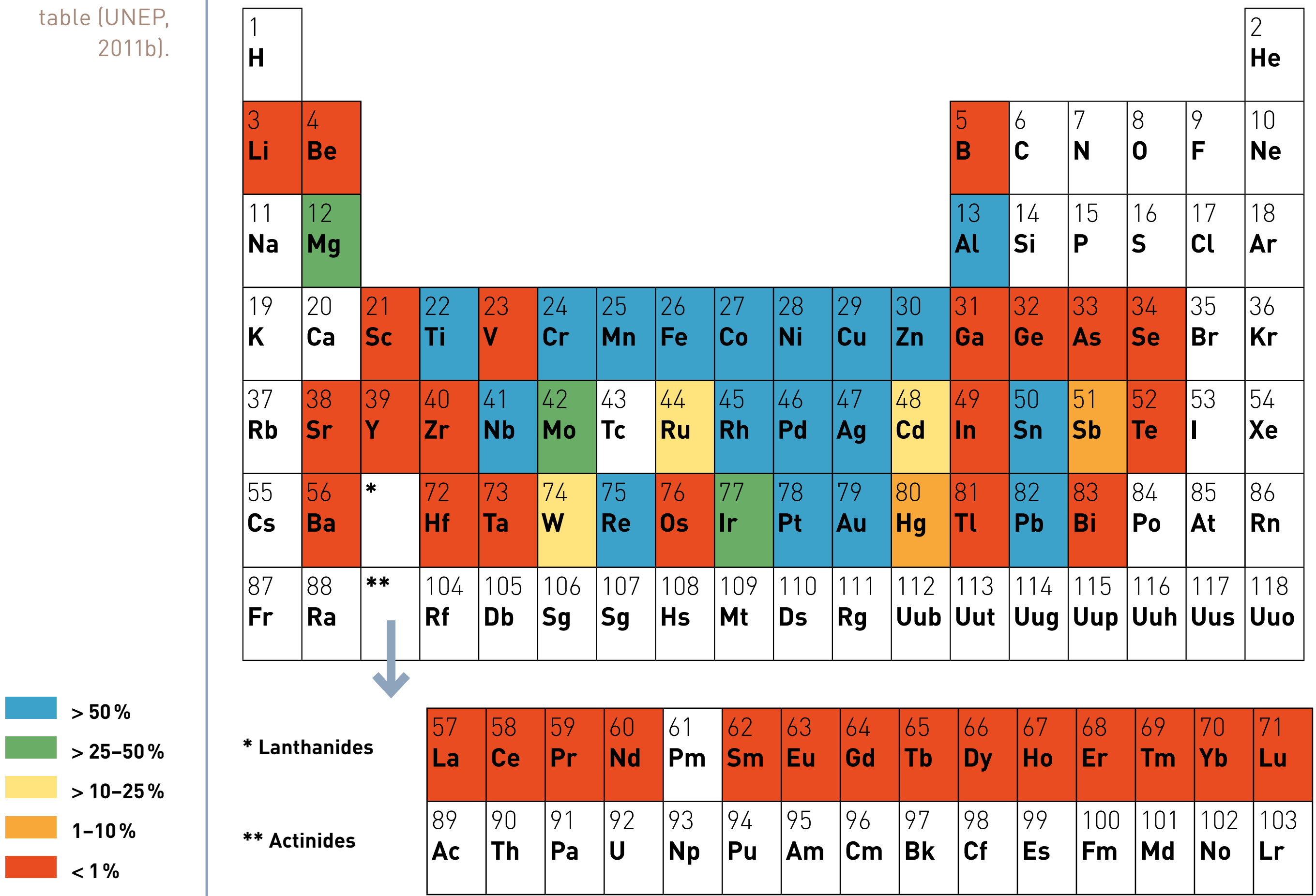
Steel-can recycling rates, left, and steel-recycling rates by sector in the USA (Yellishetty et al., 2011).

Sector	Recovery rate 2007 (%)	Estimated Recovery rate 2050 (%)	Life cycle in years
Construction	85	90	40 – 70
Automotive	85	90	7 – 15
Machinery	90	95	10 – 20
Electrical and domestic appliances	50	65	4 – 10
Weighted global average	83	90	N/A

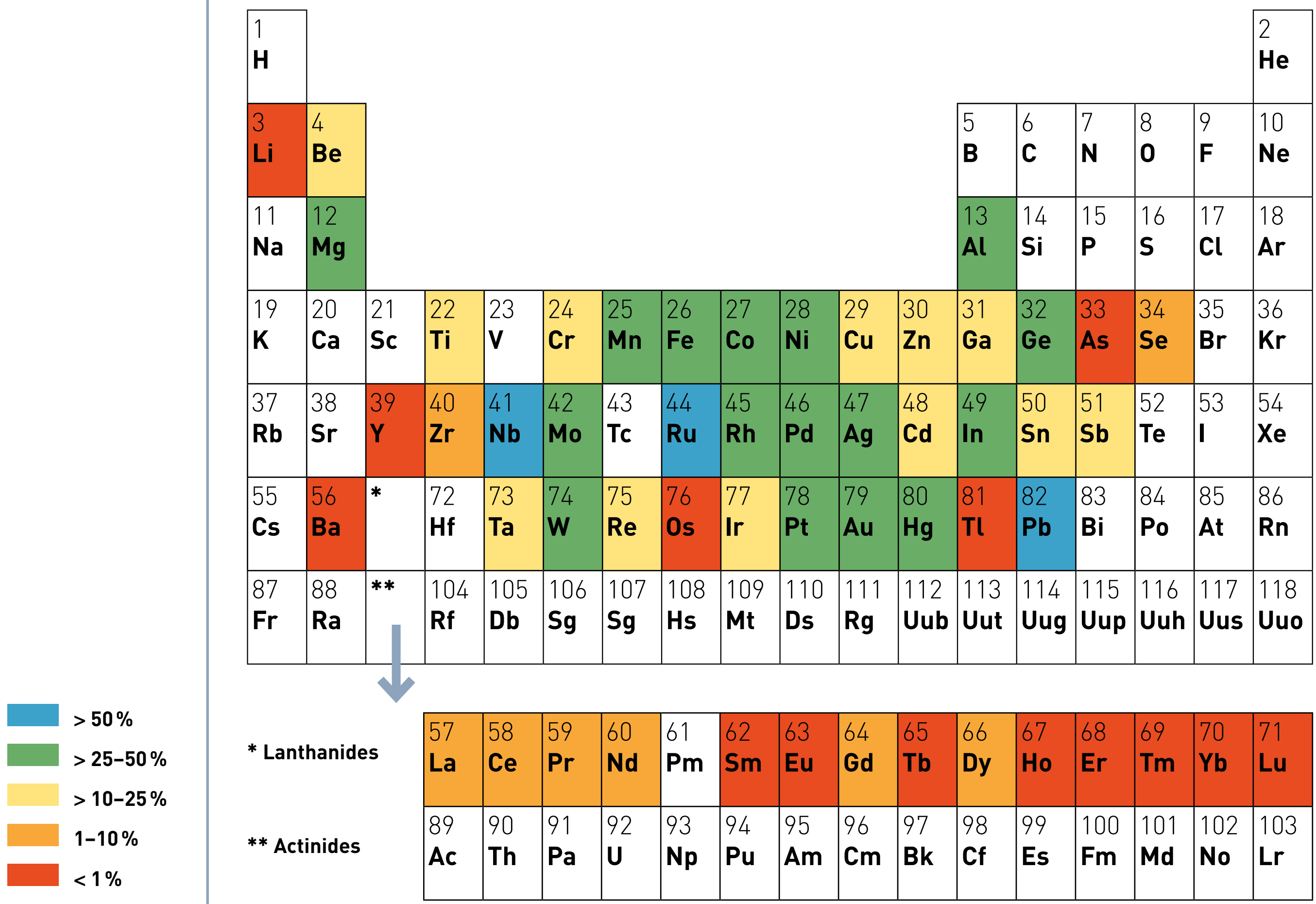
UNEP's report on Recycling Rates of metals (UNEP, 2011b) reported ranges for various recycling rate metrics for sixty metals as summarized by Figure 9, which uses simple one-dimensional recyclate rate definitions. These are, however, limited in their use for single metals and do not reflect the use of a variety of metals in complex products (van Schaik and Reuter, 2004a, 2010), i. e. these recycling-rate definitions exclude non-linear physical interactions in the complete recycling chain and therefore have a limited theoretical basis and little predictive value.

Figure 9:

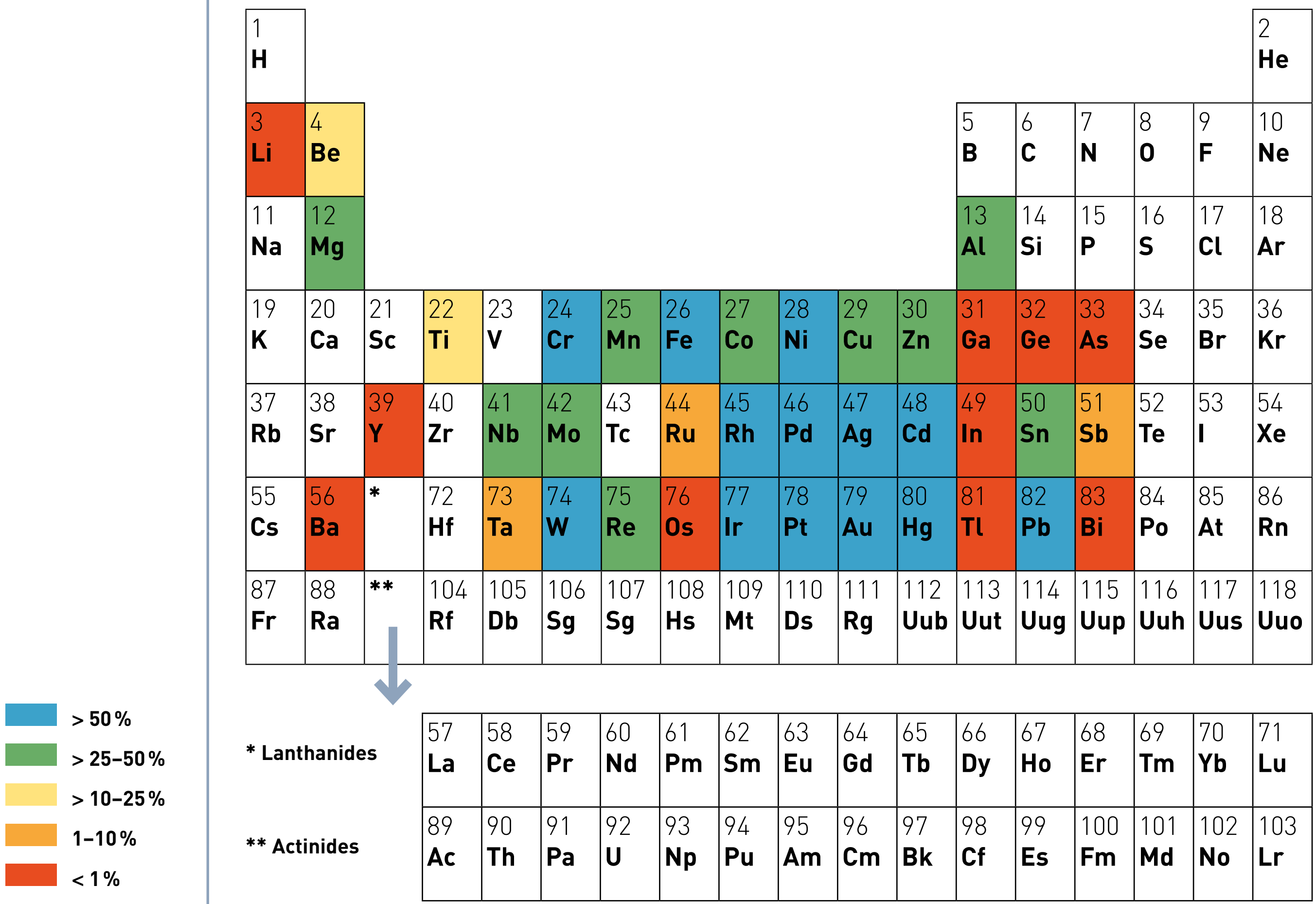
Various definitions of recycling rates and corresponding data for elements in the periodic table (UNEP, 2011b).



EoL-RR for sixty metals: The periodic table of global average EoL (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.



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.



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.

The first of the three periodic tables of Figure 11 is based on one-dimensional recycling-rate definitions and thus provides the EoL recycling rate, i. e the metal percentage from EoL products that returns to the manufacture of new products. The second table shows Recycled Content, or the share of recycled metal of the total metal produced. The last table shows the share of post-consumer recycled metal in the total recycled metal flow.[a]

Considering the complexity of recycling, remarkable accomplishments have been achieved in recycling the most common – mostly bulk and simple – commodity metals.[b] Ingenuity in BAT metallurgy has helped industry pushing the recycling efficiency of ferrous and base metals, e. g. (stainless) steel, aluminium, copper, zinc, lead, nickel, tin, always closer to the limits permitted by physics and thermodynamics, although the industry's continuing use of non-BAT technology leaves room for improvement.

Yet, despite the resulting benefits from an environmental, economic and social perspective, current recycling rates are still rather low for most metals. High scrap-recycling rates seem to exist only for metals mainly used for simple (bulk) products, such as iron and nickel in carbon- and stainless steels, and for precious metals (mostly jewellery and similar simple products). It is also worth noting that there is often a long delay before the recovery of steel and other metals from their use, for example in buildings and other infrastructure, which markedly affects how much metal can be recycled.

Figure 10 shows that EoL recycling rates can be vastly different, depending on the economic actuators used, and whether they focus on material or energy recovery, or both. This indicates that economics rather than simple legislation-imposed rates should drive recycling, as legislation cannot capture fully the complexity of a recycling system. Figure 10 also shows that that there is more than one recycling rate for metals in a product. Depending on whether economics, processing technology, etc., are the main motivation for recycling, the recycling rates will be different. It is thus obvious that these rates reflect, at most, a statistical-distribution range (van Schaik and Reuter, 2004a). In addition, it is also clear that one-dimensional linear recycling-rate definitions (UNEP, 2011b) are, at best, limiting cases, as they cannot consider the complex non-linear interactions found in most recycling systems. We discuss this in more detail hereafter.

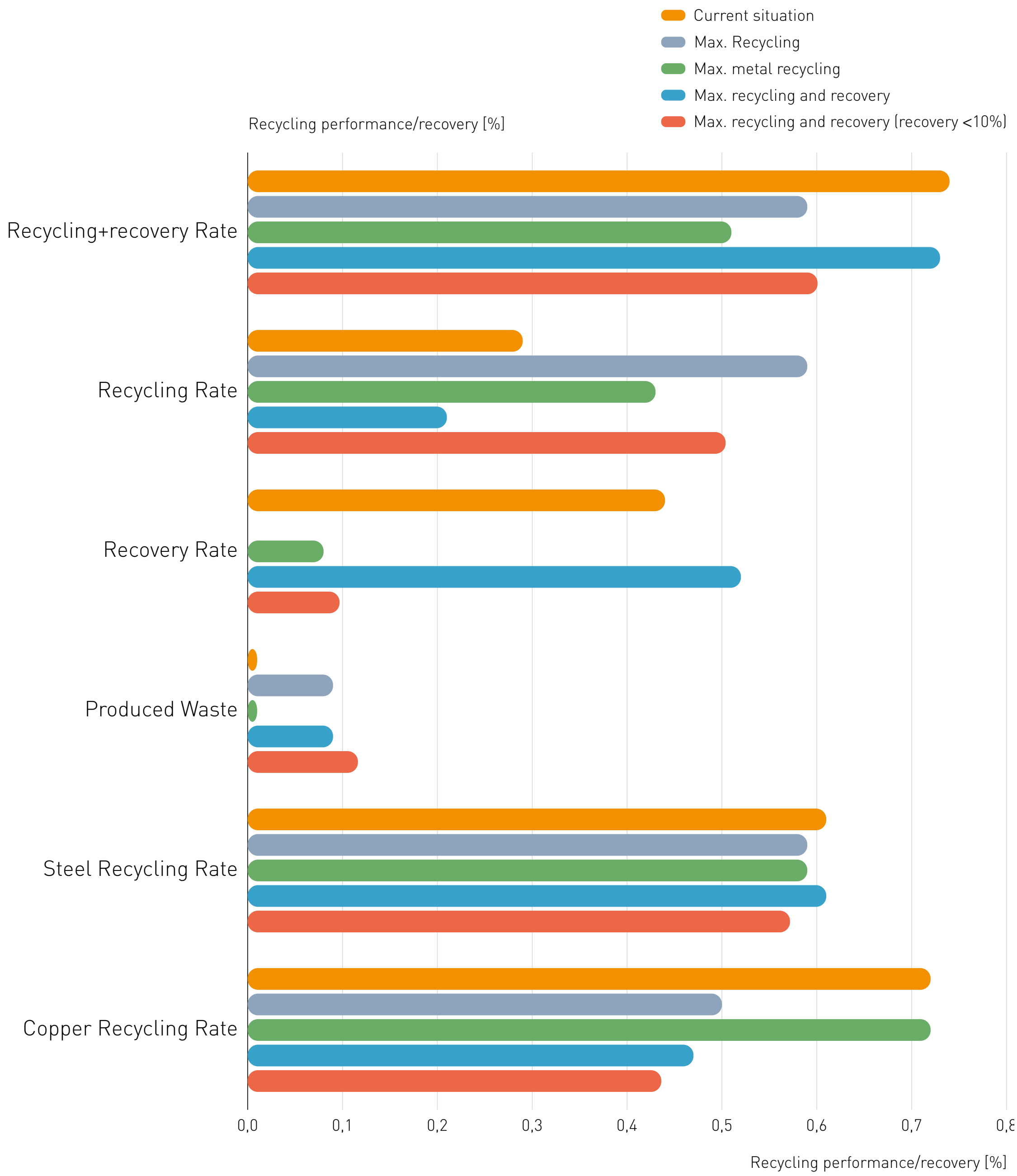
a Note that scrap input quality is crucial in recycling, which is hidden by the methods used to create these rates.

b Bureau of International Recycling (BIR)

Although plastics are not discussed here, their complex interactions with some metals, lowering their recycling rate as well as their energy content, make them an intimate part of metal- and residue recycling. This also affects the recycling rate of plastics, which is generally rather low. In fact, due to their complexity, most plastics today are used in energy-recovery processes (Plastics Europe, 2012).

Figure 10:

Recycling performance calculations as a function of various objectives, constraints and scenarios. Results are expressed per scenario in terms of overall Recycling + recovery rate; Recycling rate (material recycling); Recovery rate (energy recovery); Produced waste; as well as Steel and Copper recycling rates.

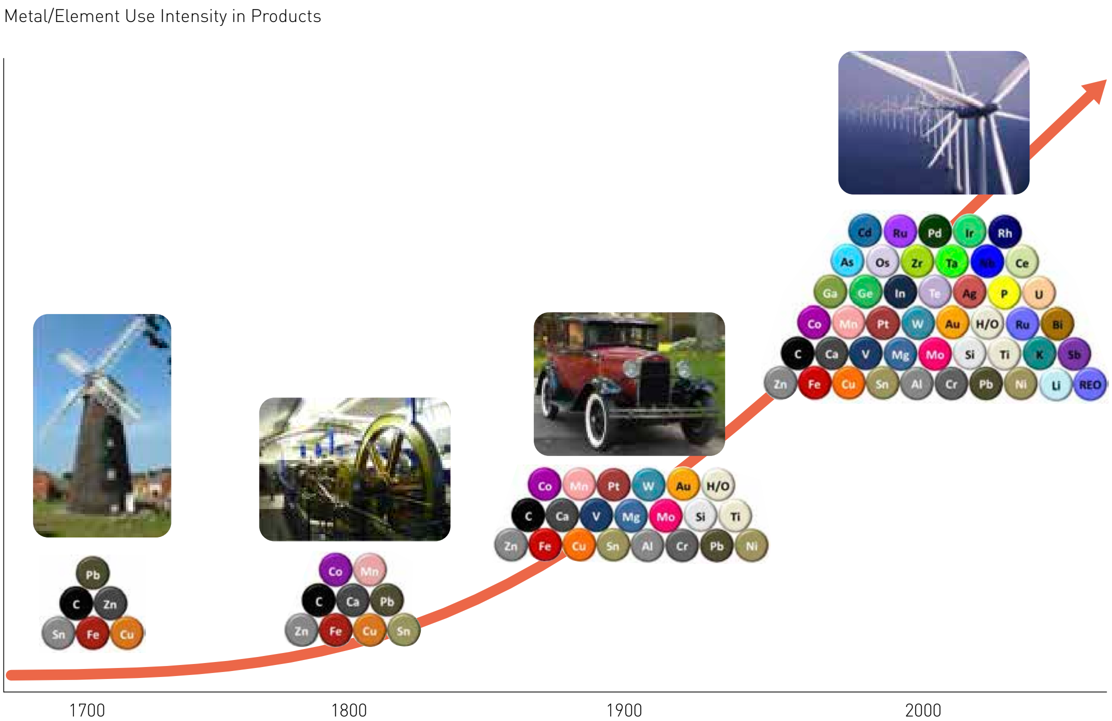


1.7 The impact on recycling of increased material complexity

Materials within products are selected to fulfil a specific function. The increasing complexity of this functional demand has led to the use of an increasing number of elements (Figure 11). To improve functionality, product design increasingly mixes a large variety of different materials within products. Metals are used as chemical compounds, as components in metal alloys, or, in some special cases, as pure metal. Depending on which metals are being alloyed, properties change as shown by Figure 12, with copper being the principal metal alloyed with the various shown alloying elements.

Figure 11:

The ever-increasing use of complex mixtures of metals in products has a key effect on the recyclability of metals (Adapted by Reuter from Achzet and Reller, 2011).



BOX 1:

Alloys

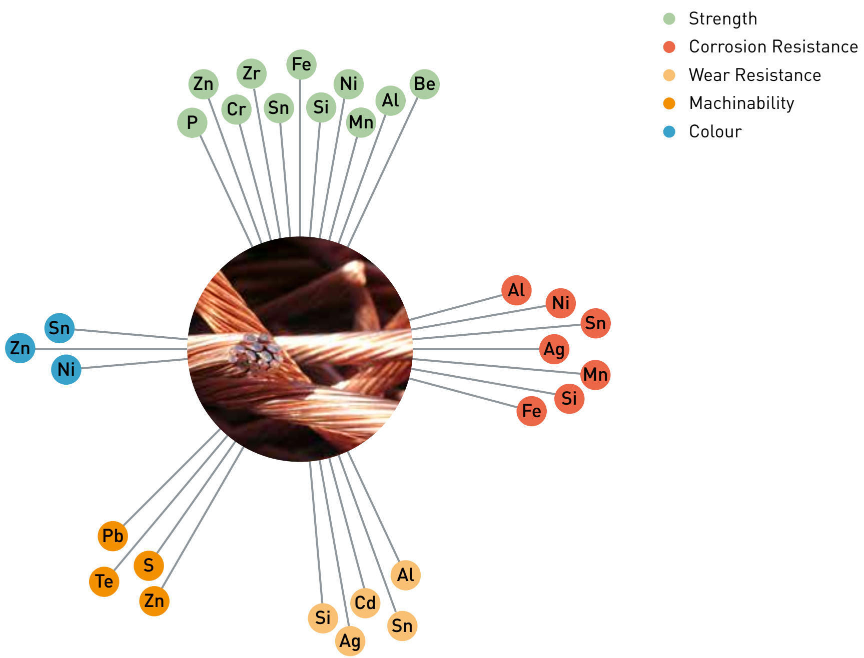
Alloying of metals is done to achieve better strength, workability and for better welding, to name a few reasons. Different alloys improve different properties (Figure 12). An alloy typically contains a major component and several other components in much smaller concentrations. Not all alloys of the same main components will be compatible from a recycling point of view, as is shown by the three examples below:

- Steel: There are about 5000 carbon-steel alloys, from simple construction steel to ultra-high-strength steel, in addition to steels for high-temperature and high-wear uses. Stainless steels also come in six major alloy groups.

- Aluminium is alloyed into seven main wrought alloy groups with varying properties, suitable for making such different products as airplane frames, beverage cans, engines, electrical cables and foils. Aluminium is also used in several types of cast-alloy grades.

- Copper alloys fall in eight main groups, the most common ones being with zinc (brass) and tin (bronze), and together as gunmetal. Copper alloys have moved from the age-old bronze and brass to more than four hundred alloys, with different alloying metals (Figure 12) creating different properties of the Cu-alloys.

Figure 12: Example of alloying elements affecting copper-alloy properties ranging from strength, wear resistance to corrosion resistance (Copper Development Association, 2012).



To achieve more advanced functions, other complex materials structures include combining metal alloys with ceramics and fibres for creating composites, gluing honeycomb structures, making metal foams, depositing thin films, and creating nanoparticle structures. Functionality is often further enhanced by coatings for improving wear, corrosion or fire resistance, for safety and for improving aesthetic aspects.

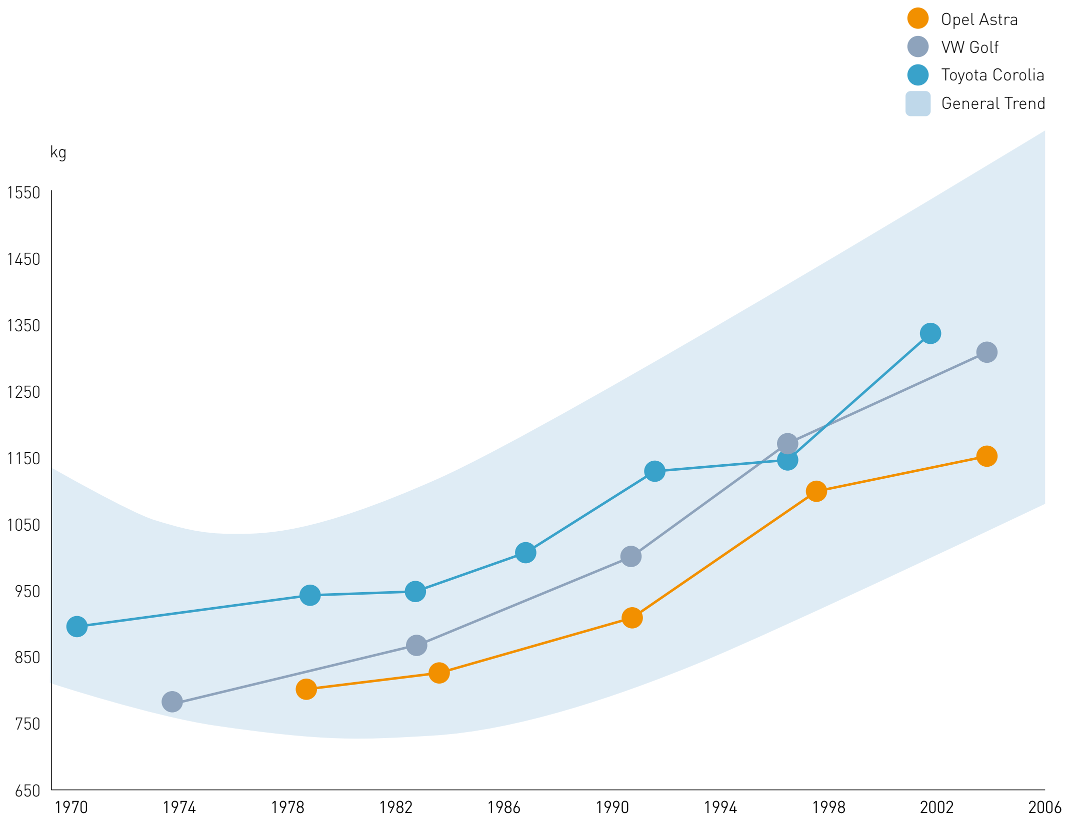
1.8 Implications of product complexity for recycling

Continuous product development affects its design, components and weight. This, in turn, changes its composition and volume for waste-recycling streams, as illustrated in BOX 2 for cars (Figure 13, Tables 6 and 7). This increased use of many compounds, complexly bound together for functional reasons, dictates the physical and chemical properties of the materials available for recycling. In addition, the combining of such different materials also changes from simple rivets or nuts and bolts, to welding, gluing and molecular deposition, dictated by functionality and production cost.

BOX 2:

Car recycling
The average weight of a vehicle in the EU has increased substantially (Figure 13 and as documented by van Schaik and Reuter, 2004a) from 856kg in 1981 to 1207kg in 2001.

Figure 13: The changing weights of cars over the years (International Aluminium Institute, 2007).



BOX 2_c:

The mass of vehicles has increased further, also reflecting the power and capacity changes (Nemry et al., 2008).

Table 6:

Some average data for petrol and diesel vehicles (Nemry et al., 2008).

	Petrol	**Diesel**
Average lifespan (years)	12.5	12.5
Air emission standard	EURO4	EURO4
Average annual distance (km)	16 900	19 100
Average total mileage (km)	211 250	238 750
Average cylinder capacity (cm^2)	1 585	1 905
Average power (kW)	78	83
Average weight (kg)	1 240	1 463
Body model	Saloon	Saloon

BOX 2_d:

Table 7 provides details on the composition of an average vehicle and, for example, the changing aluminium content of a car over time (Nemry et al., 2008; International Aluminium Institute, 2007).

Table 7:

Average composition of a car (Nemry et al., 2008) and changing aluminium content (International Aluminium Institute, 2007) to mitigate the weight gain of vehicles.

Materials (kg)	Petrol	Diesel
Total content of ferrous and non-ferros metals	**819**	**1040**
Steel Basic Oxygen Furnace (BOF)	500	633
Steel Electric Arc Furnace (EAF)	242	326
Total content of iron and steel	**742**	**959**
Aluminium primary	42	43
Aluminium secondary	26	29
Total content of aluminium	**68**	**72**
Copper	9	9
Magnesium	0.5	0.5
Platinum	0.001	0.001
Palladium	0.0003	0.0003
Rhodium	0.0002	0.0002
Glass	**40**	**40**
Paint	**36**	**36**
Total content of plastics		
Polypropylene (PP)	114	114
Polyethylene (PE)	37	37
Polyurethane (PU)	30	30
Acrylonitrile Butadiene Styrene (ABS)	9	9
Polyamide (PA)	6	6
Polyethylene Terephthalate (PET)	4	4
Other	**27**	**27**
Miscellaneous (textile, etc.)	**23**	**23**

BOX 2_e

Materials (kg)		Petrol	Diesel
Tyres			
	Rubber	4	4
	Carbon black	2	2
	Steel	1	1
	Textiles	0.4	0.4
	Zinc oxide	0.1	0.1
	Sulphur	0.1	0.1
	Additives	1	1
	Sub-total (4 units)	31	31
Battery			
	Lead	9	9
	PP	0.7	0.7
	Sulphuric acid	4	4
	PVC	0.3	0.3
	Sub-total	14	14
Fluids			
	Transmission fluid	7	7
	Engine coolant	12	12
	Engine oil	3	3
	Petrol/diesel	23	25
	Brake fluid	1	1
	Refrigerant	0.9	0.9
	Water	2	2
	Windscreen cleaning agent	0.5	0.5
	Sub-total	50	52
Total weight		**1240**	**1463**

BOX 2_f

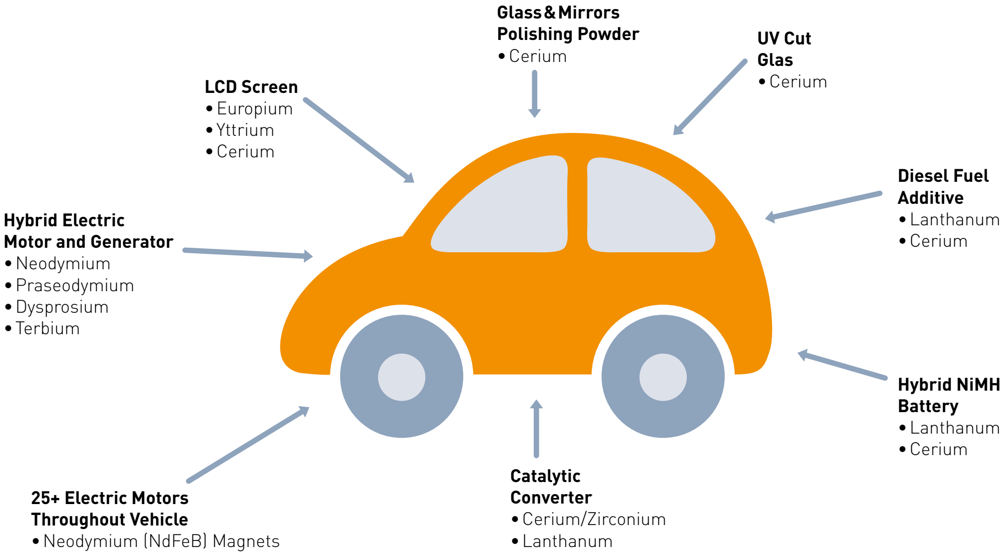
Component Aluminium form*	North America		Europe*		Japan	
	2002 kg/car	2006 kg/car	2002 kg/car	2006 kg/car	2002 kg/car	2006 kg/car
Engines **Castings**	42.0	51.6	36.6	40.3	44.5	45.8
Transmission and driveline **Castings**	28.1	31.5	15.4	16.3	20.5	21.8
Chassis, suspension and steering **Castings**/Forgings/ Extrusions/Sheets	6.2	10.1	8.2	12.5	2.9	3.7
Wheels and spares **Castings**/Forgings/ (Sheets)	22.4	23.6	14.2	17.7	17.8	18.9
Heat exchanger **Sheets**/Extrusions	14.5	14.5	11.0	12.3	12.0	13.6
Brakes **Castings**/Forgings	2.5	3.5	2.7	3.7	1.7	3.4
Closures **Sheets**/Extrusions/ (Castings)	2.0	2.5	2.4	4.0	0.3	1.6
Body and IP beams **Sheets**/Extrusions/ Castings	0.5	0.5	1.8	2.8	0.1	0.2
Heat shields **Sheets**	1.7	1.8	1.2	1.4	0.5	1.0
Bumper beams **Extrusions**	0.6	0.8	1.4	2.8	0.8	0.8
All other components Sheets/Extrusions/ Castings/Forgings	4.1	4.1	3.9	3.9	2.8	3.2
Total	**124.6**	**144.6**	**98.8**	**117.6**	**103.9**	**114.0**

BOX 2_g

The recycling of old cars and vans – End-of-Life vehicles (ELVs) – already plays an important role in closing resource cycles for a variety of critical commodity materials. Yet the modern car is ever more complex, with increasing electronics and other gadgets that render it an extremely complex product. This will become even worse for electric cars; several "critical" materials including Rare Earths Elements (REEs) and Platinum Group Metals (PGMs) in fuel cells will be needed in vehicles such as shown in Figure 14.

Figure 14:

Various REEs and their application in electric vehicles.



The increasingly complex composition of End-of-Life (EoL) scrap, including cars, now includes a multitude of interlinked materials: commodity materials (pure metal, alloys and compounds, such as steel, copper, aluminium, zinc and nickel), plastics, rubber, and scarce elements identified as 'critical' [a] for the future economy. Recycling now commonly has to deal with over 50 elements, rather than a "mere" 20 or so in a zinc concentrate. This has large implications for metal purity and makes recovery of the metals and materials increasingly difficult, in addition to intertwining different metal cycles.

Losses further increase if no metallurgical infrastructure is available for the economic production of high-purity metals and materials from a mix of incompatible elements. For example, some metals contaminate steel and aluminium in which they dissolve during processing and from which they cannot be removed economically, or even not at all for thermodynamic reasons.

This inherent complexity requires a Product-Centric view to recycling rather than a Material-Centric view, a point that will be further discussed later on and also briefly in the following section.

a e. g. the EU Raw Materials Initiative (COM, 2008).

1.9 Simulation and design tools – Design for Resource Efficiency (DfRE)

Product function may require a complex interaction of its components, thus creating complex waste streams. To recover the metals and materials in them requires a thorough understanding of separation physics as well as of the complete system. Design for Recycling (DfR) tools will incorporate these complex physics for showing the inevitable losses due to the functional connections in products. Appendix E: Models and Simulation in Recycling and Appendix F: Physics of Extractive Metallurgy explain this in more detail. Figure 15 shows the underlying thermodynamics and design issues that close the material cycle.

Commonly, DfR makes no sense, as the metal value is too low. In that case, the design effort should bear on Recycling Systems for optimal Resource Recovery and Resource Efficiency. Design for Resource Efficiency should drive the creation of a BAT-based recycling system that is certified to meet this requirement.

Not all the metals can be extracted from EoL goods, for reasons explained here and shown by Figure 4. Common commodity metals like steel, magnesium and copper can be recovered relatively easily, as these are often used in relatively simple applications, but the small amounts of precious/critical/valuable metals in, for example, WEEE can be harder to recover from commonly in excess of 50 elements.

Table 1 considers some of these precious/critical metals and illustrates where they can be recovered with current BAT practices.

Although different appliances may contain similar suites of functional materials loosely called "mineralogies", i.e. contained elements and functional connections, their recovery is not the same and hence their recycling rates are different. Table 1 shows that, depending on the product and the combinations of materials, the recovery of metals may be different due to chemistry, concentration and metallurgical processes being incompatible.

Figure 15: 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. As there are so many different combinations of materials in End-of-Life products, only physics-based modelling can provide the basis for valid predictions. In essence, primary metallurgy is situated in a segment a complete processing plant, while the complexity of consumer product mineralogy requires an industrial ecological network of many metallurgical production infrastructure to maximize recovery of all elements in end-of-life products (Reuter and van Schaik, 2012a&b; Ullmann's Encyclopaedia, 2005).

Society's Essential Carrier Metals: Primary Product Extractive Metallurgy's Backbone (primary and recycling metallurgy). The metallurgy infrastructure makes a "closed" loop society and recycling possible.

Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy) Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

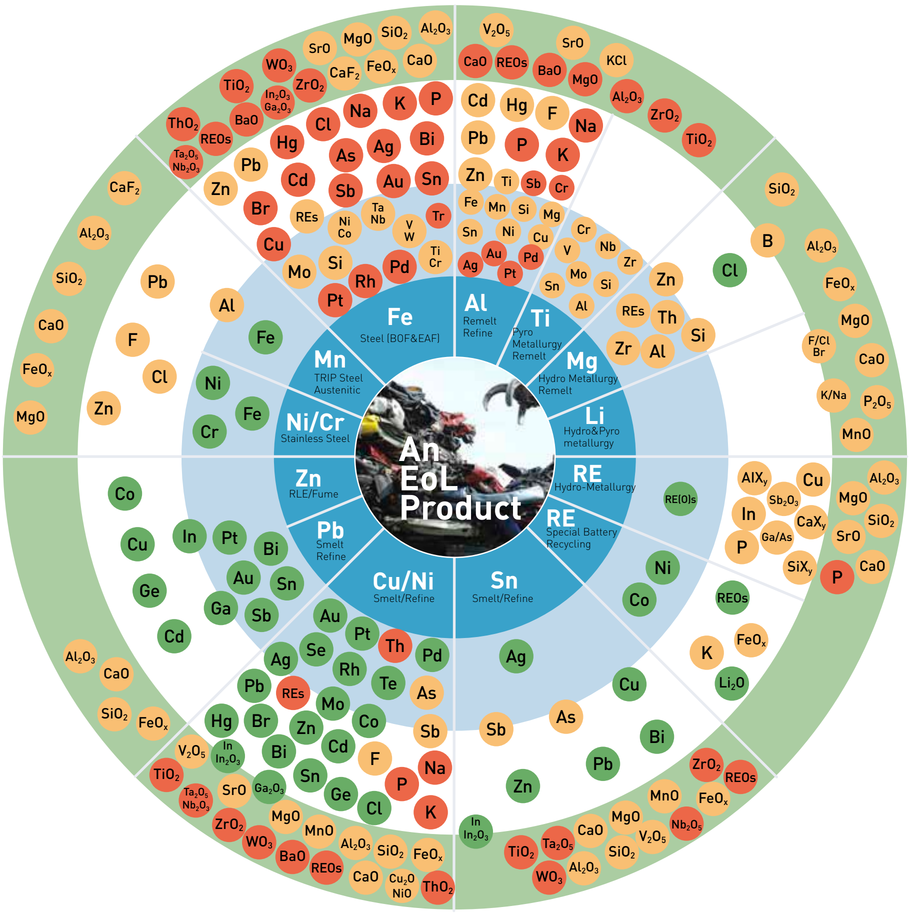
Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy) Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

Mainly to Benign Low Value Products Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

El **Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.

El **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag/slag also intermediate product for cement etc.).

El **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.



Therefore, forced recycling-rate quotas for especially the minor metals are a fallacy, and the focus should rather be on maximizing recovery of the elements. This suggests that KPIs for recycling should have a monetary basis rather than a prescriptive recycling-rate basis. Providing a correct economic basis, BAT infrastructure and market driven policy (for example enforcing zero landfill) will help maximizing recovery and recycling rates.

In any case, all metallurgical plants have always tried to recover valuable elements. After all, if there is an economic incentive to do so, recovery will happen.

BOX 3:

Material-Centric Approaches

Allwood et al. (2011) discussed a Material-Centric perspective. This refers more to alloys and very "simple" products within the constraints and confines of a Carrier Metal segment, which is also mainly the basis for the data on Figure 4. This approach usually works well for bulk materials and alloys, but not for the more than 50 elements in many of our modern products. These are not concentrated in, for example, an alloy to impart a specific function, but are rather a complex mixture of alloys, compounds, metals, etc., that collectively imparts a functionality to the product. Often, these elements are thermodynamically incompatible, thus requiring them to be glued, riveted or bolted together.

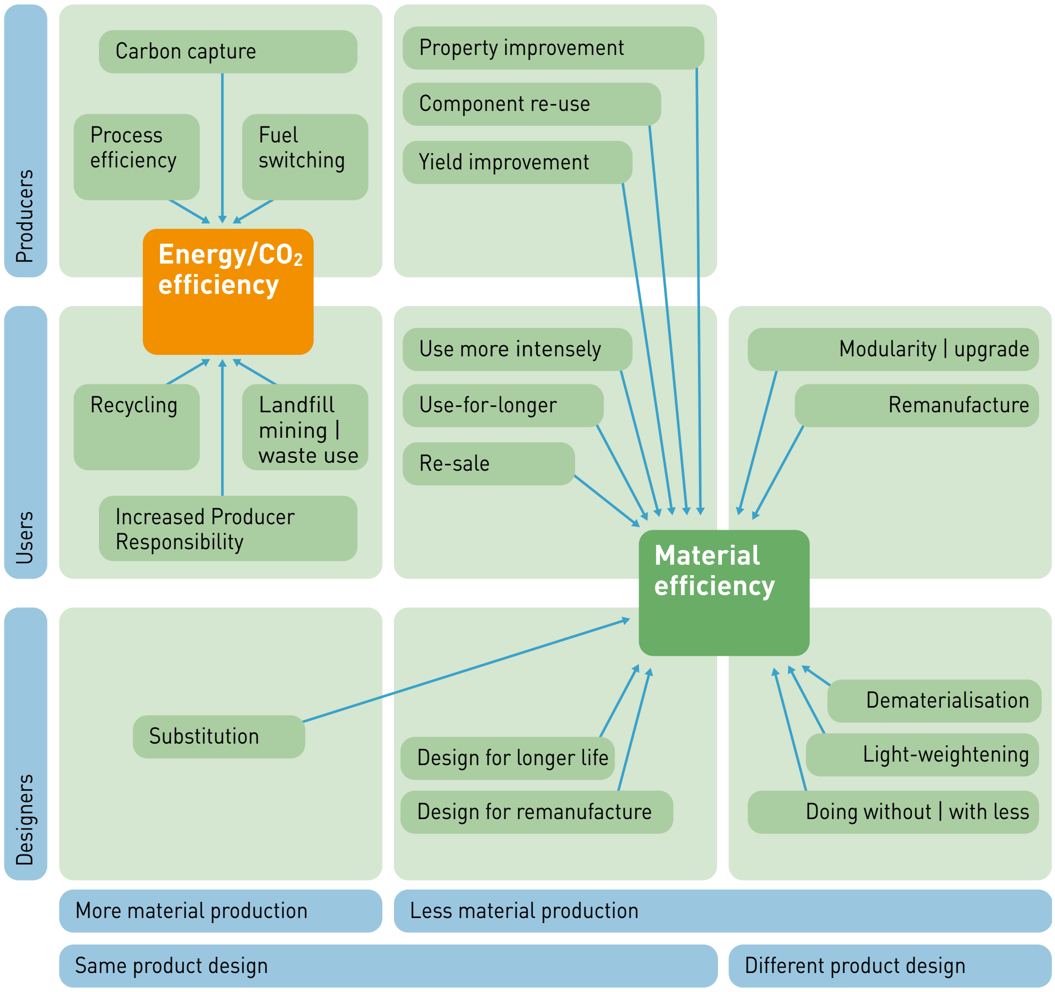


Figure 16:

Material efficiency vis-à-vis energy efficiency (Allwood et al., 2011) in a context of Material and Product-Centric Recycling.

This complexity of connections and products means that parts, functional groups and sections cannot just simply be remanufactured, repaired, etc., as shown in Figure 16, leading to material efficiency. Any one element or part can affect the whole and its material efficiency. While dematerialization is an important avenue to resource efficiency, this will affect the economics of recycling materials from complex products. Furthermore, the move to nano-technology as an extreme case of dematerialization will irrecoverably dissipate valuable materials, although it can be argued that these are small amounts that will have no effect on the overall materials balance.

1.10 Recycling Data

Design for Resource Efficiency not only requires detailed knowledge on the total flow of materials and recyclates, but it also requires these data as (statistical) standard-deviation and average-distribution values for each flow. The shape of this distribution (Normal, Weibull, or even multi-modal) must be known as well. In addition, as the metals contained in recyclates are the economic target, their average and standard-deviation distributions in the input recyclates should be known as well.

Such understanding within a context of physical and metallurgical recycling technology and its economics, permits the calibration of detailed mass-balance models (van Schaik and Reuter, 2004a, 2007a&b, 2010). It also facilitates the construction of detailed Design for Resource Efficiency models for maximizing resource efficiency, a point already discussed in detail by Buckminster Fuller (1981). Such theoretical knowledge is common practice in standard mineral processing and extractive metallurgy, used daily for optimizing metal recovery at all levels of the business. While the theoretical basis was developed for dealing with physical recycling, it is not generally applied. To advance recycling, the theoretical basis of physical recycling will have to be applied in industry, in order to match the sophistication of classic mineral processing that now is on par with metallurgical processing.

Identifying the detailed metal, compound, etc., contents in all flows will help optimizing the recycling system, as is already the case for the maximum recovery of metals in concentrates from known ore and product streams, giving a rather precise mass balance for all total, compound and elemental flows.

1.11 Some policy trends

Given the above-described trends in metal content of waste-recycling flows, policies in many parts of the world increasingly aim at better recycling efficiency. Government policies for waste treatment were usually first put in place to tackle environmental problems caused by waste dumping or poor treatment. Today, they increasingly move toward extracting valuable materials and energy from waste streams.

Recycling can have two goals: a means for End-of-Life management and securing a material resource supply. Figure 17 shows these trends for consumer waste (Municipal Solid Waste, MSW) and industry waste (IW), indicating estimated future evolution. However, care must be taken to ensure that the "Urban Mine" has a well-defined mineralogy. It is already difficult to recover metals economically from the Earth's minerals, but "chaotically" dumped materials in a landfill further complicate their economically viable "mining", due to a poorly described, for the most part unknown and large heterogeneous composition.

Figure 17:

Schematic overview of the historic and (potential) future evolution of waste management. (Jones, 2008; Jones and De Meyere, 2009; Jones et al. 2012).

MSW: Municipal Solid Waste

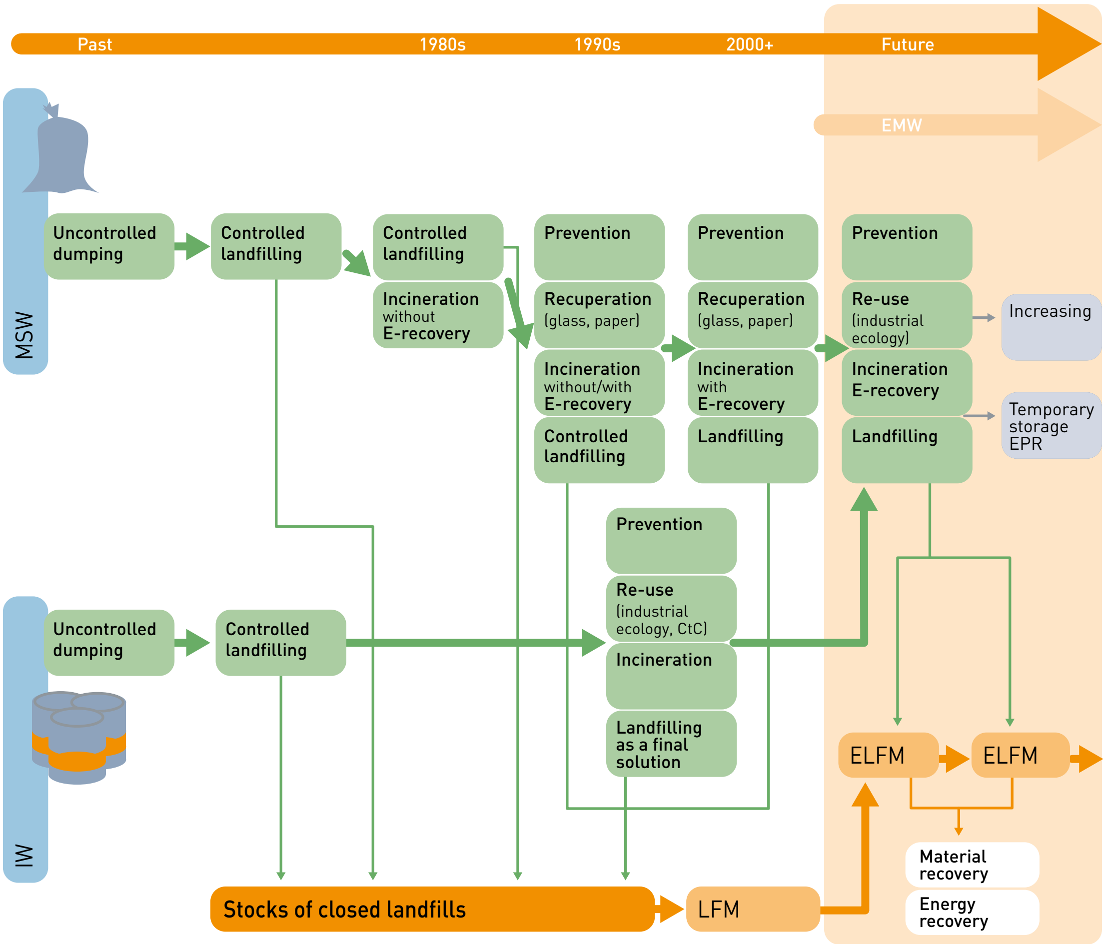
IW: Industry Waste

LFM: Landfill Management

ELFM: Enhanced Landfill Management

EWM: Enhanced Waste Management

EPR: Extended Producer Responsibility

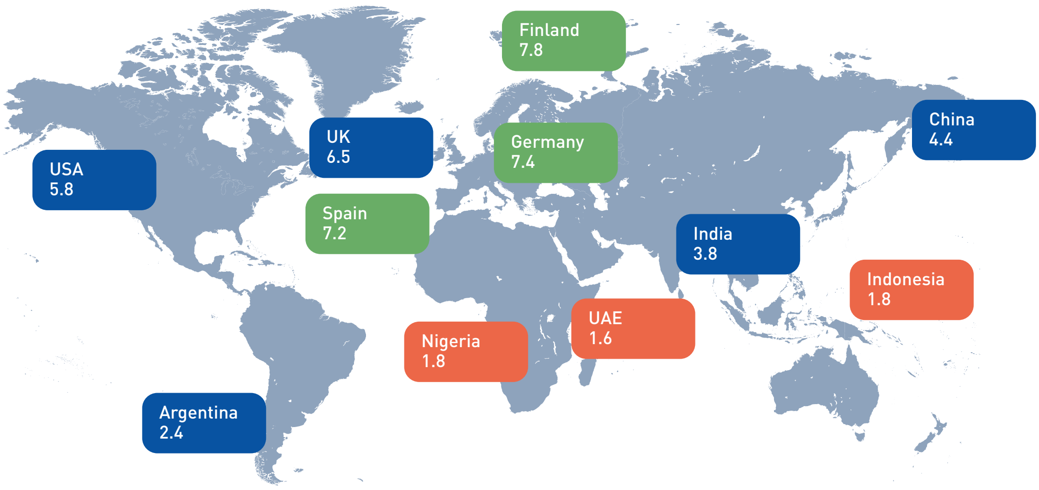


Recycling legislation for EoL home appliances, especially for the larger ones (air-conditioners, refrigerators, TV sets or washing machines), now exists in various parts of the world (e.g. European Commission). In Japan, EoL legislation has been effective since April 2001. Though this law had more an end-of-life-management motivation, the Japanese government now has implemented various recycling policies for securing resources. This has been one of the four important approaches in Japanese mineral resource policy: securing stable supplies from (mostly overseas) mines, material substitution, stockpiling and recycling.

As a result of such legislation, the recycling of products made of one material type, such as newspapers, glass or plastic bottles, or metal cans, is already common practice in many countries, and becoming more so. More complicated products, such as cars, batteries and electronic products, are now slowly entering the recycling stream as well. These, however, require a careful policy rethink for maximizing resource efficiency. Figure 18 shows how the recycling of 11 products (paper/cardboard, plastic bottles, cans, glass, metals, clothes/shoes, cell phones, batteries, television sets, refrigerators and computers) varies for various countries, showing that there is much room for increasing resource efficiency.

Figure 18:

Mean number of items out of 11 that are being recycled (Damanhuri, 2012).



Recycling is one part of a wider transition to a 'Green' or 'Resource Efficient' Economy. Many nations and international organizations have seen the benefits from a well-paced move to an economy that delivers social progress, while using fewer natural resources. The UN's own Green Economy Initiative and the OECD's Green Growth Strategy are two examples. Another one is China's 12th 5-year plan (released in 2011) that has a strong focus on reducing the material and energy intensity of its economy. Finally, the EU has prioritized increasing resource efficiency as a key part of its economic goals for 2020, and has laid out its strategy for achieving this goal.

The World Business Council for Sustainable Development (WBCSD) supports increasing material efficiency as the route to the future. It promotes recycling within a wider strategy of longer and more efficient use of materials and "products" in improved designs, through repair, re-manufacture, reuse, re-sale, modularity, dematerialization, and light-weighting (Ellen McArthur Foundation, 2012). While this report (ibid.) discusses recycling, it does so more from a Material (& Metal)-Centric point of view, without addressing in detail the various limitations for providing a complete picture of recycling.

1.12 Summary: Enabling and achieving resource efficiency

In summary, we discuss how the environmental footprint of society can be minimized, by maximizing resource efficiency on a technological and economic basis as well as through a deep understanding of physics.

It is obvious that, when considering metals, all other resources, such as water, land, energy, etc., come into play as well. Hereafter, we briefly discuss the inherent multi-level complexity of the system, providing indications how this system can be optimized for maximizing resource efficiency.

This report's intention is also to empower the highest level of recycling. The opportunity is therefore also discussed of fostering clean recycling (inclusive of dismantling) in the developing world.

2. Recycling Opportunities

Recycling can greatly increase the amount of available metals for society, provided the potential sources and recycling technologies exist. The opportunities described below indicate why increased recycling is one of the important ways that the global economy can continue to sustain itself in the future.

The benefits of recycling are potentially very significant: it reduces the future scarcity of some high-demand elements, creates economic value, reduces greenhouse gas emissions and limits other environmental harm. It forms a vital part of the transition to a green economy, where societal progress is decoupled from unsustainable natural-resource depletion, and, last but not least, it provides a source of metals in high demand for sustainability-enabling technology.

The opportunities come from a wide range of recycling sources. Some of these are described below, but the reader can also consult Appendix A: "Details on Recovery of Metals from Recyclates", Appendix B: "Details on Metals found in WEEE", Appendix C: "Details on Battery Recycling", and Appendix D: "Mobile Phone Collection".

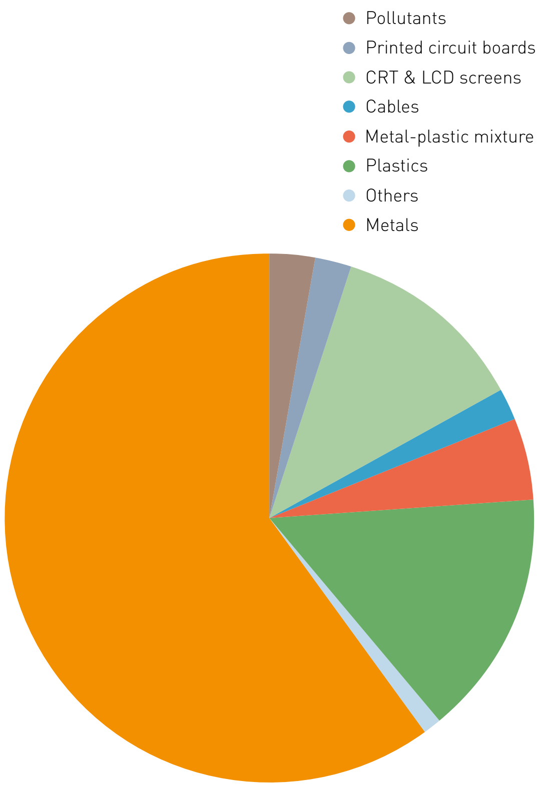
2.1 Recovery of high-tech and high-value metals from different sources

2.1.1 Waste electronic and electrical equipment, lamps, LEDs, batteries etc.

One of the most promising recycling sources is waste electronic and electrical equipment (WEEE), containing many of the metals with rising demand. It is the post-consumption waste of consumer and business devices like mobile phones, computers, screens, monitoring appliances and kitchen appliances. Figure 19 shows just how much of WEEE is typically metal – not only the 60 % 'Metals' slice, but also the metal and metallic compounds found in printed circuit boards, CRT and LCD screens, cables and metal-plastic mixes. See also Appendix B: "Details on Metals found in WEEE", Appendix C: "Details on Battery Recycling", and Appendix D: "Mobile Phone Collection".

Figure 19:

Typical material fractions in WEEE (Ongondo et al., 2011).



Box 4:

Various elements contained in WEEE
A wide range of metals, including those now used in electronics, is found in EEE and hence in WEEE. Table 8 gives some indication of the wide application of metals in various products.

Table 8:

The use of different metal/ elements in EEE.

Metal/Element	Metal usage in EEE
Ferrous metal	Casings, as major element in magnets, magnetic coils etc.
Aluminium	Casings, partly cables
Magnesium	Casings, body of cameras
Copper	Cables, connectors
Gold	Contacts, transistors, diodes, switches, transistors, integrated circuits
PGM (Palladium, Platinum, Rhodium)	(Multilayer-)capacitors, connectors, contacts, transistors, diodes, Ag-Cu-Pd-soldering
Silver	Lead-free soldering, capacitors, contacts, batteries, RFID-chips, photovoltaic cells
Antimony	Alloying element, additive for flame retardants, soldering element, semiconductor technology and photocells "Transparent Conductive Oxide" (ATO), Antimony oxide as additive in cathode ray tube glass
Gallium	Semiconductors, GaAs, GaN, GaP, InGaN in Laser diodes LEDs, photo detectors Photovoltaic cells, integrated switches, semiconductors
Germanium	Photovoltaic cells, glass fibre, optical glasses glass fibre, semi-conductive chips
Indium	Indium-tin-oxide (ITO) in flat panels, thin-film-photovoltaic cells, semiconductors, InGaN in LEDs
Cobalt	Lithium-ion-&NiMH batteries magnets (SmCo, NdFeB)
Rare Earth Elements (Neodymium, Dysprosium, Scandium, Lanthanum and Yttrium)	Magnet, compact florescent bulbs, phosphors, fuel cells, NiMH-Batteries
Tantalum	Capacitors
Beryllium	Beryllium-copper-alloys, beryllium oxide-ceramics, metallic beryllium
Tellurium	Thin film photovoltaic cells, photoreceptors, photoelectrical devices
Tungsten	Tungsten carbide, electrodes, cables and electrical components, additives in cathode ray tube glass
Niobium	Niobium-steel alloys, super alloys magnets, capacitors
Tin	Lead-free soldering, Indium-tin-oxide (ITO) in liquid crystal display and Photovoltaic cells, miniaturized capacitors

With increasing GDP, world consumption of these products accelerates and the size of their waste streams increases. WEEE volumes are already enormous, estimated to be between 20 to 50 million tonnes per annum, or 3 to 7 kg/person each year (assuming 7 billion people).

In Europe alone, the amount of WEEE generated today is about 12 million tonnes per year. This is expected to increase in the coming decades at a rate of at least 4 % per annum; about three times higher than the growth of municipal waste. Table 9 provides an overview of a potentially very large global metal stream.

The European pre-processing industry treats WEEE using a combination of manual and mechanical methods, with varying efficiency. Much innovation is possible for improving pre-processing performance and incentives must be created for treating all WEEE with certified BAT technology. Part of the WEEE is exported, possibly under dubious conditions, for reuse/recycling under inadequate working and environmental conditions that do not necessarily result in recycling much of the valuable content.

Table 9_a

E-waste generation in different countries (Ongondo et al., 2011).

Country	Generation (tonnes/year)	Per capita generation (kg/inhabitant)	Reported discarded items	Collection and treatment routes
Germany	1,100,000 (2005)	13.3	Domestic WEEE	PWMA, retailers takeback
UK	940,000 (2003)	15.8	Domestic WEEE	DTS and PCS
Switzerland	66,042 (2003)	9	Diverse range of WEEE	SWICO, S.EN.S, SLRS
China	2,212,000 (2007)	1.7	Computers, printers, refrigerators, mobile phones, TVs	Mostly informal collection and recycling
India	439,000 (2007)	0.4	Computers, printers, refrigerators, mobile phones, TVs	Informal and formal
Japan	860,000 (2005)	6.7	TVs, air conditioners, washing machines, refrigerators	Collection via retailers
Nigeria	12,500 (2001–06)	–	Mobile phones chargers and batteries	Informal
Kenya	7,350 (2007)	0.2	Computers, printers, refrigerators, mobile phones, TVs	Informal
South Africa	59,650 (2007)	1.2	Computers, printers, refrigerators, mobile phones, TVs	Informal and formal

Table 9_b

E-waste generation in different countries (Ongondo et al., 2011).

Country	Generation (tonnes/year)	Per capita generation (kg/inhabitant)	Reported discarded items	Collection and treatment routes
Argentina	100,000	2.5	Excludes white goods, TVs and some consumer electronics	Small number of takeback schemes, municipal waste services
Brazil	679,000	3.5	Mobile and fixed phones, TVs, PCs, radios, washing maschines, refrigerators and freezers	Municipalities, recyclable waste collectors
USA	2,250,000 (2007)	7.5	TVs, mobile phones, computer products	Municipal waste services: a number of voluntary schemes
Canada	86,000 (2002)	2.7	Consumer equipment, kitchen and household appliances	A number of voluntary schemes
Australia	–	–	Computers, TVs, mobile phones and fluorescent lamps	Proposed national recycling scheme from 2011; voluntary takeback

WEEE: waste electrical and electronic equipment;
TV: television;
PWMA: public waste management authorities;
DTS: distributor takeback scheme;
PCS: producer compliance scheme;
SWICO: Swiss association for information, communication and organisation technology;
S.E.N.S: Swisss foundation for waste management;
SLRS: Swiss light recycling foundation

High-value or potentially scarce metals are not equally distributed in different scrap equipment. Specifically, small WEEE will have high concentrations of precious and specialty metals (Table 10).

Table 10:

Value versus weight distribution of different materials in various devices (Hagelüken et al., 2009).

Weight-share	Fe	Al	Cu	plas-tics	Ag (ppm)	Au (ppm)	Pd (ppm)
Monitor-board	30 %	15 %	10 %	28 %	280	20	10
PC-board	7 %	5 %	18 %	23 %	900	200	80
Mobile phone	7 %	3 %	13 %	43 %	3000	320	120
Portable audio	23 %	1 %	21 %	47 %	150	10	4
DVD-player	62 %	2 %	5 %	24 %	115	15	4
Calculator	4 %	5 %	3 %	61 %	260	50	5

Value-share	Fe	Al	Cu	Sum PM	Ag	Au	Pd
Monitor-board	4 %	14 %	35 %	47 %	7 %	33 %	7 %
PC-board	0 %	1 %	13 %	86 %	5 %	69 %	12 %
Mobile phone	0 %	0 %	6 %	93 %	11 %	71 %	11 %
Portable audio	3 %	1 %	73 %	21 %	4 %	16 %	3 %
DVD-player	15 %	3 %	30 %	52 %	5 %	42 %	5 %
Calculator	1 %	4 %	10 %	85 %	6 %	76 %	3 %

Printed circuit boards can form a significant part of EEE, providing a wealth of metals, compounds and alloys (Figure 20). Together, mobile phones and desktop personal computers (PC) account for 39 % of the precious metal in WEEE, based on data for 2007 for Germany (Chancerel and Rotter, 2009a&b). The global sales volumes of these devices suggest that they contain significant metal volumes (Table 11). However, adequate collection of all devices remains a significant challenge for tapping this large source of material.

Figure 20:

Metals found in printed circuit boards.

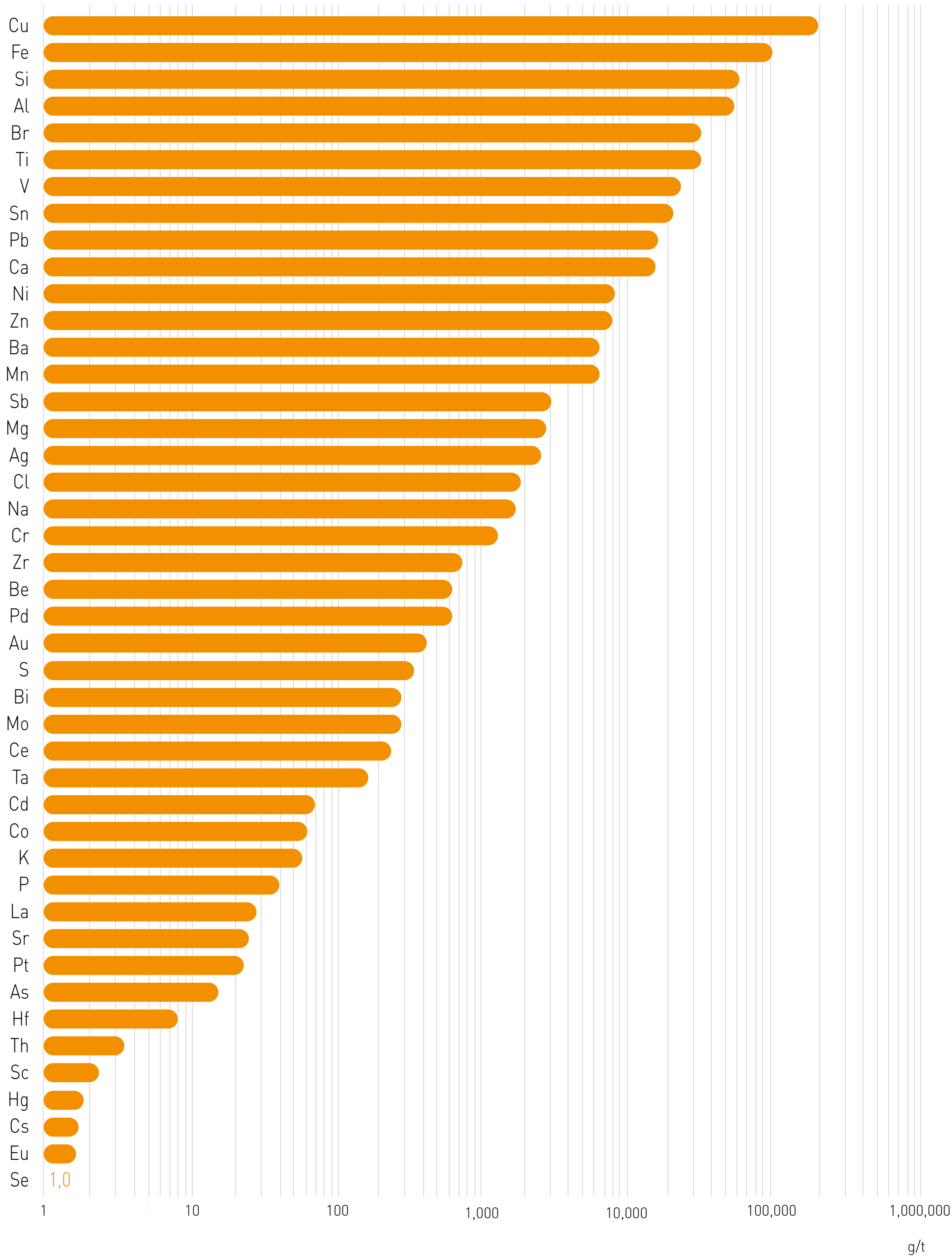


Table 11:

Examples of composition of mobile phones, PCs and laptops and the impact on 'metal demand' based on 2010 sales (UNEP, 2009; Hagelüken and Corti, 2010).

Mobile phones (a)				
1600 million units/year				
x 250 mg	Ag ≈	400 t	Ag	
x 24 mg	Au ≈	38 t	Au	
x 9 mg	Pd ≈	14 t	Pd	
x 9 g	Cu ≈	14,000 t	Cu	
~1300 million Li-Ion batteries				
x 3.8 g	Co ≈	6100 t	Co	

PCs & Laptops (b)			
350 Million units/year			
x1000 mg	Ag ≈	350 t	Ag
x 220 mg	Au ≈	77 t	Au
x 80 mg	Pd ≈	28 t	Pd
x ~500 g	Cu ≈	175,000 t	Cu
~180 million Li-ion batteries			
x 65 g	Co ≈	11,700 t	Co

Urban Mine (a+b)		
	Mine production	Share
Ag:	22,200 t/a	3 %
Au:	2,500 t/a	5 %
Pd:	200 t/a	21 %
Cu:	16 M t/a	1 %
Co:	88,000 t/a	20 %

Fluorescent lamps also contain various materials and elements, including Rare Earths, e. g. yttrium, lanthanum, cerium, europium, terbium and gadolinium (USGS, 2002; 2010a; 2010b; 2010c) in phosphorescent or fluorescent powders, while LEDs also contain an interesting suite of elements and compounds. Other "critical" resources, such as indium, gallium and tungsten (van den Hoek et al. 2010) are also present, while germanium is found in the fluorescent powder of high-pressure mercury lamps. In summary, lamps contain various amounts of metals (W, K, Th, Re, Mo, Fe, Cr, Cu, Nb, Na, Hg, Zr, Al, Ba, Ni, Ta, Al, Zn, REE, In, Ga) (van den Hoek et al. 2010; Franz et al., 2010; McGill, 2010).

The recycling of lamps, LEDs, batteries and other WEEE is further discussed in Appendix A: "Details on Recovery of Metals from Recyclates".

2.1.2 Catalyst recycling

Many types of catalysts contain valuable platinum group metals (PGM), rare earth elements (REE) that can be lost if treated pyrometallurgically, base- and other metals (e. g. Ni, Co, Mo, Al, V, etc.). These can be technologically treated and catalyst-recycling installations already exist due to the high economic value of these metals and other elements in the catalysts. However, recycling rates can be relatively low in countries with an inadequate collection infrastructure, or due to economic reasons for viably running a catalyst recycling plant. See Hagelüken (2012) for further details on PGM-containing catalysts.

2.1.3 Solar cells and renewable energy

Solar cells and other renewable energy devices are of crucial importance for a sustainable future economy. Several metals enable the application of such technologies and their subsequent EoL recycling plays a crucial role in their availability and hence in lowering the carbon footprint of society. This is discussed in more detail in Appendix A: "Details on Recovery of Metals from Recyclates".

2.1.4 REE recovery from EoL products and residues – A key issue

New processing capacity for recovering REE is being installed (Toyota Tsusho Corporation, 2010; Lynas Corporation, 2011; Schüler et al., 2011). Appendix F: "Physics of Extractive Metallurgy" provide more information. REE can also be recovered from various other secondary sources, residues, magnets, etc. The problem lies not so much in the chemistry of REE extraction, but rather in providing suitable concentrates/recyclates from which they can be economically recovered. Hence, efforts must focus on physical separation and concentration. The metallurgical extraction chemistry is well-known, but must learn how to deal with the unusual impurities that accompany recyclates.

2.2 Recovery of Carrier Metals and materials from recycled metals, materials and sludges

2.2.1 Steel (Fe-C-X), high Mn steel (austenitic Fe-Mn-X), stainless steel (Fe-Cr-Ni-X), copper (Cu-X), nickel (Ni-X), aluminium (Al-X) (where X are alloying elements)

These important metals and alloys generally have a higher recycling rate than others that, however, can be improved, for example by better separation of metals from recyclates and residues. Contamination is the biggest challenge, as is the fact that many stainless-steel types as well as high-Mn austenitic steels are non-magnetic, and therefore are not readily recovered by simple magnetic means.

In addition the various speciality nickel alloys, such as Hastelloy (molybdenum, chromium, some tungsten, used as premier corrosion-resistant alloys in various tough environments), Alnico (aluminium, cobalt; used in magnets), etc., which, if collected, can again be refined into these valuable alloys. See also Appendix A: "Details on Recovery of Metals from Recyclates".

2.2.2 Recovery of metals from residues

A group of potentially rich recycling sources of metal are the various residues produced by industrial processes. Though the technology commonly is available for the recycling and recovery of metals and/or their compounds from residues, this may not always be economically viable – e.g. when only one or two of the metals in the residue are recovered – as gate fees, processing costs, etc., can exceed processing and treatment incomes. However, this economic hurdle can be overcome by an intelligent combination of different metallurgical processes for recovering a wider range of metals. For example, although hard metal scrap contains only relatively small amounts of elements such as niobium, tantalum and titanium, these can be recovered from a residue produced during the extraction of tungsten from such scraps.

2.2.2.1 Zinc-containing residues
When zinc metal is produced from primary sources, some of the created residues (e.g. goethite precipitate) are potential sources of recycled zinc and other valuable metals, like silver, cobalt, indium, germanium and antimony. These can be processed in an existing type of integrated plant that is suitable for dealing with elements that are associated, and thermodynamically "compatible", with Cu, Zn and Pb.

Estimates based on pioneering work by Piret (2006) and Alfantazi and Moskalyk (2003) suggest that the worldwide amounts of these jarosite and goethite residues from zinc hydrometallurgy are: jarosite: 3290 ktpa untreated (ca. 100 ktpa contained Zn); goethite: 310 ktpa untreated (ca. 20 ktpa contained Zn). Assuming around 200 g/t and 130 g/t silver in jarosite and goethite, respectively, an estimated further 120 tonnes of silver might be recovered per year from these residues, or about 0.6 % of 2007 world production (Piret, 2006), together with the other valuable metals. Companies such as KoreaZinc economically recover various metals and materials from zinc-processing goethite residues.

2.2.2.2 Electric arc furnace dust and other Pb, Zn, Cu containing residues
When steel scrap is processed in an Electric Arc Furnace (EAF), about 15 – 20 kg of dust is formed per tonne of steel. Extrapolating figures for EAF production in 2010, this means that between 5.2 and 7 million tonnes EAF dust is produced each year (Global Steel Dust, 2012). This EAF dust contains quantifiable amounts of zinc, lead and other metals. Most of it is processed through a 'Waelz' kiln, which produces an oxide that can then be further processed in a zinc plant for producing LME-grade zinc. Other zinc- and lead-containing residues or waste from zinc-using industries, or dust from a cupola furnace, can be similarly processed. The main recycling route for EAF dust is the Waelz kiln, proven to consume much less energy than other recycling processes for steel mill dust (Befesa, 2012). Other processes such as REZEDA exist, that produce Zn powder directly. The powder can be directly remelted and reused for the galvanizing of steel.

2.2.2.3 Red Mud from alumina production
Worldwide disposal areas of bauxite residue ('Red Mud') contain an estimated 2.7 billion tonnes of residue, a figure that each year grows by about 120 million tonnes (Klauber et al., 2011a; 2011b). This mud contains valuable gallium with a considerable economic value, in addition to up to 10 % by weight of TiO_2, chromium, vanadium and zirconium (and about 1000 ppm scandium, yttrium and other REE). The current form of disposal – dumping into 'ponds' – increasingly runs into problems of environmental permits.

In the past, several attempts were made to recycle and process this residue. Many of these investigations aimed at extracting iron, titanium, or aluminium, but some attempts were also made to recover other elements, such as REE (Luidold and Antrekowitsch, 2011). Usually, the economics are prohibitive, although technology such as TSL (Outotec) can treat this material and mitigate the environmental issues. However, the reprocessing of Red Mud, combining the reclamation of iron, titanium and concentrates of different scarce elements, is now potentially feasible due to the currently (2012) high prices of REE and other "critical" elements, such as gallium.

2.2.2.4 Residue cleaning
In various parts of the world, furnaces are now in use that recover a wide range of elements from residues and produce a final benign granulated slag for construction purposes. This is usually done as a combination of processes that can also recover elements such as indium, silver, germanium and other valuable metals. By understanding the physics and economics of recycling, these processes permit maximal recovery of metals through an intelligent and innovative combination of pyro- and hydro-metallurgy (Figure 21).

The type of infrastructure and knowledge shown in Figure 21 is a good example of what

is needed for recycling and residue processing. It provides all the technology for dealing with elements that are associated and work thermodynamically with Cu, Zn and Pb metallurgy. In this respect, we should also highlight metal recovery from foundry sands and other contaminated sands.

to 75 % of the aluminium comes from packaging, much of which will oxidize. Pruvost (2011) estimated that residual MSW in the EU-27 in 2006 contained about 1684 kt of aluminium, of which 533 kt went to WtoE plants.

These numbers – and thus the potential – vary from country to country, depending on

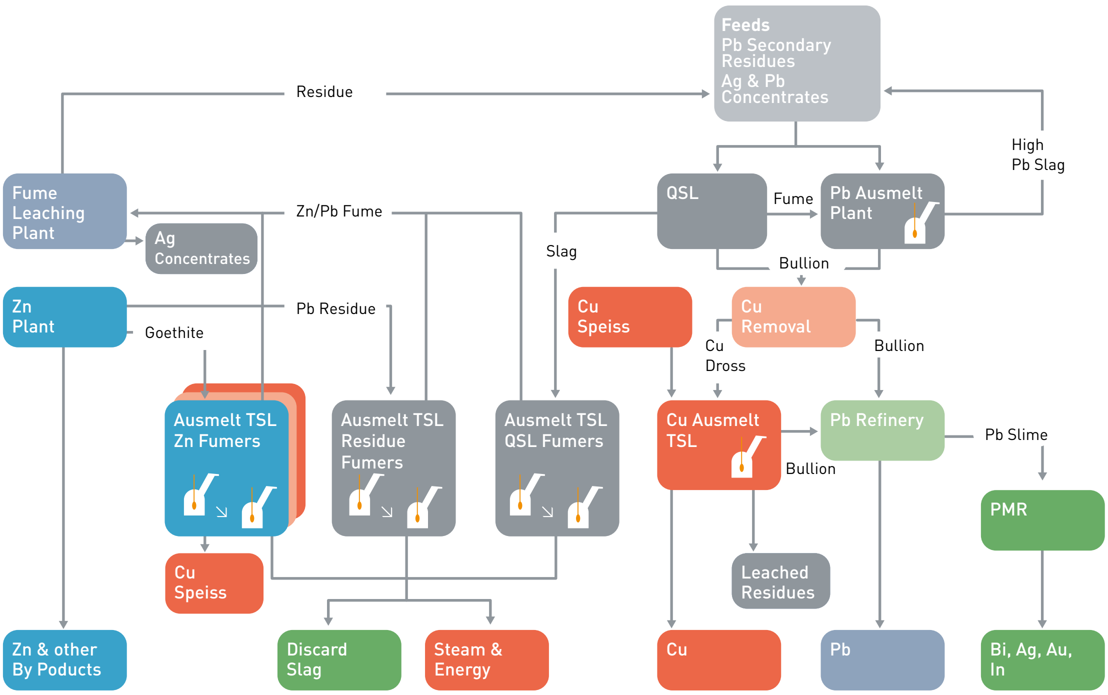


Figure 21:

Plant solutions based on commodity-metals production technology best handle the, often low-volume, critical-element recycling. The above Korea Zinc flowsheet not only creates no ponded residue, but also recovers many valuable elements associated with zinc minerals, such as indium, which are critical to flat-panel TV technology (Hoang et al., 2009).

2.3 Other end-of-life waste streams

Further potential metal sources are other EoL waste types in either current or past streams, as described hereafter and discussed in more detail in Appendix A: "Details on Recovery of Metals from Recyclates".

2.3.1 Aluminium in municipal solid waste (MSW)

Municipal Solid Waste (MSW) often contains aluminium metal. Based on MSW sample analyses, CEWEP (Coalition of European Waste to Energy Plants, WtoE) estimates an average aluminium content of 1 % or more in all metallic and non-metallic MSW sent to WtoE plants, the maximum amount that can be transferred to bottom ashes as metallic aluminium. It is estimated that between 50

the aluminium packaging mix (e. g. a small or large market share of aluminium cans) and the alternative collection schemes in place. Aluminium also turns up in MSW from non-household sources, such as small- and medium-sized businesses or restaurants, or as a compound within other materials, demolition debris or street waste.

Non-ferrous metals extraction is already a profitable activity, with metal prices ranging from 300 €/t to 1000 €/t. Most operators interviewed for a 2009 study (Pruvost, 2011) mentioned a payback period for their equipment investment of maximum two years. However, this situation is open for improvement. For example, in the EU-27 and EFTA countries, it was estimated that, in 2006, about 130,000 tonnes of non-ferrous metals

(gross weight) were extracted from bottom ashes, with around 60 – 65 % of that being aluminium (about 80,000 tonnes) or around 75 % of the potential. Better technology and increased waste flow into WtoE plants could triple this to 250,000 tonnes of aluminium a year by 2020.

Another major objective of waste management should be to avoid incinerating valuable materials, as these usually get lost in the rather unsophisticated operation of this technological option.

2.3.2 Enhanced landfill mining (ELFM) and enhanced waste management (EWM)

The waste that has already been dumped (and thus stored) in landfills worldwide, is a valuable resource. Landfill "mining" of waste from the ground for valuable metals such as copper or aluminium, or methane gas reclamation, are relatively common operations (van der Zee et al., 2004; Jones, 2008; Prechthai et al., 2008; Jones et al. 2012). Billions of tonnes of waste are now in landfill; for instance, it is estimated that there are around 150,000 landfills in Europe (Hogland et al., 2011).

Enhanced landfill mining is a relatively new concept that valorizes landfill waste for both materials and energy (Bosmans et al., 2012). Organic and high-calorific value waste can be used by advanced technology for producing energy from plasma, together with producing a usable slag containing valuable metals. It must be stressed that this option should only be used for existing landfills and should not be considered as a technology and policy option for the future, due to its inherently high losses of valuable metals.

Box 5:

The Houthalen-Hechteren landfill in Belgium

A joint venture was set up to exploit the Houthalen-Hechteren landfill site in Belgium using ELFM, storing more than 16 million tonnes of waste, half municipal solid waste and the other half industrial waste. Preliminary calculations showed that about 45 % of the waste could be recycled, either directly or after controlled treatment. The recycling residue can be used as energy (and material) by firing a 75 to 100 MW electrical power plant based on plasma technology. In addition to the electricity/heat generating plant, up to 50 hectares of greenhouses are planned, heated by steam and using part of the CO_2 emitted by the generating plant. The project is expected to require an investment of approximately 230 M € and would employ up to 800 full-time staff. The installations should become operational by the end of 2013 and be in use for at least 20 years.

2.3.3 Recovery of phosphorus from recycled sources

Phosphorus is an essential nutrient for plants and animals, with increasing global demand and for 80 – 90 % used in agriculture. There are no substitutes for phosphorus. Its mineral supply is concentrated in only a few countries, and recent years have seen price volatility due to supply and demand imbalances. In addition, it poses significant sustainability challenges (Abelson, 1999; Christen, 2007).

However, substantial dissipation of phosphorus occurs in metal production. In Japan, for example, the amount of phosphorus ending up in dephosphorization slag from steel making is equal to its total phosphate-ore import. The proposed phosphorus-recovery technology (Yokoyama et al., 2007) could significantly reduce worldwide losses of this valuable resource, providing new phosphorus streams to mitigate the problems with existing mineral extraction (Figure 22).

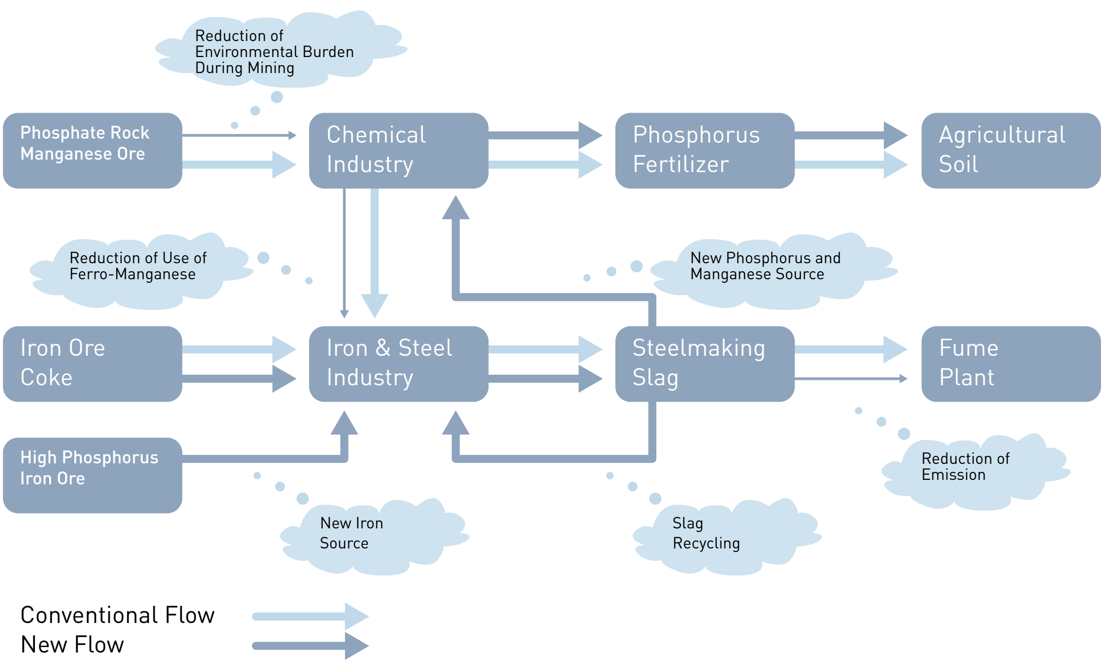
2.4 Benefits from increased recycling

More and better recycling holds great economic rewards: from the sale of metal that would otherwise be lost, including various valuable and scarce elements, and from recycling processes that reduce energy use in metal production. Substantial savings are also possible in Greenhouse Gas emissions and other environmental benefits.

2.4.1 Value of recovered metals

Metal prices directly or indirectly influence the financial rewards of recovery. These are related to the physics of primary and recycled recovery of a metal, to the relative abundance of the various elements in primary minerals, and to the demand for greater sustainability and other services provided by the metal. Table 12 shows the economic potential of world (mine) production compared to electrical and electronic equipment (EEE) demand, estimating the value of metals going into EEE in billions of dollars. This is a strong incentive for setting up profitable recycling sys-

Figure 22: Conventional phosphorus flow through chemical and iron & steel industries and possible new flow (grey arrows) when P-recovery technology from steelmaking slag comes on stream. Arrow width corresponds to quantity of flow (Yoshida et al., 2012).



tems with a sufficient economy of scale and based on BAT. However, these metals often are intimately linked, calling for technological ingenuity to separate them and produce pure metal and compounds. The key to recycling is thus to do this in an appropriate metallurgical infrastructure that is protected by suitable long-term vision and policy.

The (precious) metal content of various devices can do much to boost the economic recycling of WEEE products. For instance, the metal value of used rechargeable batteries is significant, driven mainly by Co and Ni, which in 2010 had average prices of $45 and $21 per kg, respectively (Metal Bulletin, 2010). The Ni contained in one tonne of NiMH batteries has a value of about $6,000. Even more value can be extracted from recycled batteries, if their materials are recovered as compounds instead of breaking them down to an elemental state. However, this obviously requires a market for these compounds to flow back into the products, implying that these could have a high market value and thus rendering the recycling economic.

Table 12: World mine production, electrical and electronic equipment (EEE) demand and application relative to mine production for several critical elements. Values exceeding 100 % are due to recycling. Metal prices from Metal Bulletin, Mine production from USGS (Ru from Johnson-Matthey, 2011), (see some recent metal prices Sept/Oct 2011 [a] reflecting the large possible changes).

Important EEE metals	World mine production t/a	EEE demand t/a	EEE demand/ mine production	Metal price $/kg	Value of EEE use billion $
Silver Ag	22,200	7,554	34 %	$ 649	$ 4.90
Gold Au	2,500	327	13 %	$ 39.443	$ 12.90
Palladium Pd	229	44	19 %	$ 16.948	$ 0.74
Platinum Pt	188	7	4 %	$ 51.811	$ 0.37
Ruthenium Ru	29	21	72 %	$ 5.069	$ 0.11
Copper Cu	16,200,00	7,174,000	44 %	$ 8	$ 54.08
Tin Sn	261,000	129,708	50 %	$ 20	$ 2.65
Antimony Sb	135,000	67,500	50 %	$ 9	$ 0.61
Cobalt Co	88,000	16,470	19 %	$ 45	$ 0.75
Bismuth Bi	7,600	1,216	16 %	$ 20	$ 0.02
Selenium Se	2,260	185	8 %	$ 82	$ 0.02
Indium In	574	717	125 %	$ 566	$ 0.41
				Total	$ 77.56

a Metal prices from Metal Bulletin 7/9/2011 pp. 35–41 ($/kg): Ag 972; Au 58,546; Pd 24,981; Pt 59,253; Re 4,800; Ru 5,626; Rh 60,282; Cu 9 (down lately to 7); Sn 24; Sb 15; Co 35; Bi 29; Se 136; In 785 (others not in table Ga 850; Ge 1,650; Ni 22; Pb 2.5; Te 380; Zn 2.2; W 470)

2.4.2 Value of energy saved in metal production

Improved recycling processes can be much cheaper than primary production, primarily because they can use much less energy in production of the metals. Data from World Steel (Figure 77) indicate the significant lowering in energy consumption required for the recycling of steel through Electric Arc Furnace smelting (9 to 12.5 GJ/tonne) compared to primary production from a Blast Furnace-Open Hearth Furnace (26.4 to 41.6 GJ/tonne), Blast Furnace-Basic Oxygen Furnace (19.8 to 31.2 GJ/tonne) and Direct Reduction-Electric Arc Furnace (28.3 to 30.9 GJ/tonne). Such data, reflecting the difference between the energy requirements of primary and recycling production, will show similar decreases in energy consumption for other metals as well. Hence, considering Table 12 and Figure 24 and the amount of valuable elements that could be recovered through recycling, it is self-evident that substantial lowering of the footprint is possible. In addition, a more sophisticated approach to recycling can help reducing the energy use of existing recycling processes, for example for steel. Scrap with impurities increases the energy required for producing metal of a required purity. Integrating new technology into existing processes may deal with some of these impurities; a metal-recycling system that capitalizes on this can maximize profits.

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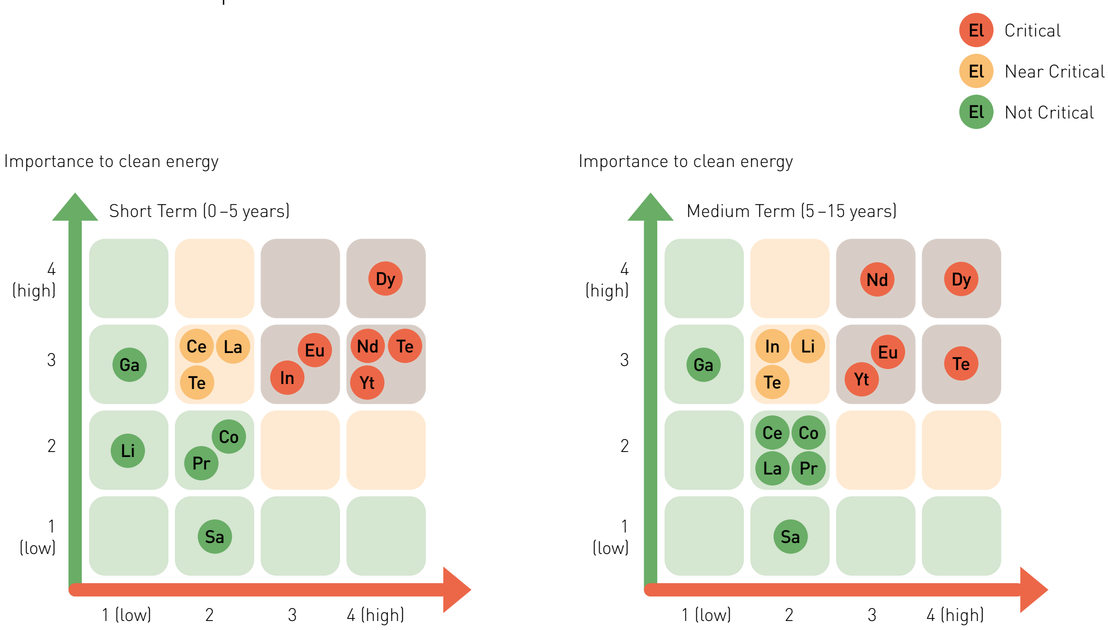
2.4.3 Reducing the risk of metal scarcity, particularly of metals needed for transition to a green economy

Recently, the EU, Japan and the USA produced documents discussing scarce materials (Figure 23), classifying some metals as "critical" because their future supply may be compromised. This can be due to resource depletion, poor design, a 'throw-away' society, cheap landfill costs, insufficient policy, insecurity of supply through geopolitical risks, insufficient development of current and future technologies, etc. The EU's list of critical metals includes antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, PGMs (platinum group metals), rare earth minerals, tantalum and tungsten (EU, 2010).

Figure 23:

Critical levels of some elements (U.S. Department of Energy, 2010).



Many of these metals enable sustainability in future products and infrastructure required by a low-carbon, resource-efficient, sustainable society, including energy production (e. g. solar, wind, smart grids), water purification (e. g. enhancing water quality by using sensors, filter materials, smart water systems), transportation (e. g. electric cars, planes), and construction (e. g. various materials in eco-cities) (Reuter et al., 2005). Rare earths and metals in alloys and their oxides play an increasingly important role in this context (Table 13).

Table 13_a:

The use of rare earth elements (REE) in 2012 and projected demand and growth by 2016 (Lynas Corporation, 2011).

Forecast Global Rare Earths Demand in 2012 (t REO ± 15 %) (source: IMCOA and Rare Earth Industry Stakeholders)

Application	China	Japan & NE Asia	USA	Others	Total	Market Share
Catalysts	12,000	2,000	5,000	2,000	21,000	18 %
Glass	5,500	1,000	500	500	7,500	7 %
Polishing	15,000	2,000	1,000	1,000	19,000	16 %
Metal Alloys	16,000	4,000	1,000	1,000	22,000	19 %
Magnets	18,000	3,500	500	500	22,500	20 %
Phosphors (including Pigments)	7,000	1,500	500	500	9,500	8 %
Ceramics	2,500	2,000	1,500	500	6,500	6 %
Other	3,500	1,500	1,500	500	7,000	6 %
Total	79,500	18,000	11,500	6,500	115,000	100 %
Market Share	69 %	16 %	10 %	5 %	100 %	

Table 13_b:

Forecast Global Rare Earths Demand in 2016 (t REO ± 15 %) (source: IMCOA and Rare Earth Industry Stakeholders)

Application	China	Japan & NE Asia	USA	Others	Total	Market Share
Catalysts	14,500	2,500	6,500	1,500	25,000	15 %
Glass	6,000	1,000	1,000	1,000	9,000	6 %
Polishing	19,000	2,000	3,000	1,000	25,000	15 %
Metal Alloys	20,000	2,500	2,000	1,500	26,000	16 %
Magnets	28,000	4,500	2,000	1,500	36,000	22 %
Phosphors (including Pigments)	9,000	2,000	1,000	500	12,500	8 %
Ceramics	4,000	2,000	2,000	1,000	9,000	6 %
Other	6,500	3,500	8,000	2,000	20,000	12 %
Total	107,000	20,000	25,500	10,000	162,500	100 %
Market Share	66 %	12 %	16 %	6 %	100 %	

For example, the scarcity issue linked to battery recycling revolves mainly around Co, Li and rare earths, each of which presents its own challenges. Cobalt is seen as the main metal with scarcity concerns, but at least there is an economic incentive for its recycling and it can be substituted by nickel and manganese, both of which are less scarce. Lithium, on the other hand, has no foreseeable substitute and presents geopolitical concerns with 80 % of its world resources based in Chile, Bolivia and Argentina.

Although the list of today's "critical" elements may change as applications and technology change, prudent safeguarding of these materials, e. g. the recovery of these critical resources from consumer products such as cars and WEEE, will play an important role in the sustainable development of our society.

2.4.4 Job creation

The complexity of EoL scrap and materials makes dismantling and hand-sorting important activities within the materials-flow chain. If well controlled with suitable health and safety guarantees, this has a large potential for job creation. A recent report concluded: "Recycling creates more jobs at higher income levels than landfilling or incinerating waste. The overall employment related to the recycling of materials in European countries has increased steadily from 422 per million inhabitants in 2000 to 611 in 2007. This represents an increase of 45 % between 2000 and 2007, corresponding to an annual increase of 7 %" (http://www.eea.europa.eu/publications/earnings-jobs-and-innovation-the).

2.5 The contribution to sustainable development

2.5.1 Reduction of greenhouse-gas emissions

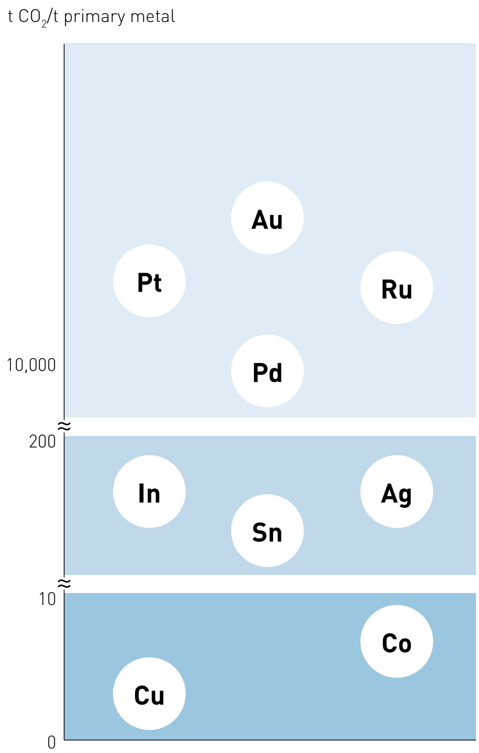
The production of metals from primary ores is energy intensive and a significant source of greenhouse-gas emissions. When recycling metals, energy use is minimized as scrap metals usually require less energy to convert back into high-grade materials, than processes of mining and refining. Hence carbon emissions from recycling are substantially inferior to those from mining, which are likely to increase due to the rising use of lower-grade ores. The decrease of such emissions largely depends on the thermodynamic stability of the primary minerals and on the way they are distributed in the ores, as well as on the suitability of input from recycling sources.

Recycling of purer metals often "simply" consists of remelting, generating a small fraction of the emissions shown in Figure 24. To remelt pure copper using methane gas and air creates ca. 0.1 t of CO_2 per tonne of Cu, compared to around 3 t of CO_2 per tonne of Cu from ore. Recycling of platinum group metals and many of the scarce/critical/valuable metals found in WEEE can lead to particularly large CO_2 savings, because initial CO_2 emissions per tonne of these metals can be very high. Figure 24 shows the average CO_2 tonnage that results from the primary production of metals (NB: in 2010, global GHG emissions were 33.6 Gt CO_2).

Considering the 33.58 Mtpa of CO_2 emitted during production of the base- and precious metals shown in Figure 24, 0.1 % of the world's CO_2 emissions can be attributed to these important metals in WEEE products. It is clear from the above example for pure copper that significant emissions savings are possible. However, the more important consideration is that these metals are all part of a future sustainability-enabling infrastructure and, through their high-tech use, will indirectly help decreasing society's carbon footprint.

Figure 24:

Primary carbon footprint of selected elements in WEEE goods (EU, 2010) (Appendix F: "Physics of Extractive Metallurgy").



Metals used in EEE	Primary production intensity t CO_2/t metal	Demand for EEE t/a	CO_2 emissions Mt/a
Au – Gold	16,991	327	5.56
Pt – Platinum	13,954	8	0.11
Ru – Ruthenium	13,954	16	0.22
Pd – Palladium	9,380	30	0.28
Au – Silver	144	4,917	0.71
In – Indium	142	717	0.10
Sn – Tin	16	129,708	2.09
Co – Cobalt	8	16,470	0.13
Cu – Copper	3	7,174,000	24.39
		CO_2 total [Mt/a]	**33.58**

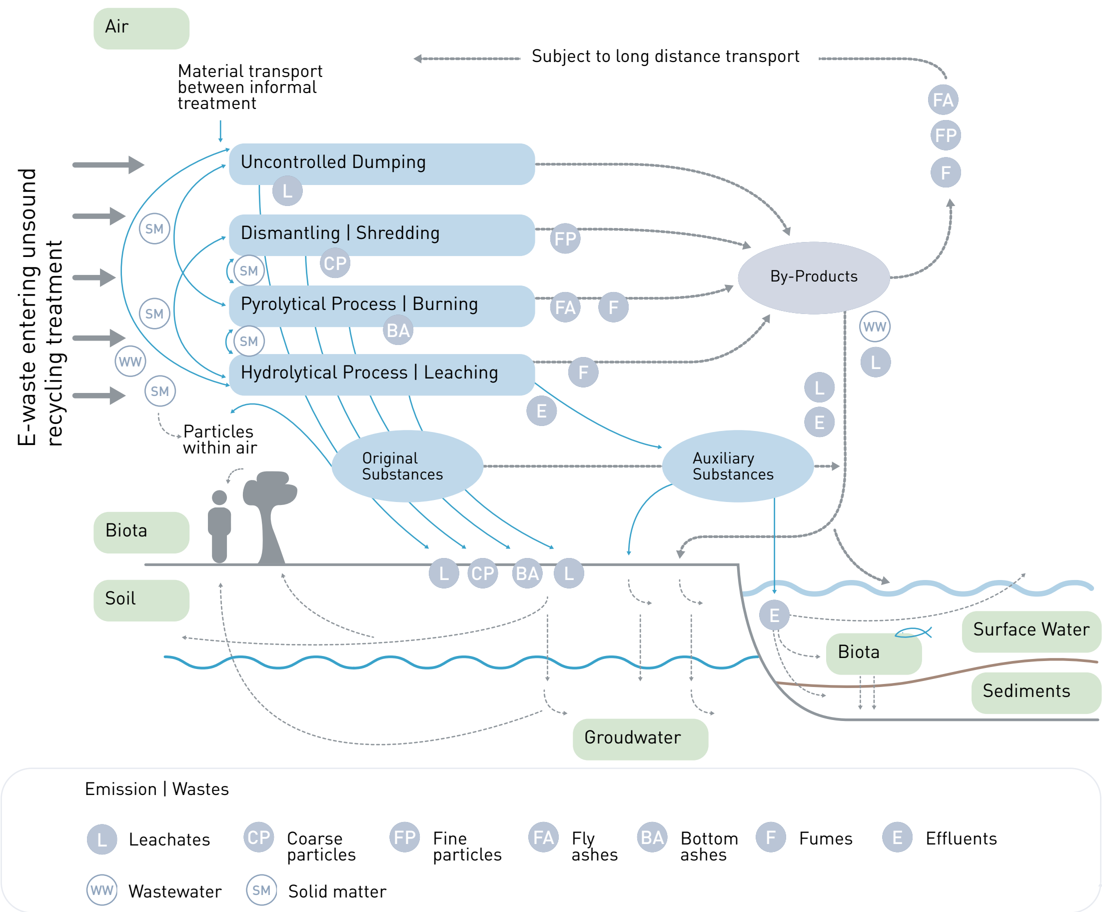
2.5.2 Sustaining biodiversity and human health

By maximizing the efficiency of materials recovery (both primary and end-of-life), pressure on the supply side for primary metals is eased. Less land is used for mining ore and less landfill is required. Metal-production processes commonly produce residues, wastes and emissions that can interact with the environment. These are potentially harmful if the compounds in the final materials are non-benign and interact unfavourably with water and air (Figure 25).

Integrated recycling that extracts more metals from residues also is better suited for dealing with potentially toxic elements, thus avoiding or minimizing their release into the environment, and rendering the final smelting or processing product benign. It commonly liberates land as existing residue ponds are processed and eliminated. This also has practical direct benefits for recycling operations, as environmental regulators increasingly stop the licensing for new residue ponds, decreasing the scope for potential expansion of primary production.

Figure 25:

Main WEEE recycling activities in China and India, types of produced emissions and general environmental pathways. (Sepúlveda et al., 2010).



Ovals: Types of substances contained within emissions.
Continuous bold lines: Fate of original and auxiliary substances.
Dotted bold lines: Fate of by-products such as dioxins and furans.
Black arrows with a bold dot: Material transport fluxes between treatments.
Fine dashed arrows: General environmental pathways. Environmental fluxes are driven by processes such as atmospheric deposition (dry/wet), leaching, adsorption-desorption, complexation (forming secondary heavy-metal and cyanide products), uptake, degradation (chemical/biological) and volatilization. In addition, the environmental fate of pollutants depends on the physico-chemical properties of the media.

3. Limiting Factors in Recycling

This chapter looks at the factors that currently, and for the near future, constrain our ability to achieve higher recycling rates of metals. At the base are the limitations set by nature, such as physics, chemistry, metallurgy and thermodynamics. These dictate the outcome of a given input into a recycling process, the constraints of nature tying together the use of energy, metal recovery, and quality and quantity of the inevitable losses. The more complex a multi-material recyclate input is, the more metal will be lost in the metallurgical system. Where recycling uses less sophisticated metallurgical technology, mixed waste will be even more of a limitation.

Different processing routes give different outcomes and thus different recycling rates. Pre-processing technology, using mainly physical separation for preparing suitable fractions for further processing, influences the quality and quantity of the input streams. However, several thermodynamic, technical, economic and environmental issues must be considered as well. A limiting factor at this stage is the relationship between quality and recovery of a given metal or metals. Though their quantity depends upon the policies and actions governing materials collection, the issue becomes more complex when discussing the quality of the streams to be pre-processed. A large variation in stream properties will adversely affect product quality and recovery, thus increasing losses at this stage. The streams may even become economically unviable for processing.

Another major issue at this stage is the way (consumer) goods are produced. Products to be recycled must be separated into suitable streams as soon as possible, but will have optimal ranges depending on stream values and collecting costs, which are affected by policies and collection schemes. Product design with recycling in mind will improve the recyclability of any product (consumer) goods, especially at the pre-processing stage and also at the final processing stage.

3.1 Limits arising from the collection of recycled material streams

The main collection options for post-consumer goods are collective municipal or commercial collection, individual producer and retailer collection, and collection by the informal sector (waste pickers). The balance between these routes depends on the policies and economics of the different countries. In addition, other initiatives like charity, small-scale pilot projects, or event-based collection contribute to the collection of small, high-value waste of electrical and electronic equipment (WEEE), also called e-waste. The main metal containing resources for post-consumer waste are cars, electronic appliances, packages and diverse small metal products like toys, bicycles etc.

Chartered recyclers, who can process the various liquids, batteries, tyres and produced metal fractions, as well as the difficult light fractions (rubber, textiles, various plastics), commonly treat end-of-life vehicles (ELV). In Europe, the ELV directive stipulates strict targets for recycling. For electric and electronic appliances, the producers are increasingly responsible for recycling; consumers in many countries can return an old appliance to the seller, though detailed schemes vary from country to country. The European Union has also stipulated targets for recycling WEEE.

Collection of packaging is commonly structured like the German 'Duales' system, where the consumers are encouraged to return packaging by recovering a small deposit. These systems are highly efficient for, e.g., aluminium beverage cans. However, packages containing metal foil are not effectively collected but generally end up in Municipal Solid Waste.

The collection of post-consumer waste is very much a logistics challenge. There are typically several stakeholders in the logistics chain

with different aims and motivations, a major actuator often being the minimization of collection cost rather than the maximization of material efficiency. An obstacle to recycling consumer products often is neither technical nor economic, but the lack of consumer awareness concerning collection and recycling possibilities. Taking products to collection sites or facilities is felt as an inconvenience, leading to low collection volumes and mixed waste streams with different compositions. This is even seen for ELVs, but more for small electronic appliances, batteries, small toys, packaging, etc.

The technical recycling process obviously cannot exist without returning products for recycling. However, well-organized collection and pre-processing systems often are lacking, which makes it impossible to ensure that metals, alloys and other materials do not end up in waste streams where they are lost.

Box 6:

Cell-phone recycling attitudes

A survey on consumer-recycling behaviour and attitudes in 2007 found that, although households worldwide own five phones on average, very few of these were recycled. Nearly half of the consumers were even unaware that a mobile phone can be recycled. Two-thirds said they did not know how to recycle an unwanted device and 71 % were unaware of where to do this. Only 3 % said they had recycled their old phone. The survey was based on interviews with 6,500 people in 13 countries, including Finland, Germany, Italy, Russia, Sweden, the UK, the United Arab Emirates, the USA, Nigeria, India, China, Indonesia and Brazil. Figure 26 shows what people did with their redundant phone according to a 2011 repeat of the study, now including Argentina, Spain and Nigeria, but not Sweden, Brazil, Italy and Russia. Most old phones are kept at home or given to somebody else for further use. Fortunately, the survey in 2007 showed that only 4 % of the old phones ended up in a landfill (Damanhuri, 2012).

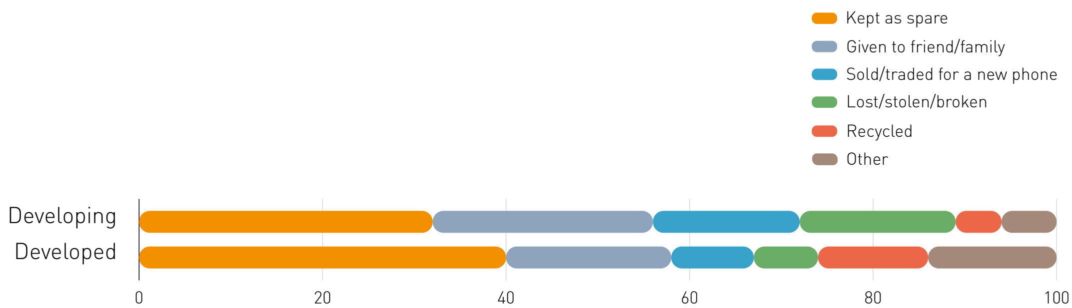


Figure 26: Study of developing and developed markets about what people did with their previous cell phone (Damanhuri, 2012).

According to the 2011 survey, 9 % of respondents claimed to have recycled their last cell phone, a 6 % increase over 2007. The developed market leads in this, although strong growth has been seen in India and China since 2007.

One of the problems with estimating future recycling streams comes from the delay between the sale of products and the time that they become available for recycling at the end of their life. Even where the quantities of metals in the products are known, their availability will be influenced by many factors – as the above example of phone recycling shows.

An additional factor affecting the volume and availability of material for recycling is the leakage of waste into the 'grey market' of informal, or illegal, low-technology recyclers. This typically leads to losing the small quantities of hard-to-extract metals in the products.

3.1.1 The case of E-waste

E-waste (of electrical and electronic equipment), or WEEE, constitutes about 8 % of municipal waste and is considered to be one of the fastest growing waste streams worldwide (Widmer et al., 2005). As shown in Figure 27, especially China and India, but also some African states, are important destinations for e-waste flows. These mostly derive from the US, which has not ratified the Basel Convention, and to a lesser degree from the European Union (EU).

WEEE represents the fastest-growing waste stream in the EU, generating about 8.7 million tonnes in 2005. By 2020, this amount is estimated to reach 12.3 million tonnes, corresponding to an annual growth of about 2.6 % (European Commission, 2008; Hester and Harrison, 2008). The e-waste stream also contains substantial amounts of metals, such as rare earths, lithium (batteries), ruthenium, antimony and even tin. Most of the production of, for example, indium is used in electronic appliances.

In many cases, sometimes despite legislation, small WEEE articles are not collected separately for recycling, but disposed of with mixed Municipal Solid Waste (MSW). For example, data on collection rates for WEEE in Europe for 2005 (United Nations University, 2007) mention figures of 20 % for electrical and electronic tools to 60 % for monitoring and control instruments. Chancerel and Rotter (2009a&b) showed cell-phone collection rates of 18 % in Germany and of 12 % in the United States. For larger WEEE items, the rates are higher: PC collection rates, for instance, are 76 % in Germany and 54 % in the United States.

Figure 27:

Asian e-waste traffic – who gets the waste? (Baker et al., 2005).

3.1.1.1 E-Waste policy in the European Union

EU directives 2002/96/EC and 2012/19/EU define their objectives as: "The purpose of this Directive is, as a first priority, the prevention of waste electrical and electronic equipment (WEEE), and in addition, the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste. It also seeks to improve the environmental performance of all operators involved in the life cycle of electrical and electronic equipment, e. g. producers, distributors and consumers and in particular those operators directly involved in the treatment of waste electrical and electronic equipment".

The directive also stipulates "target values for different classes of electronic appliances, and requires that producers are responsible of recycling their products and that producers design their products for better recyclability …"

The target values are given as percentages of the total mass of appliances produced, but as most of the appliance weight does not consist of critical "high-tech" or valuable metals, but in lower value plastics and steel, the directive does not encourage a better recycling of these materials. However, collecting many types of appliances together can fulfil the targets. Such combined collection minimizes collection cost, but often reduces the concentration of the valuable constituents below economically feasible limits.

Although the amount of separately collected WEEE is estimated to be much higher, only one-third of WEEE generated in the EU is officially reported as being treated in line with the WEEE Directive. Part of the collected, but unreported, two-thirds is suspected of being treated in the EU without appropriate environmental care, or shipped illegally to treatment sites outside the EU that do not meet European environmental and health standards. Various studies have shown that, despite a tightening of legislative measures, waste and especially e-waste is still likely to be exported illegally as long as an economic incentive exists (European Commission, 2008; Skinner et al., 2010). In order to address some of these loopholes, the EU published a revision of its WEEE Directive (2012/19/EU, European Commission, 2012).

3.1.1.2 E-Waste policy in China and India

In order to address – among other issues – the challenge of handling domestically produced and imported e-waste, China introduced the 'Circular Economy Promotion Law of the People's Republic of China' that was approved on August 29th, 2008, and came into force on January 1st, 2009 (see Box 7). Articles 38 and 39 address the issue of e-waste directly and mandate that "recovered electrical and electronic products that have to be dismantled and recycled shall be sold to qualified dismantling enterprises." (Ministry of Commerce of the People's Republic of China, 2009).

Today, however, only a few recycling facilities exist that are labelled "qualified". These are often operated by governmental agencies, but have – as in India – significant problems for obtaining enough products to ensure an economically viable operation. Instead, much of the e-waste still flows into informal recycling channels, such as second-hand markets and manual-recycling workshops. Waste is considered a valuable resource in China by a large group of low-income earners (mainly past and present migrant workers) and thus much of the e-waste is first re-circulated into the economy and reused, instead of being directly recycled and broken down into components or raw materials (Veenstra et al., 2010; Chi et al., 2011).

Box 7:

"Circular Economy" policy in China
A wide range of metals, including those now used in electronics, is found in EEE and hence in WEEE. Table 8 gives some indication of the wide application of metals in various products.

The Circular Economy (CE) concept was developed in China as a strategy for reducing the demand of its economy upon natural resources, as well as for mitigating environmental damage. Circular Economy refers to "reducing, reusing and recycling (3Rs) activities conducted in the process of production, circulation and consumption". Development based on the Circular Economy will be essential for China for building a generally well-off society by sustaining fast-paced economic growth while offsetting negative ecological impact and creating more jobs.

The Circular Economy approach to efficient resource-use integrates cleaner production and industrial ecology in a broader system, covering industrial firms, networks or chains of firms, eco-industrial parks, and regional infrastructure, for optimizing resource use. State-owned and private enterprises, government and private infrastructure, and consumers all play a role in achieving a Circular Economy (Ministry of Commerce of the People's Republic of China, 2009). The three basic levels of action are:

- At the individual firm level, managers must seek much higher efficiency through the 3Rs of cleaner production, reduced resource consumption, reduced emission of pollutants and waste, reuse of resources, and recycling of by-products.
- The second level is to reuse and recycle resources within industrial parks and clustered or chained industries, so that resources will circulate fully in the local production system.
- The third level is to integrate the different production and consumption systems in a region, so that the resources circulate among industries and urban systems. This level requires development of municipal or regional by-product collection, and of storage, processing, and distribution systems.

Efforts at all three levels include the development of resource recovery and cleaner production enterprises and public facilities for implementing the CE concept. This adds a strong economic-development dimension through investment in new ventures and job creation. As a result, the Circular Economy opens opportunities for both domestic and foreign enterprises with regards to properly treating waste, including e-waste, in China.

Most Indian e-waste is generated domestically. Imports still account for a substantial amount of WEEE, but their share is decreasing. The main sources of WEEE are government institutions, public and private sector institutions, product and component manufacturers, and individual households. Concerning imported e-waste, a study by ÖkoPol prepared for the German Federal Environment Agency assessed that 80 % of the waste is imported from the US and the remaining 20 % mainly from the EU (Sander and Schilling, 2010).

Up to 2011, a patchwork of regulations covering e-waste had been in place, which ham-

pered effective WEEE regulation and enforcement (Sinha-Khetriwa et al., 2006). With the introduction of the new E-Waste (Management and Handling) Rules 2011 that entered into force on May 1st, 2012, India introduced comprehensive legislation addressing the issue of e-waste, which resembles the EU WEEE Directive and follows the principle of Extended Producer Responsibility (EPR) (Ministry of Environment and Forests, Government of India, 2011). It remains to be seen whether the legislation will be effectively enforced.

While some formal recycling facilities already exist in India, they have significant problems of receiving enough e-waste for operating at an economically viable level. So far, informal recyclers handle up to 20 times as much e-waste as formal recyclers. The new rules intend to change this ratio in order to decrease the environmental impact of e-waste recycling, which is significantly larger in the informal sector. In addition to environmental impact, the use of child labour and the exposure of workers to far higher toxin levels than in the formal sector, provide a further incentive of enforcing the new rules (Skinner et al., 2010).

3.1.2 Policy responses addressing waste flow

Metal recycling is a highly complex process, relying on various steps that need to be followed in order to ensure an environmentally sound recycling process. One of the most challenging aspects concerning the recycling of consumer goods, is to ensure that end-of-life products end up in the right facilities. Unfortunately, several studies have shown that waste is often, and mostly illegally, shipped to locations where this aspect is not ensured (e. g. Sander and Schilling, 2010). For metals, the problem of illegal waste-streams mostly concerns mobile goods, e. g. cars or waste of electrical and electronic equipment (WEEE).

The high value of some scrap also has a strong attraction for thieves, not only affecting material flow, but above all criminalizing the image of recycling. The Association of British Insurers says, for example, that scrap theft costs the UK economy £770 million per year. There are 1000 thefts per week, the payout is over £1 million per week and, for example, a Henry Moore statue-insurance payout is £3 million, while the scrap value is around £2,000 (Voss, 2012). A possible way of mitigating this problem is to enforce cashless payment for scrap; however, this must be adopted globally to close all leaks.

3.1.3 The Basel Convention: a policy response to uncontrolled and illegal waste flow

In the late 1980s, waste in general (e-waste was not much of an issue at the time) received much attention on the global political agenda. A tightening of environmental standards and a resulting rise in disposal costs in industrialized countries led the latter to ship their hazardous waste to countries with lower environmental and health standards, where indiscriminate dumping and improper management of hazardous wastes caused air, water, and soil pollution and sickness. When this uncontrolled dumping of waste – particularly in developing countries – was revealed, international outrage led to the drafting and adoption of the 'Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal' in 1989 (UNEP, 2007b; Basel Secretariat, 2012). This Convention, which entered into force in 1992, is the United Nation's primary instrument for dealing with international waste issues. Its key objectives are to diminish the generation of hazardous waste, reduce transboundary movements of such waste by disposing of it as close to its source as possible, and ensure its environmentally sound management (Basel Secretariat, 2012). To reach these objectives, a system was set up of prior written notifications for transboundary movements of hazardous waste, which are only allowed when all participating states agree and are informed beforehand. According to Article 11 of the Convention, transboundary movements of hazardous waste to 'non-party states' are only permissible if bi- or multi-lateral agreements exist that are in line with the Basel Convention. The responsibility for comply-

ing with the Convention lies with the exporter and requires the take-back of waste, for instance in cases of illegal transports (Basel Convention, Article 9). According to List A of Annex VIII (A1180), WEEE is considered hazardous and thus generally covered by the Convention's jurisdiction. However, the convention only addresses transboundary shipments between OECD and non-OECD states, and does not regulate waste shipments between non-OECD states for example (Sinha-Khetriwa et al., 2006).

In 1997, the EU decided to implement the Basel Ban – a 1995 amendment to the Basel Convention that has not yet been ratified – through an amendment to its Waste Shipment Regulation. Not only does the EU ban the export of hazardous (and e-waste) to non-OECD countries, but it has also introduced the WEEE- and RoHS Directives that, respectively, force producers and resellers to implement take-back systems and to phase-out hazardous materials in electrical and electronic equipment (EEE) (European Commission, 2008).

The policies concerning e-waste earlier had a strong emphasis on hazardous environmental effects. However, as the volume of e-waste increases, the increased and effective recovery of metals in sophisticated plants using BAT technology will have to be stressed as well.

3.2 The physical limits of "closed loop" recycling

Whilst great improvements are possible in the recycling of metals, a fully "closed" recycling system cannot exist due to physical laws, regardless of what Cradle-to-Cradle (C2C) claims (McDonough and Braungart, 2002). C2C concepts are useful psychological tools for drawing people's attention to recycling, but should not to be used as a basis for policies. There will always be a slight loss of metals due to imperfections in the systems and many other aspects, such as thermodynamics, technology, human error, politics, theft and economics (Figure 3, Figure 15). A Product-Centric view and good understanding of recycling, dealing with the product as a whole rather than as separate contained metals, helps in pushing back the limits of "closing" the loop.

Figure 3 shows the flow of materials, harmonizing a primary and recycled metal production based on metallurgical recovery and refining of metals. Recovery is obviously based on physics, but may also reflect the economics of metal recovery from multi-material recyclates, residues, sludges, drosses, slags, fumes, flue-dusts, etc. Losses from the system can be attributed to physical constraints (see below), but also to theft and collection issues as mentioned before. Technically speaking, good recovery requires considerable (often tacit) knowledge, not only for hand sorting of EoL material, but also for applying sophisticated metallurgical process technology. An understanding of unaccounted losses due to unregistered flows, take-back systems not collecting all materials, theft, etc., is needed as well, to maximize resource efficiency.

All products, simple to complex, require a minimum of primary metal flowing into the chain to compensate for losses over the whole cycle, and recycling output thus usually needs mixing with primary metals to reach the level of purity required for new uses. Each step in the chain also requires a minimum of energy to complete. The recovery of materials and energy in metallurgical operations is largely dictated by the Second Law of Thermodynamics: energy will be dissipated and so new energy will be needed. Technology can help us in getting as close as possible to the thermodynamic limit.

So even just to keep a constant stock of metals in society, recycling of metals would require replenishment through resource extraction and use of primary metals. Even though recycling can save great amounts of energy (and therefore minimize carbon emissions) compared to primary extraction, it will still require new energy input.

The reality of recycling metals is that it often uses less energy and has a lower environmental impact than primary production (e.g. the Ecoinvent database for Life Cycle Assessment, www.ecoinvent.ch), but not always. This is the case for highly mixed fractions, or for chemically or metallurgically challenging material-input feeds. In these cases, while metal ores are being saved, other resources, mainly energy carriers, are consumed for recycling the target material.

3.3 Incomplete material liberation from EoL products – A key reason of resource loss

3.3.1 What is material liberation?

The difficulties caused by thermodynamically related elements in metallurgical processes, can be reduced by trying to purify the input entering the process. For complex waste, this means sorting material into its constituent parts and physically separating the material, alloys, elements, etc., into clean fractions (Froelich et al., 2007). In recycling we call this 'liberation', i.e. liberating materials from each other by physical force.

Figure 28 shows the effect of liberation on recyclate quality, where in some cases the imperfectly liberated particles land in the wrong recyclate stream, due to randomness and to their physical properties, but also due to the connected materials that affect the physical properties and therefore separation. Refer also to the right side of Figure 3 for understanding the losses due to physical phenomena and separation physics.

Liberation involves crushing, grinding or shearing (generically called 'shredding'), though this rarely leads to complete liberation. It is normal that different materials remain stuck to each other, or are broken apart but still remain together. The degree of liberation of the different materials determines the quality and recyclability of materials in different recycling streams (van Schaik and Reuter, 2004a; 2007a&b).

Figure 28:

The link between joined particles, their shredding or dismantling into groups, and their subsequent separation into economically valuable recyclates (van Schaik and Reuter, 2012; Reuter and van Schaik, 2012a&b).

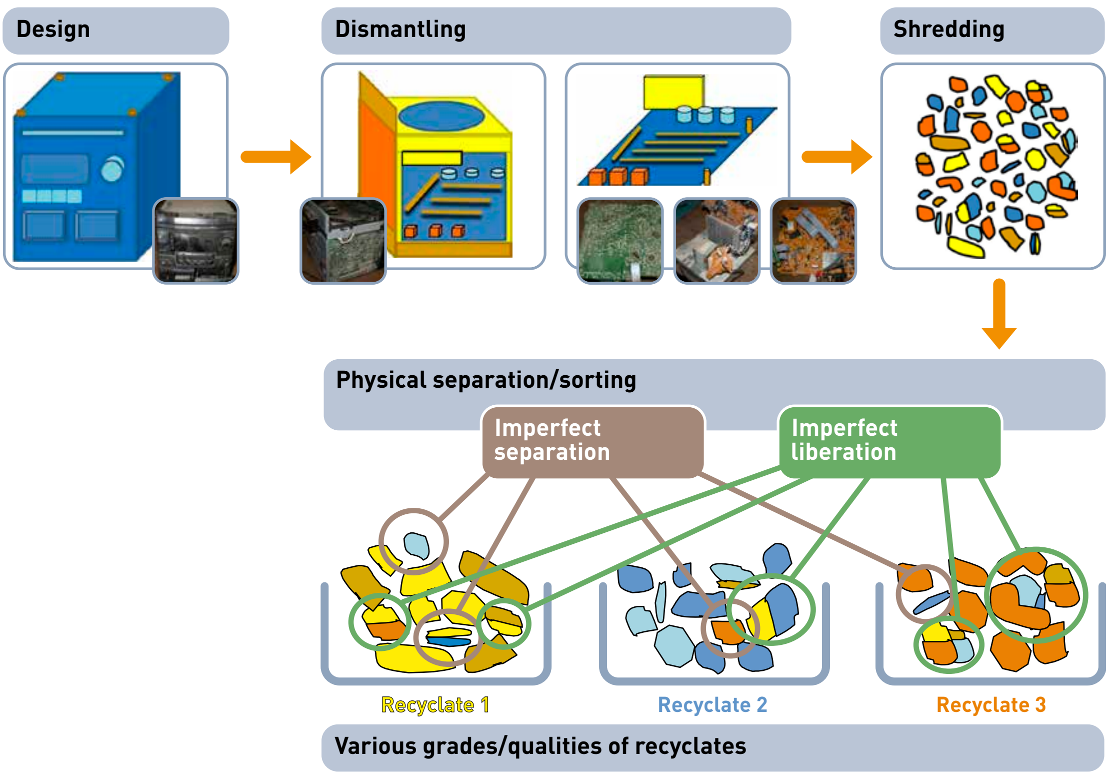


Figure 29 shows some types of recyclates that can result from sorting (schematically shown in Figure 28).

Figure 29:

Impure quality recyclates created during physical separation of shredded cars (Reuter et al., 2005).

Clockwise from top left:

(i) Major fraction of steel scrap.

(ii) Mixture of wires.

(iii) Non-magnetic mixture of magnesium/aluminium/zinc/copper/stainless steel.

(iv) Mixture of plastics used as fuel.

(v) Smaller-fraction mixture of Mg/Al/Zn/Cu/Stainless Steel.

(vi) Zooming into the steel fraction (above) containing contaminant copper.

Mechanical sorting commonly produces imperfect recyclates (Figure 28) and society is probably best suited to discern between the vast combinations of materials, to produce the highest grade of recyclates possible. Typical recyclates created through dismantling are shown in Figure 30.

Figure 30: Groups of components best sorted by hand for producing the cleanest recyclates (van Schaik and Reuter, 2010b).

Coils
Copper, Ceramics, Plastics, PVC, Copper wire

Cu, Fe_3O_4, $[-C_3H_6-]_n$, PbO, SiO_2

PWBs
Epoxy, PMs, Solder, Aluminium, Steel, Stainless Steel, Cables (PVC+copper), Electronic Components

Au, Ag, Pb, Pd, Sn, Ni, Sb, Al, Fe, Al_2O_3, Epoxy, Br etc.

Wires
Copper, PVC

Cu, $[-C_2H_6Cl-]_n$

Getters
Glass, W, Plastics

W, BaO, CaO, Al_2O_3, SrO, PbO, SiO_2

Wood Housing
Steel (staples), Plastics

Fe, $[-C_3H_6-]_n$

CRT
Glass (front and conus), Ceramics, Steel (mask etc.), Fluorescent powders

PbO, BaO, SrO, Fe_3O_4, Fe, Eu, ZnS, SiO_2, Y_2O_3, etc.

Plastic Housing
Plastics, Steel (bolts etc.)

$[-C_3H_6-]_n$, $[-C_{11}H_{22}H_2O_4-]_n$, Cl, Br, Sb_2O_3

Metal
Steel

Fe

Box 8:

The effect of joints on liberation

In many products, such as cars, different components are joined by welding, bolting, riveting, gluing, inserting contracted bushings, foaming connections, and chemically connected materials/phases in compounds. Moreover, such components often are non-metallic, such as rubber, plastics, glass and ceramics, and the joints have different degrees of difficulty for recycling.

Figure 31 shows a selection of some typical connection types and their liberation behaviour if they pass through a shredder/cutter. It shows that joints, like many other product parts, generally do not break into pure materials. The figure also mentions 'randomness of liberation' that predicts the degree of randomness with which the materials in a joint will break up.

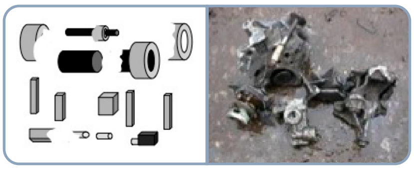
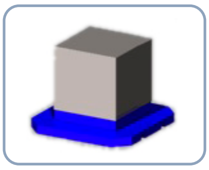
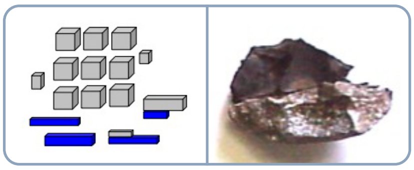
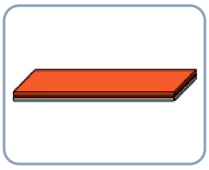
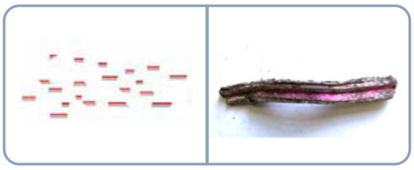
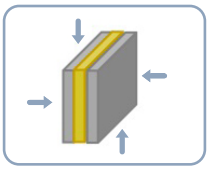
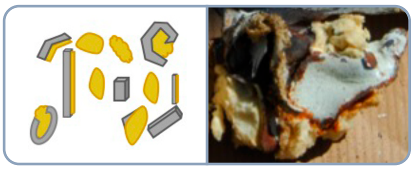
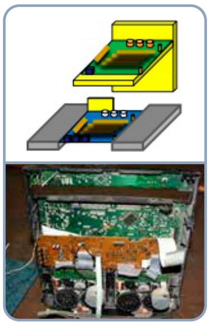
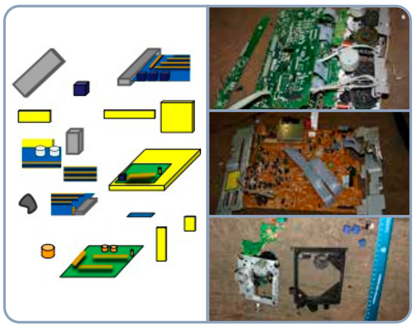
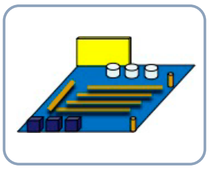
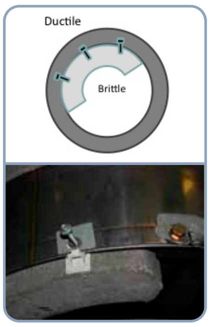
The degree to which the different connected materials are liberated to mono and multi-material particles during shredding and/or dismantling is determined by the following design properties (van Schaik and Reuter, 2010a; van Schaik and Reuter, 2012):

- The combined material properties (e. g. brittle, ductile) of the connection/product/component.
- The type of the material joints and connections (e. g. bolted, rivet, shape, glue, surface coating).
- Characteristics of the connection/joint, e. g. size of the connections in relation to particle size distribution after shredding.
- Complexity and homogeneity or heterogeneity of the product/component/connection (e. g. spatial distribution of the connections in the product, number of materials connected per connection).
- The thermodynamic compatibility among metals, alloys and metal compounds.

Box 8_b:

Figure 31:

Characteristics of connection types related to their specific degree and non-randomness of liberation behaviour after a shredding operation (van Schaik and Reuter, 2007a&b; van Schaik and Reuter, 2012).

Connection types (design)	Before shredding	After shredding	Liberation behaviour
Bolting/riveting			• High liberation • High randomness
Gluing			• Medium liberation • Medium randomness
Coating/Painting			• Low liberation • Low randomness of liberation
Foaming			• Medium liberation • Medium randomness
Examples (including effect of characteristics of connection)			
Connected materials/ components of different levels of complexity			• High/medium liberation from structure • High/medium randomness (both depending on joint type and connected materials)
Heterogeneous/ high number of connections per surface area			• Low liberation on component • Low randomness
Material properties, low complexity, low number of joints			• High liberation • High/medium randomness (depending on joint type and connected materials)

3.3.2 Size reduction

In addition to the aims of liberation, the particle size must suit the chosen processing method. The different material behaviours will dictate the method of size reduction. Metal alloys, for example, must be sheared in order to leave surface coatings almost intact. A common method of size reduction is shredding, which is used for end-of-life cars, but most electronic scrap has to be manually broken before shredding.

The resulting output from size reduction is a mix of broken pieces containing different combinations of materials and of different sizes, the latter expressed by a distribution curve.

3.3.3 Understanding the physics of separation

The performance of liberation and separation processes strongly influences the limits of recycling complex, multi-material consumer products, which often uses a network of different processes. These liberate and separate the different interconnected materials into several recyclates (steel, copper, aluminium, plastic, etc.), before taking them as input to final treatment processes, such as metallurgical processing (Figure 32).

A shredder or any other device for size reduction produces a set of particles with a range of physical and/or chemical properties and a size distribution. The physical properties will dictate the separation methods, and the chemical properties will influence the results of metallurgical processing. All of these properties have a (statistical) distribution. For instance, ordinary carbon steels are (ferro) magnetic, but copper alloys are not, which makes the first susceptible to magnetic separation. A thumb-size electric motor of a car with a magnetic core and a copper coil, if not shredded, will be attracted by a magnetic separator, adding some copper to the magnetic steel fraction. Such a combination of properties will thus affect the outcome of any separation step before metallurgical processing; in addition, particles with the same magnetic susceptibility will behave differently in separation depending on their size.

3.3.3.1 Physical sorting processes

The purity of recyclates [a] created by sorting is limited by the efficiency and thus the physics of the liberation and sorting process. Physical sorting processes can be used for separating materials from waste (e.g. metal cans from mixed waste) before it goes into a shredder, or after it is broken into pieces (so-called 'post shredding technology'). Such sorting processes make use of the physical properties of the inputs, such as magnetic properties, conductivity and density (Figure 33), and can either be dry or in solution ('wet'). Note that in wet processes the medium has to be cleaned, creating sludge, but that dry processes can produce dust –containing both metals and other possible hazardous compounds.

Dry separation methods include manual and ballistic sorting, and also: (i) magnetic separation; (ii) eddy-current separation; (iii) air separation/zigzag wind sifter; (iv) screening; (v) fluidized-bed separation; (vi) sensor based sorting (by image analysis, colour, x-ray, spectroscopy); (vi) wire sorting; and (vii) electrostatic sorting. Wet separation methods include: (i) sink-float; (ii) heavy-medium cyclones; (iii) jigging; (iv) shaking tables; and (v) flotation (Cui and Forssberg, 2003).

a Recyclates are inputs into recycling processes.

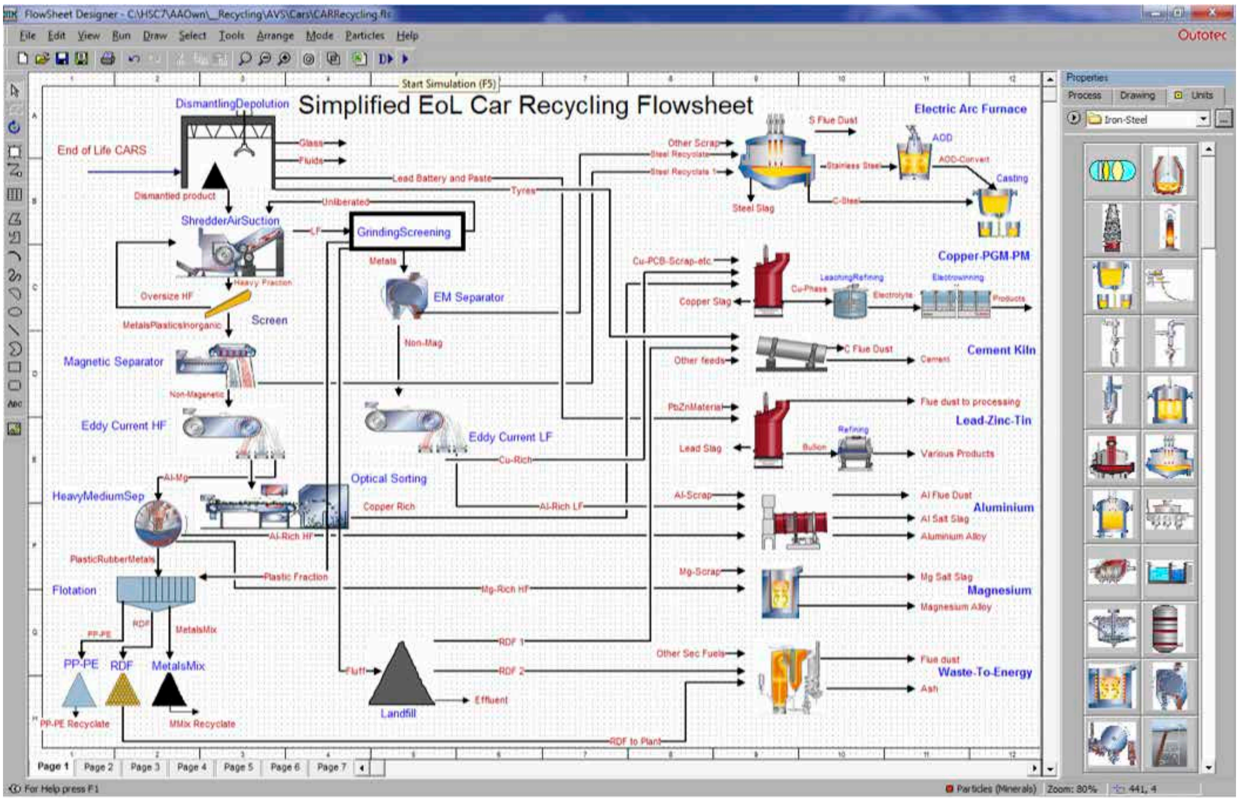


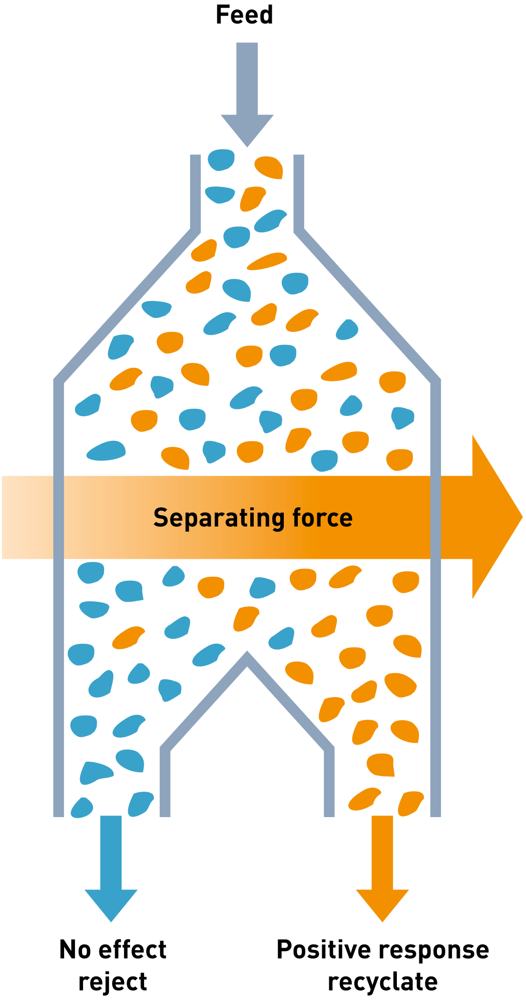
Figure 32:

Example of recycling cars, a complex network of processes and interconnected material flows. Separation processes are of key importance in producing suitable recyclates for processing in a metallurgical plant (van Schaik and Reuter, 2012, HSC Sim 1974 – 2013).

Zoom

Figure 33:

Generic separator using the laws of physics and material properties for separating materials.



Variables affecting separation include

- Fluid viscosity (ease of flow)
- Solids volume concentration (significantly affects viscosity)
- Flow turbulence (and turbulent energy dissipation)
- Boundary flow along the separator walls
- Eddy flows, i. e. swirls that dissipate energy and efficiency
- Particle shape affecting terminal velocity, e. g. plate-like particles will fall differently than more spherical ones (shape-factor)
- Hindered settling, i. e. particles affect each other's flow
- Momentum transfer between phases and within a phase
- Uneven force field separation, e. g. due to technological constraints
- Zeta potential, e. g. the electrical surface charges on particles
- pH of fluid
- Physical distribution of particle properties, e. g. density, conductivity, magnetism (and other properties than those used for separation)

3.3.3.2 Combined use of separation methods

None of these separation methods creates pure streams of material, but only increases purity. Using the example of a density-based separator, Figure 34 illustrates that the fate of a particle in a separator is best predicted by a probability distribution. The red line shows what would happen in an ideal separator – which does not exist – that sends all particles to either a 'heavy' or a 'light' fraction, depending upon their density. The blue line shows the actual cumulative probability that a particle of the density on the x-axis will end up in the heavy fraction. Particles in the shaded areas are misplaced. Similar separation efficiency curves exist for separations based on any property.

When particles are mixes of material, such as pieces of Printed Wire Board, separation is problematic. The physical property distributions used in separation may not be compatible with the chemical property distributions, which are important for final processing. If, for example, density is the separation method, it is evident that particles consisting of three joined materials of different chemical composition will separate on the average density of the three materials, thus creating a recyclate fraction with an unsatisfactory composition. Recycling operations usually have to combine separation methods for obtaining the required purity levels. Table 14 shows various combinations used for mixed metallic waste streams (mainly old cars, but also WEEE) by different operators.

Figure 34:

Separation-efficiency curve for an arbitrary material during physical separation (Heiskanen, 1993; King, 2001).

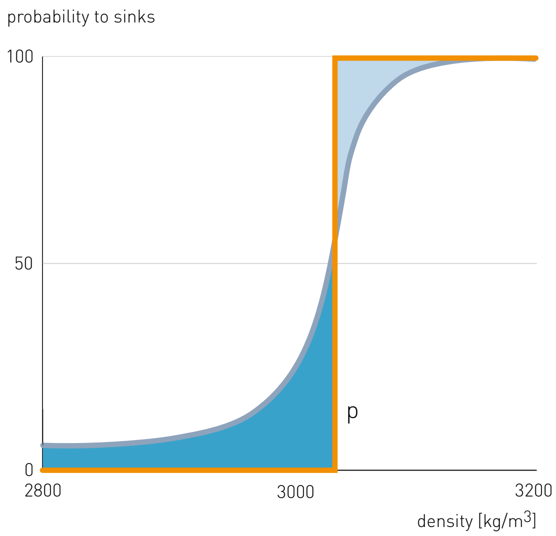


Table 14: The selection of technology in various recycling plants (Vermeulen et al., 2011).

Separation techniques	Argonne	Galloo	MBA-polymers	Salyp process	Stena	R-plus (WESA-SLF)	VW-Sicon
Air classification	x	x	x	x	x	x	x
Magnetic separation	x	x	x	x	x	x	x
Eddy current separation	x	x	x	x	x		x
Screening		x		x	x	x	x
Trommel separation	x	x		x	x		
Optical sorting				x			x
Manual sorting					x		
Drying						x	
Sink/float separation		x		x	x		x
Froth flotation	x						
Thermo-mechanical sorting				x			
Wet grinding			x				
Hydrocyclone			x				
Static, hydrodynamic separation tanks		x					
Heavy media separation					x		
Status of development	Operating plans	Operating plans	Operating plans	Operating plans	Operating plans	Operating plans	1 trial plant + 2 under construction
Overall recovery rate	90 % of polymers > 6 mm 90 % of metals > 6 mm	90 %	Not given	86 %	80 %	92 %	95 %

Even in combination, liberation and separation methods do not create pure material streams. This is illustrated by two studies on the recovery of precious metals from PCs with different pre-processing separation techniques. One study compared a fully manual sorting process with a combined dismantling and shredding process using automatic sorting (Meskers et al., 2009). The other study investigated the precious metal flows in a state-of-the-art European facility processing a mixture of ICT and consumer electronics. Both studies investigated precious metal recoveries from material streams after pre-processing.[a] Table 15 summarizes the results, showing that high recovery can be achieved, although the cost of manual dismantling must also be considered (see Table 4).

3.3.4 Tradeoffs between recovery grade and recovery rate

As will be clear from the above, commercial recycling systems cannot create completely pure recyclate streams (van Schaik and Reuter, 2004a&b) and never achieve 100 % material recovery, there being a trade-off between these two goals. The recovery vs. grade curve in Figure 35 (left) shows how much recovery can occur, depending on the required grade (purity) of the output. If the grade has to be 100 %, a relatively small amount will be recovered, as only a fraction of the input feed is pure and totally liberated. For instance, a grade of 50 % can be obtained with a recovery of 94 %, while a grade of 80 % will give a recovery of only 75 %.

Table 15: Comparison of precious metals recovery rates from suitable material streams after pre-processing.

Reference	Process description	Silver	Gold	Palladium
Meskers et al. 2009	Manual dismantling (first dismantling) 1.4 tonne PC	49 %	80 %	66 %
Meskers et al. 2009	Manual dismantling (second dismantling) 1.4 tonne PC	92 %	97 %	99 %
Meskers et al. 2009	Manual depollution and smashing and hand picking, hammer mill and automating sorting automatic sorting 1.4 tonne PC	75 %	70 %	41 %
Chancerel et al. 2008	Manual depollution and shredding and automatic sorting 27 tonnes ICT and consumer electronics	11 %	26 %	26 %

The liberation behaviour of the example is complex. It shows that, though a large percentage of particles was liberated from the compound, liberation was insufficient for a large fraction of the particles (Figure 35, right). This form of curve is often seen in WEEE systems, where the housing does not contain the values sought after, and other parts of the device contain combinations that are difficult to liberate. If a large percentage of material has low liberation, only poor grades will be obtained.

a Both investigations were a snapshot at a certain time for a certain input material and do not allow a direct comparison and assessment of the used pre-processing technology.

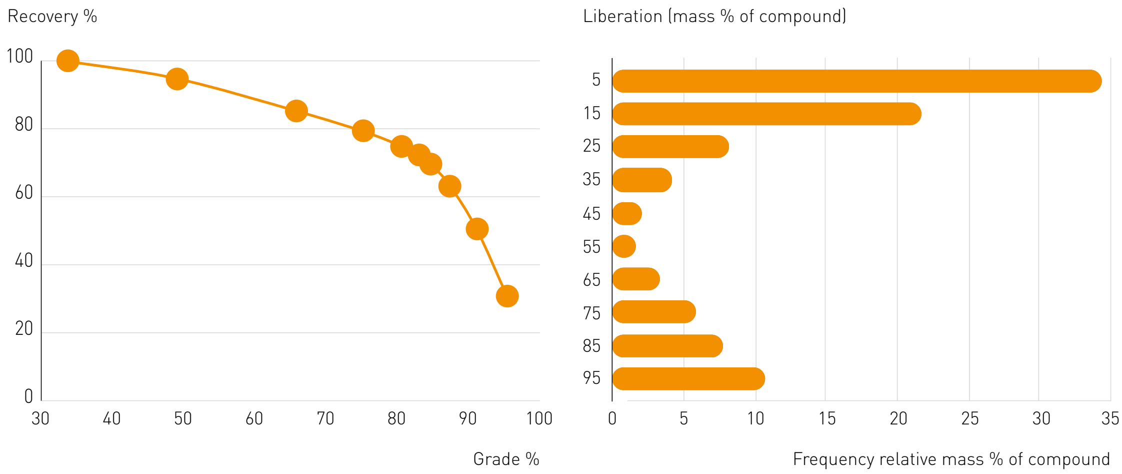


Figure 35: Maximum grade-recovery curve (left) for liberation characteristics of scrap (right).

The second example (Figure 36) shows simple characteristics of the material with relatively good liberation, except for a material joint that is difficult to break, seen as a peak at 65 % liberation of the mineral. It is clear from this figure that 90 % purity of the recyclate can be achieved with an 80 % recovery, i. e. a relatively high-grade recyclate can be created with higher economic value than for the previous example.

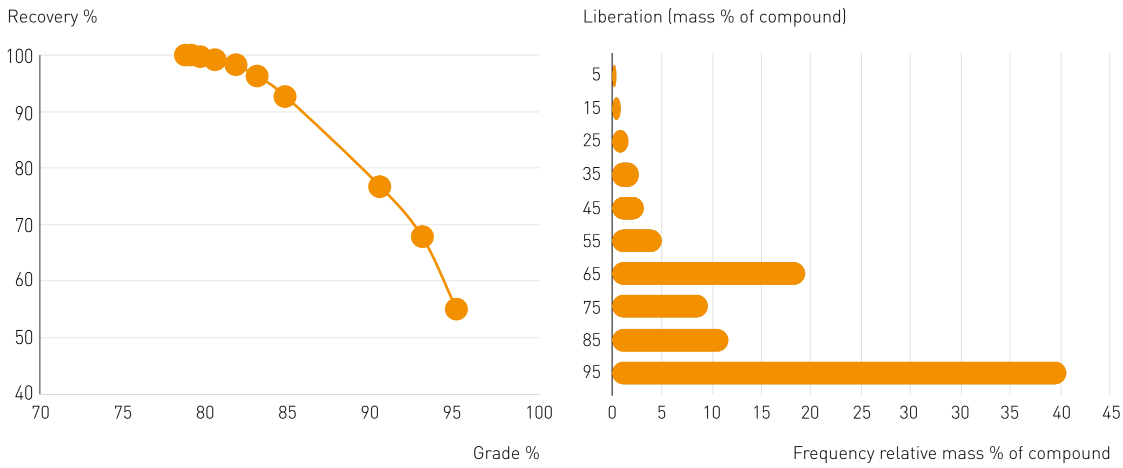


Figure 36: Maximum grade-recovery curve (left) for liberation characteristics of scrap (right) (Heiskanen, 1993).

These grade-recovery curves also illustrate that where end-of-life products do not shred perfectly into 100 % liberated and separated streams, valuable metal losses will be a fact of physics and nature.

3.3.5 The impact of system dynamics and distributed nature on recycling

When assessing the possibilities of improving recycling, it is imperative to fully understand the dynamic nature of product design, recyclate quality and plant operation. This is the prerequisite for predicting the recycling and recovery rates of the different materials in the product that will change over time, as well as the particulate properties, particle-size distributions and recyclate qualities. The different aspects affecting the dynamics of the resource cycle have been included in dynamic modelling approaches for ELVs and different WEEE/e-waste products (Reuter et al., 2005; Reuter, 2011a). This understanding is a prerequisite to improve resource efficiency.

According to data from the European Topic Centre on Sustainable Consumption and Production, metals, especially iron, copper and aluminium, form most of the material weight of today's e-waste (Figure 37). However, this will change with time, due to rapidly changing product designs and consumer behaviour.

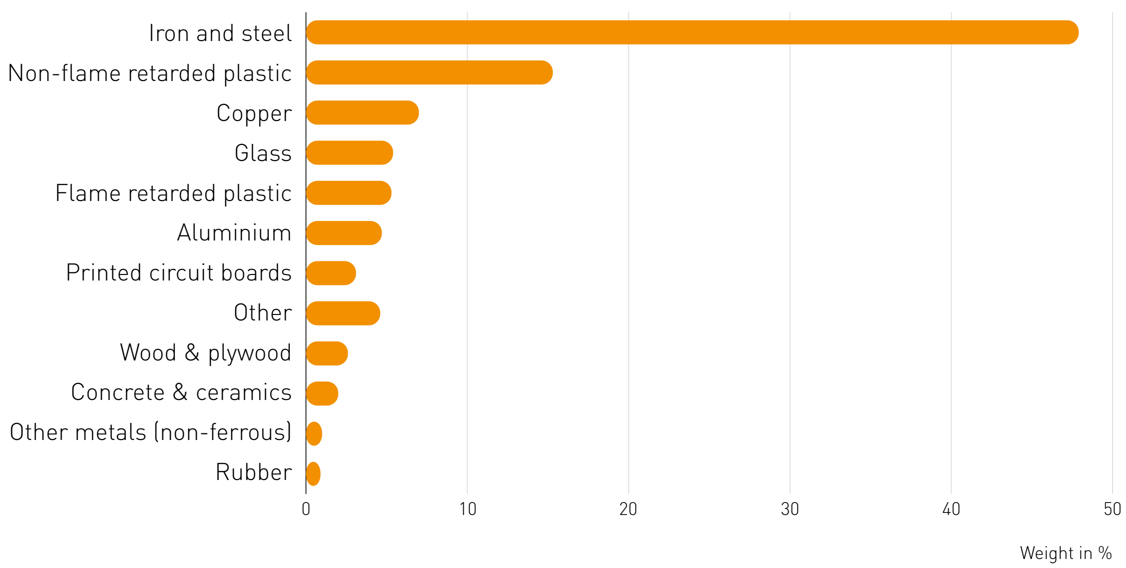
3.4 Thermodynamic understanding: The key to optimizing Product-Centric recycling

Physics primarily determine the potential and limits of metal recycling, the thermodynamic properties of each metal being particularly important. When metals have similar thermodynamic properties, heat-based processing technology cannot fully separate them, resulting in impure, mixed alloys that may have limited or no value. In such cases, hydrometallurgy is required, for example as used during the separation of chemically similar Rare Earth Elements that are separated by several solvent-extraction steps. These physical realities have consequences for all the links in the chain of activities that support recycling.

The Metal Wheel (Figure 15) placed in the centre of Figure 38 succinctly expresses what these thermodynamic linkages mean during the processing of metal-containing materials. It also shows that elements never occur alone in nature nor in products, and that interactions between them are complicated.

Figure 37:

Typical WEEE material composition (European Topic Centre on Sustainable Consumption and Production, 2009).



Understanding these physics and the economics for separating these elements lies at the core of maximizing resource efficiency and therefore of metals and materials recycling in general. The dark blue ring near the centre of the Metal Wheel in Figure 15 and Figure 38 shows metals currently used in significant quantities by society. These are so called 'Carrier Metals' because they are the backbone of recycling processes and thus 'carriers' (usually called commodity or base metals in industry jargon). Historically, they were the target of primary production processes using concentrates derived from ores, such as:

- Haematite (Fe_2O_3) as the basis for iron (Fe) and steel.
- Chalcopyrite ($CuFeS_2$) concentrate as the basis for the primary copper (Cu).
- Sphalerite (ZnS) as the basis for the zinc (Zn).
- Galena (PbS) as the basis for lead (Pb).

Current metallurgical technology is generally found in integrated processing plants of these Carrier Metals, whether from natural ores or recycled raw materials, like residues, and end-of-life products. Each slice of the Metal Wheel shows the metals that can be processed with the technology at the tip of that slice, such as smelting, refining, etc. The light-blue ring shows other Carrier Metals that can be extracted with the same processing technology. The white ring shows other valuable metals that may be co-produced as part of the Carrier Metal's processing infrastructure. The outer green ring shows the metals and other elements that cannot be economically recovered by the same processing technology, but can be safely dealt with. The diagram is based on the current best-available technique (BAT) used in extractive metallurgy for producing metals from residues, sludges, slags, speiss, slimes, etc. (Ullmann's Encyclopedia, 2005).

Figure 38 also shows Design for Resource Efficiency, illustrating which metals can and cannot be recovered from complex recyclates and metal linkages by the main Carrier Metal processing technology. The metals and compounds whose recovery is currently impossible are shown in red on a slice of the Metal-Wheel. This therefore shows where innovative metallurgy must be developed for recovering such elements.

Box 9:

Steel recycling

Steel recycling can cope only to a certain extent with copper, tin and antimony in the input streams. These elements, because of their chemical and thermodynamic properties, pose a formidable challenge for their removal during the production of high-quality steel. Commonly, the only way to cope is to dilute them into concentrations that are tolerated by alloy requirements. Sorting helps, but the steel scrap has to be de-tinned and de-galvanized before being fed into the smelter. Plastics containing antimony flame retardant must also be removed to alleviate this problem. However, complex post-consumer scrap such as WEEE can contain 50+ elements at the same time, many of which cannot be dealt with during steel making and thus cannot be recycled. However, non-ferrous metallurgy can cope with these elements, but, as the name non-ferrous metallurgy suggests, the iron will then be lost as FeO in the slag.

Consult Appendix A: Details on Recovery of Metals from Recyclates, Appendix E: Models and Simulation in Recycling and Appendix F: Physics of Extractive Metallurgy for more details.

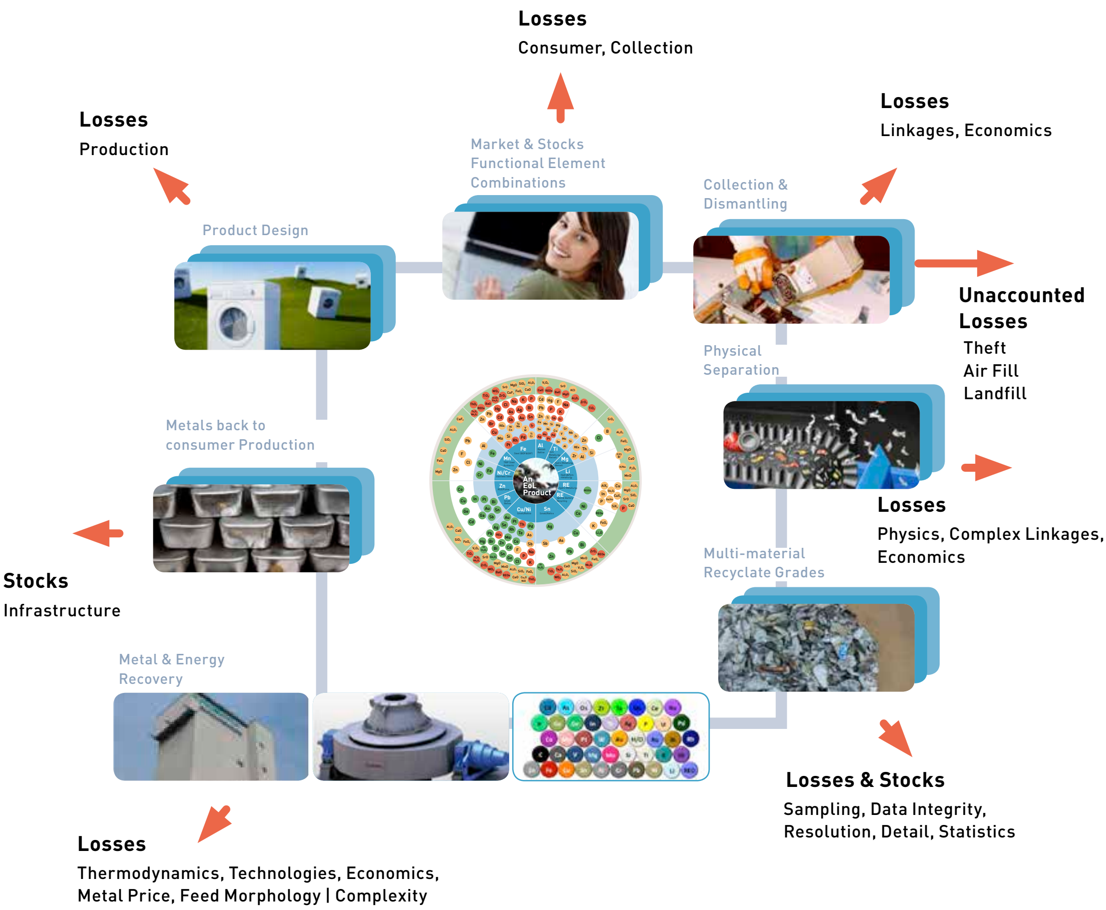


Figure 38: Design for resource efficiency showing the destination of elements from an end-of-life material. If a WEEE product falls in the copper and Zn/Pb slices, many metals can be recovered, but if it falls in the incorrect slice, e.g. the steel cycle, the metals may be lost, diminishing the resource efficiency. Policy should thus pay particular attention to the complete infrastructure and systems.

3.4.1 Process metallurgy: smelting (pyrometallurgy), leaching (hydrometallurgy) and refining (hydro- and electrometallurgy)

After separation, recycling inputs go to metal-production processes. Pure scrap metal can be simply remelted – if in metal and alloy form, and not contaminated by other materials – for returning it to the cycle. Less pure waste streams (and metal ores) are processed either by pyrometallurgy (smelting), or by hydro- and electrometallurgy (Appendix F: Physics of Extractive Metallurgy).

- Pyrometallurgy, also known as smelting, uses high temperatures (sometimes above 2000 °C) to drive chemical reactions as well as melting (just remelting metals) or smelting (chemical conversion from compound to metal) processes. The processes vary depending on the metal and materials being smelted. The advantage of smelting is that it concentrates metals into metal alloys or similar, therefore decreasing their entropy.

- Hydrometallurgy, or leaching, puts metals into a low-temperature aqueous solution, reaching +90 °C under atmospheric conditions, and +200 °C when under pressure for separating different elements and compounds. Again, various processes exist, based on either acid (low pH) or basic (high pH) aqueous solutions. Hydrometallurgy generally first increases the entropy of metals, before recovering the ions in solution with a significant input of energy for lowering the entropy again (Tuncuk et al., 2012).

Pyro- and hydro-metallurgy are commonly used in tandem for obtaining valuable metals, particularly non-Carrier Metals. Optimiz-

ing the entropy thus maximizes the resource efficiency. For many economically viable metallurgical plants, depending on the metal, pyrometallurgy does the first rough separation (concentration into speiss, metal alloy, matte, flue dust, etc.) and hydrometallurgy produces the final high-quality metals and other types of valuable products. Alloying usually happens during a second stage, for example to produce specific alloy types in alloying and ladle furnaces.

Contrary to such pragmatic pyro- and hydrometallurgical solutions, there have been various attempts to push pure hydrometallurgical recycling solutions. These often overlook that, when bringing elements into solution from complex waste such as WEEE, complex electrolyte solutions are created that have to be purified before metals can be produced from them. The purification inevitably creates complex sludges and residues that must be dealt with in an environmentally sound manner, which is often economically impossible and creates dumping/containment costs.

3.4.1.1 Steel and stainless steel scrap smelting in Electric Arc Furnaces (also see Appendix A: Details on Recovery of Metals from Recyclates)

High-quality steel scrap is usually processed in Basic Oxygen Furnace (BOF) convertors, of which the Electric Arc Furnace[a] is the most flexible. Ultra High Power Electric Arc Furnaces (with transformer ratings of 250 MVA) (Figure 39), are very efficient at producing steel in batches of over 160 tonnes per melt (see Appendix A: Details on Recovery of Metals from Recyclates for other technologies on steel recycling as well as for energy savings, also for stainless-steel recycling). Stainless-steel scrap (Fe-Cr-Ni-C-X alloys) is processed/smelted in similar arc furnaces as for normal steel, though for thermodynamic reasons it is converted in Argon Oxygen Decarburization (AOD) converters.

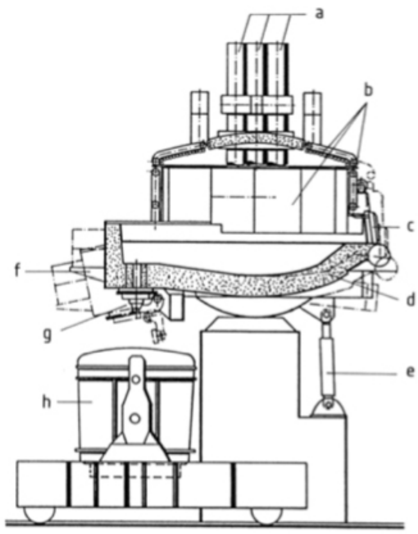


Figure 39:

Electric Arc Furnace (EAF) for smelting steel scrap (Krüger et al., 2005; SMS-Siemag: www.sms-siemag.com).

(a) Electrodes
(b) Water-cooled walls and roof
(c) Tiltable furnace
(d) Refractory lining
(e) Tilting mechanism
(f) Spout
(g) Eccentric tapping
(h) Ladle

a Steel recycling routes are discussed in various texts such as Ullmann's Encyclopaedia of Industrial Chemistry (2005).

3.4.1.2 Non-ferrous smelting (see also Appendix A: Details on Recovery of Metals from Recyclates)

Non-ferrous metallurgical smelting is well established. It uses scrap, residues and batteries from various sources, and can separate and recover the contained metals by concentrating them into metal/matte, speiss, slag, flue dust and offgas, which can be further processed. This mostly involves hydrometallurgy, with numerous flowsheet possibilities and subsequent electrowinning[a]/refining.

3.4.1.3 Aluminium scrap smelting – wrought and cast

The aluminium industry is doing much to maximize the recycling of the various aluminium-containing metal alloys and other materials.

Box 10:

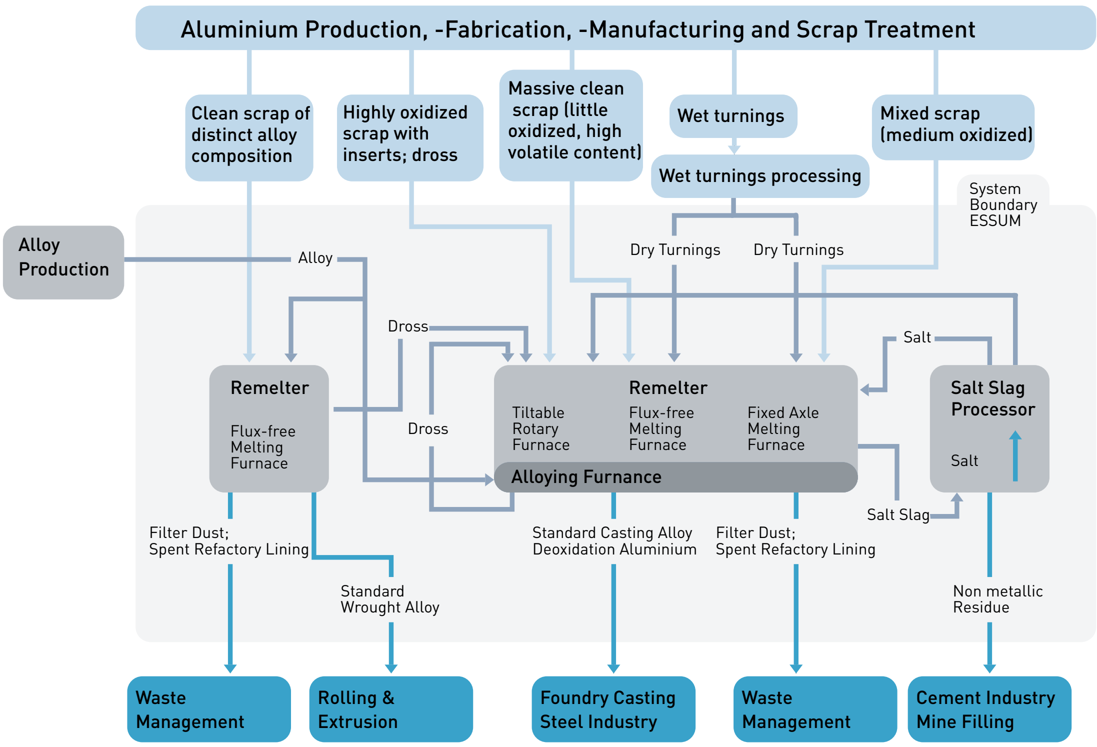
Aluminium recycling (European Aluminium Association, 2006)
Aluminium can be recycled repeatedly without loss of properties, if scrap is pure and non-contaminated by product complexity. Otherwise dilution of dissolved contaminants by virgin aluminium is required. The high value of aluminium scrap is a key incentive for recycling. Such recycling benefits present and future generations by conserving energy and other natural resources. It saves about 95 % of the energy required for primary aluminium production, avoiding corresponding emissions including greenhouse gases. Industry continues to recycle, without subsidy, all the aluminium collected as scrap, or from fabrication and manufacturing processes. However, with the help of appropriate authorities, local communities and society as a whole, the amount of aluminium collected could be increased further. Global aluminium recycling rates are high, around 90 % for transport and construction applications and about 60 % for beverage cans.

Different technologies used for processing different aluminium scrap types are shown in Figure 40. High-quality and pure scrap is remelted to produce wrought aluminium qualities. Refining under a salt (NaCl-KCl) slag is used for poorer scrap qualities.

a Electrowinning separates metals from solutions by electrolysis – applying electricity to the solution.

Figure 40:

Technologies used in aluminium recycling for various scrap types, including salt-slag smelting for producing cast aluminium from scrap (Boin and Bertram, 2005; Bertram et al., 2009).



Even with simple aluminium scrap, intimate connections to other materials can have a marked effect on recycling. The right side of Figure 41 shows smelting results from two scraps, A and B (on left). Metal recovery from scrap A is 84.3 % by weight, but that from scrap B is 95.3 %. Surface area is a major factor that determines metal recovery, but organic and other coatings and materials attached to the aluminium can create compounds, such as sulphides (e. g. Al_2S_3), phosphides (e. g. AlP), hydrides (e. g. AlH_3) or carbides (e. g. Al_4C_3), which result in losses and other issues. The losses result from the fact that the compounds are not aluminium (i. e. of an oxide nature) and collect in the salt-slag phase; other issues are when these compounds react with, e. g., water or moisture in the air to form H_2S (g), PH_3 (g), H_2 (g) and CH_4 (g), respectively, and Al_2O_3 (also lost), which are toxic, explosive or combustible. Hence, recovery is much affected by the purity and morphology of scrap.

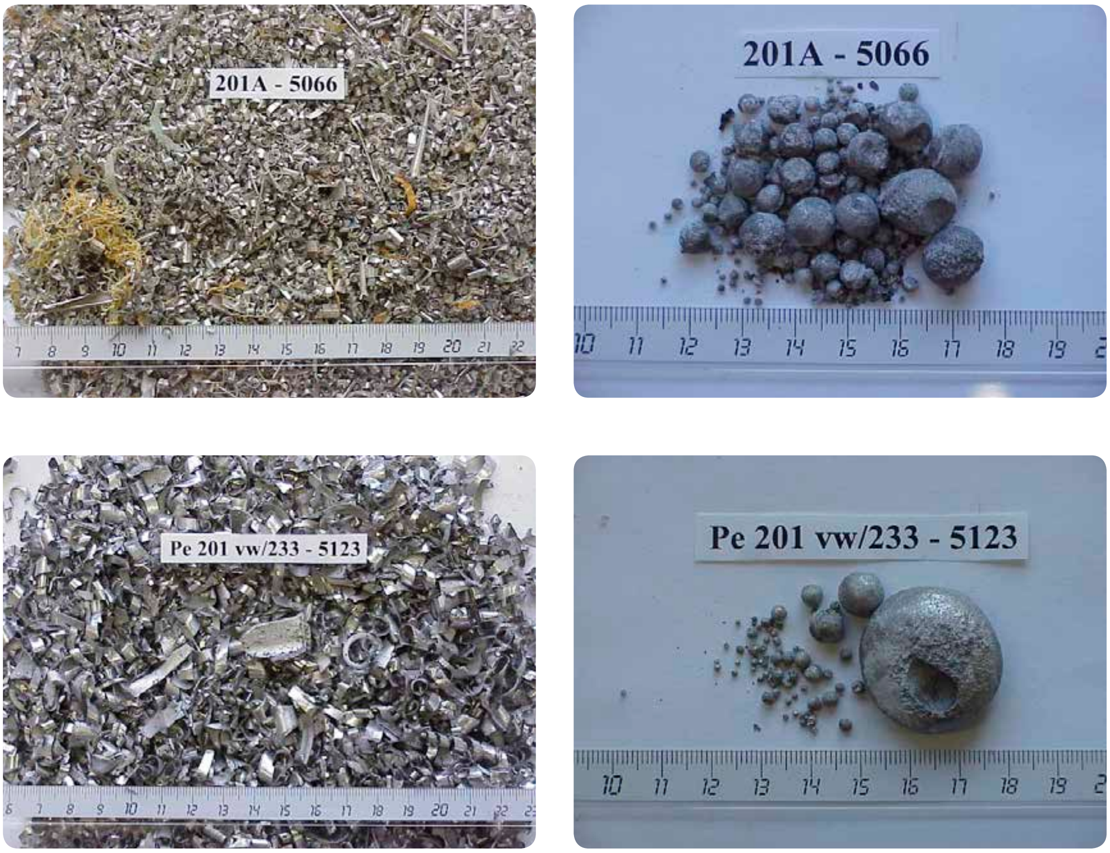


Figure 41:

The effect of scrap surface area (left) on recovery (right) of two scrap types – recovery is held back by inactive alumina coating scrap, so scrap with a higher surface area/volume ratio (upper picture) has lower recovery rates than larger pieces (bottom set) (Xiao and Reuter, 2002).

3.4.1.4 Copper and nickel scrap smelting as part of a primary copper smelter (a typical flowsheet in the Cu-segment of the Metal Wheel (Figure 15)

As for aluminium recycling, an integrated copper smelter can accept a variety of copper-scrap types. A large fraction of relatively "pure" copper scrap can be accommodated in copper converters and anode furnaces, while WEEE and lower-grade scrap is processed in a 'Kaldo' or a 'TSL' furnace. Therefore, the schematic flowsheet shown in Figure 42 is well suited for recovering the many elements associated with copper-containing scrap and residue materials, and this in an economically feasible and environmentally friendly way, while still recovering many of the minor elements associated with copper-input materials.

A hydrometallurgical process can extract some valuable elements, such as bismuth, gold, silver, platinum group metals (iridium, rhodium, ruthenium, osmium, palladium and platinum) and others that occur in copper scrap, after electro-refining. Therefore, WEEE, PGM, metal-containing catalysts and other complex recycled materials are often recycled on the back of copper metallurgy. This example also nicely shows that a combination of pyro- and hydro-metallurgy can extend the limits of recycling, thus reflecting the concept of Carrier Metal metallurgy, i. e. a segment of the Metal Wheel (Figure 15).

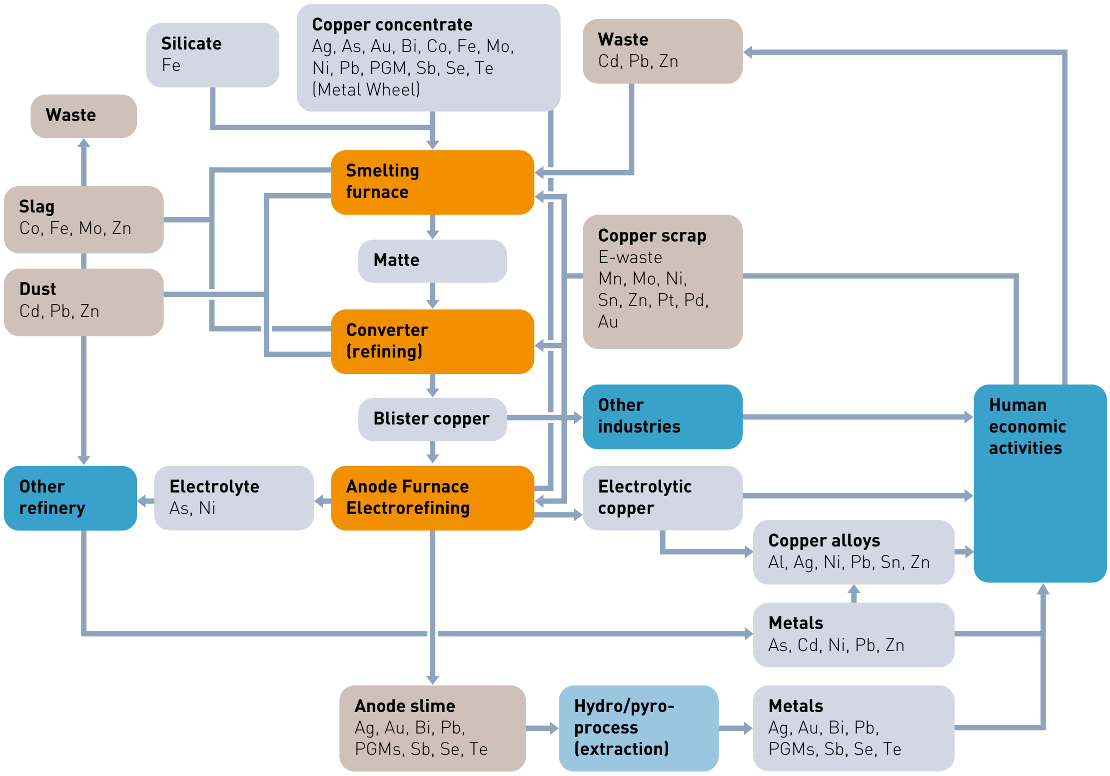


Figure 42:

The flow of elements associated with copper production (hydro- and pyro-metallurgy) showing the link between primary production and recycling. Gangue minerals are not included. (Nakajima et al., 2008; 2009; 2011; Nakamura and Nakajima, 2005; Nakamura et al., 2007). This flowsheet fits into the copper segment of the Metal Wheel (Figure 15).

3.4.1.5 Other recovery processes (see also Appendix A: Details on Recovery of Metals from Recyclates)

Dedicated pyro- and hydro-metallurgical processes exist for the recovery and refining of materials rich in valuable elements and precious metals coming from pre-processing facilities[a]. In addition, precious metals can be recovered from other material flows related to WEEE. Several plastics-recycling companies in Europe and the USA reported informally that some of the precious metals contained in the material fractions that they receive for recycling are recovered during the removal of impurities from the plastics (Biddle et al., 1998; Novak, 2001). Data on these processes are not available.

a Reviews on metallurgical processes for recovering and refining (precious) metals from printed circuit boards were issued by Cui and Zhang (2008), Goosey and Kellner (2003) and Huang et al. (2009). The European Commission (2008) provided an overview of "Best Available Techniques" to recover precious and other non-ferrous metals.

3.4.2 The limits of metallurgical process engineering

3.4.2.1 Thermodynamic limits when using BAT

The thermodynamics of the furnace technologies described in this document (Appendix A: Details on Recovery of Metals from Recyclates) dictate a set of limits for recycling. They determine which combinations of materials can, or cannot, be recovered from shredded, dismantled and physically sorted consumer goods. See Appendix F: Physics of Extractive Metallurgy for more details on the thermodynamics and physics affecting these technologies.

3.4.2.2 The impact of the input stream

The purity of the input stream is affected by product design and the whole metals recycling chain. The limits of recycling are therefore also influenced by the factors that affect each of the three main steps of that chain and by how well the interfaces between these interdependent steps are managed: i) Collection; ii) Pre-processing, incl. sorting, disman-

tling, mechanical treatment; and iii) End-processing, incl. refining and disposal (UNEP, 2011a). Such input products cannot be considered as bundles of separate metals, alloys, plastics, oxides, sulphides, etc., as these are invariably connected to each other and enter the recycling system together. Their recovery and recyclability depend upon the combination of purity with which they enter the metallurgical stream and on the expertise applied to these metallurgical processes.

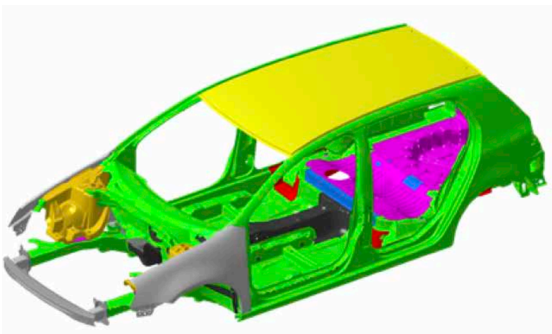
Box 11:

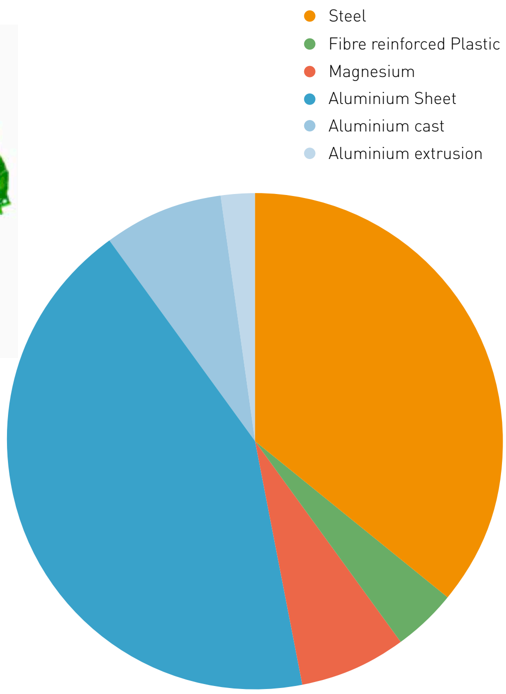
SuperLightCar

Figure 43 shows a multi-material super-light body-in-white for a car, combining various materials. The joints between the different materials must be strong enough to withstand collisions. Hence, they will also hold materials together during recycling, leading to material contamination. If these joined materials are not thermodynamically compatible, they will be lost into one of the recyclate streams. For example, if aluminium joined to steel goes to a steel-scrap smelter, the aluminium will be lost as alumina (Al_2O_3) to the slag after the deoxidation process during steel-making. If fibre-reinforced plastics go to any metal smelting operation, they will be lost after supplying energy and carbon and hydrogen to the process. All the materials in Figure 43 therefore affect each others' recovery/recyclability, and all somehow determine how much of the metals are lost during recycling. Only if the materials can be well sorted and separated into "pure" recyclates, as shown by the pie-chart, can the Carrier Metals in Figure 43 easily be processed back into metal with minimal losses. Note that a printed circuit board significantly increases complexity.

Figure 43:

Weight and material composition of the SuperLightCar light-weight BIW concept (SuperLightCar, 2005–2009; Goede et al., 2008; Krinke et al., 2009).





3.4.2.3 Technological limits for processing complex recyclates

The other key aspect affecting the potential of recycling in any particular case is the technological, economic and thermodynamic knowledge of the recycling operator. The further this is from current best practice, the less he will achieve. This is particularly an issue with complex inputs, like consumer waste. When using natural ores, the relationship between the desired metals and accessory elements is relatively clear. However, the combinations of elements in recycled resources, such as by-products and waste, are often different from those in natural ores. Conventional metallurgical processes were optimized for the economical and efficient extraction of the desired metals from large amounts of natural ores of a constant grade. Using complex scrap and waste requires changing optimization, which needs specific expertise.

For most of the metals in consumer and industrial waste, the combination of metals and compounds needs processing with technologies for more than one Carrier Metal. To extract small quantities of metals from complex products and alloys requires a deep understanding of the metallurgy of more than one Carrier Metal, and an investment in larger, more complex systems and sophisticated non-ferrous metallurgy. This, in turn, requires a mix of metallurgical and thermodynamics knowledge to bring together the infrastructure into a system that treats the residues/intermediate products from one Carrier Metal process in another's. For example, mixed lead- and copper-based metallurgy in an integrated copper smelter (Figure 44 and Figure 45) is an excellent basis for recovering a wide range of elements from the feed materials. This also illustrates how the primary smelting of – in this case – copper and lead is used for the recycling of other metals found in electronic waste and scrap (Hagelüken, 2006; Cui and Zhang, 2008). Copper, lead and matte (molten metal sulphide) are a solvent for recovering precious metals. The primary metallurgical processing of copper and lead is generally followed by electro-winning (electrolysis) and refining, which effectively removes and recovers elements from crude metals, such as the Kayser Recycling System (Figure 46).

Figure 44: Metal-production flowsheet integrating copper and lead hydro- and pyro-metallurgy for maximizing metal recovery from Boliden's operating facility (Outotec, 2012; NewBoliden, 2012), fitting into the Pb and Cu segment of the Metal Wheel (Figure 15).

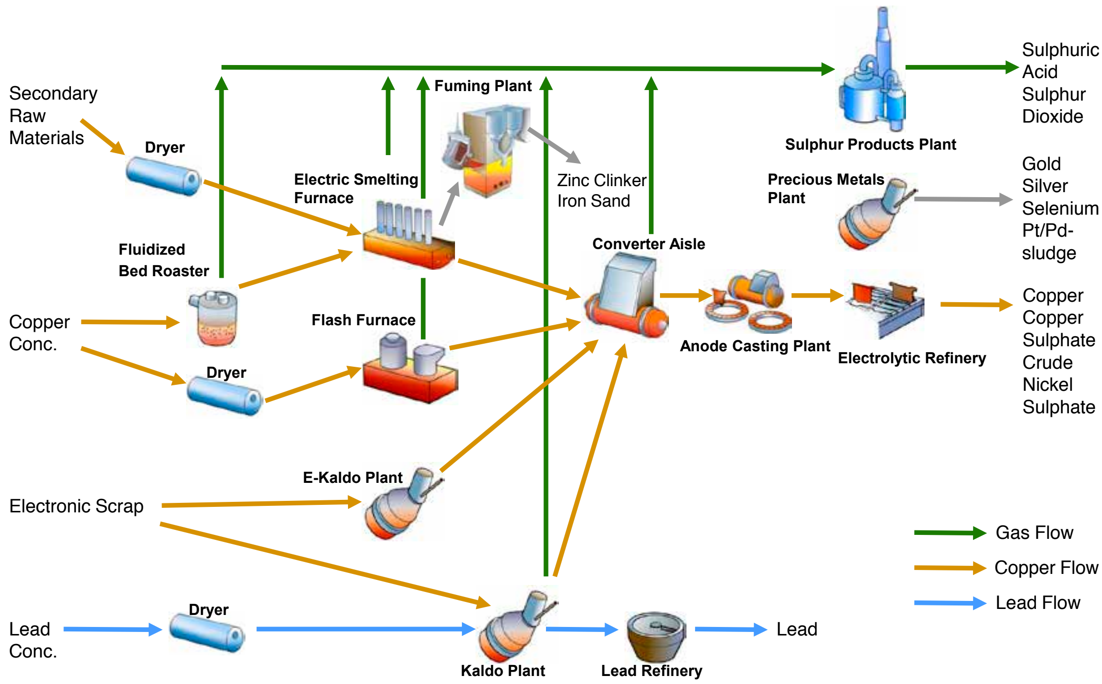
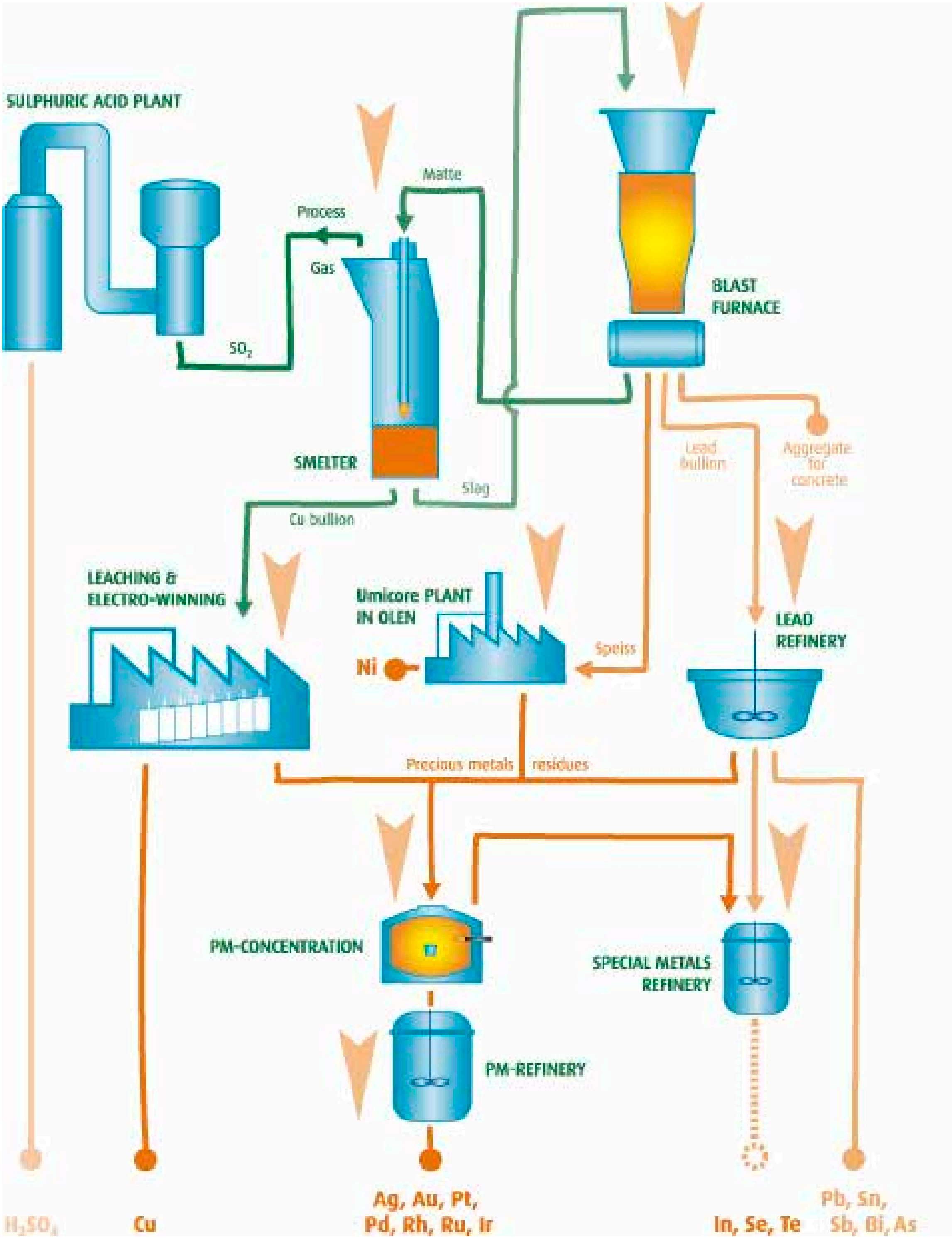


Figure 45:

The Umicore flowsheet based on copper and lead hydro- and pyro-metallurgy, using a TSL furnace for copper and a blast furnace for lead, which permits the processing of slag, matte, speiss, slimes, sludges, dross, etc. (Hagelüken et al., 2009) – This flowsheet fits in the two Pb&Cu segments of the Metal Wheel (Figure 15).



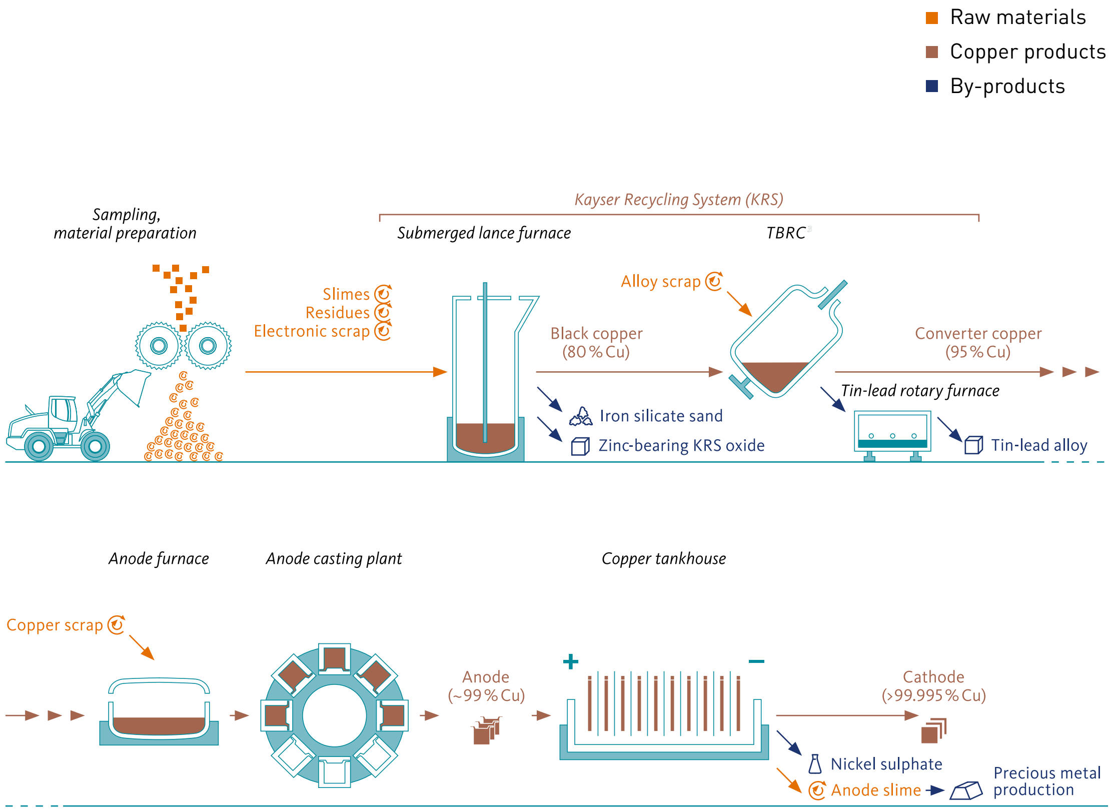


Figure 46:

The Kayser Recycling System for recycling copper metal and other copper containing residues. This flowsheet fits into the Cu segment of the Metal Wheel (Figure 15).

Metal-processing operations that integrate different Carrier Metal technologies are already operating successfully in many parts of the world, some examples of which are shown in Figure 47.

Figure 47:

Various smelters for the recycling of a wide range of materials including copper, lead, zinc, critical elements, e-waste, slimes, batteries, scrap, etc. All with high environmental standards as they are all located in or next to towns.

3.5 Economic considerations

3.5.1 Organization of the industry

In practice, one of the major limitations for metal recycling lies in the need for metal production to pay for itself. High output volumes from any one operation must pay for the cost of expensive equipment. For scarce and valuable metals, the demand and supply volume of various minor elements generally is too small to justify a dedicated recycling plant for such metals in EoL goods, such as lighting, solar panels, batteries, LEDs, or REE containing materials (like magnets). Although the need for presently critical/scarce elements is projected to grow significantly in the future, it is still iron, aluminium, copper, tin, titanium and chromium that represent the largest metal-recycling volumes.

The processing of recyclate streams currently mostly occurs on the back of large-scale production of base metals with compatible thermodynamic properties, i. e. Carrier Metals such as copper, iron, lead, lithium, nickel, rare earths (oxides), tin, titanium and zinc.

For example, for copper, with about a third of all production from recycled sources (about 8000 ktpa), only around 700 ktpa comes from dedicated recycled-copper smelting (Outotec) using recycled input as feed for its Carrier-Metal operations (e. g. the copper in WEEE). Therefore, the expertise and technology used for recycling usually is that of the primary metal producers. However, most of them for economic reasons have little interest in recycling the metals in small-quantity input streams and only use one Carrier Metal's set of processes, which complicates separation of incompatible elements more "at home" with another Carrier Metal.

Therefore, although the knowledge and technology for recycling complex products exists, this is often done in separate primary-metal silos rather than in combination. This obviously limits the recycling of complex streams. However, where an economic symbiosis exists, for example in the case of zinc-containing flue dust originating from steel-scrap smelting, then this issue can be mitigated as shown by Figure 48.

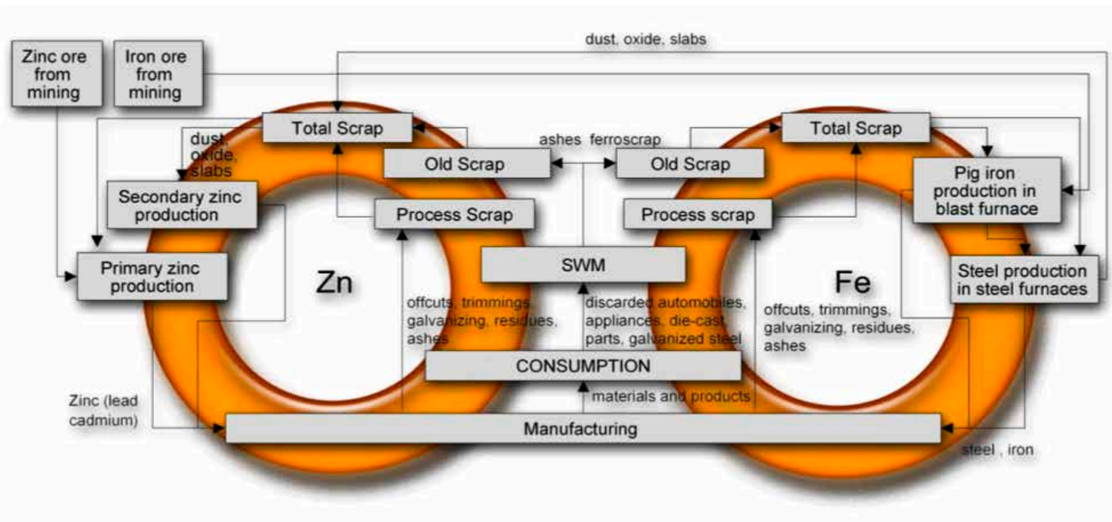


Figure 48: The link between the Iron and the zinc cycles for galvanized steel, a Material (& Metal)-Centric view (Reuter et al., 2005).

This situation with primary producers is unlikely to change by itself in the foreseeable future, as increased global demand for Carrier Metals and incomplete information on metal recycling (UNEP, 2010) provide few incentives for primary smelters to change their flowsheets. In addition, the organization of the industry tends to create inertia due to high capital investment, long plant life, etc., encouraging the continuation of single Carrier Metal operations. The metal-production industry has formed representative organizations based around the primary Carrier Metal operators; these organizations obviously promote the common denominator between their members in a more material-centric environment, so will unlikely promote innovation or explore additional sources of revenue in a more product-centric environment of metal recycling. Collaboration of different metal associations would help much to increase resource efficiency.

However, parts of this industry already operate in ways that show how the mainstream industry can change. Toll refineries (operators that charge for refining other people's ores) increasingly integrate different Carrier Metal technologies. Worldwide, various operations, many of which are mentioned in this document, already operate commercially successful integrated production sites.

Metallurgical technology providers are well placed for turning this industry limitation into an opportunity. Improved treatment and recovery of valuable metals in input streams generates additional revenue and hence profit or value-addition potential for metal producers. In addition, BAT usually is more resource efficient, significantly lowering energy demand as well as emissions and environmental impact. This can be an opening and opportunity for a fundamental resource-efficient-based change in the mainstream industry.

There is another negative consequence of this reliance on primary-metal-production expertise for recycling: where such expertise is lost in a country or region, recycling is also blocked. A case in point is the REE industry, which, through poor foresight, has concentrated metallurgical technology in one geographical area (China), which now limits recycling of Rare Earths elsewhere.

It should also be noted that a globally levelled playing field of certified BAT operators could help much to bring the system up to the required level of resource-efficient production, which in turn will maximize recycling rates.

3.5.2 Economic constraints

Any metallurgical plant will only process available metal scrap on the back of its normal operation, when economically viable to do so (Figure 49). The economic viability of recycling is a key limiting factor in the amount of recycling taking place, but this viability is also dependent upon thermodynamics: where there are thermodynamic difficulties, there will be corresponding economic costs or impossibilities that can hinder recycling. Complex linkages of metals and their compounds in products, or in mixed waste streams (e. g. smartphones with other WEEE), create economic constraints. Considering this, economic success is mainly determined by:

- The supply and demand of metals and their alloys/compounds, and the resulting monetary value, including the scrap price.
- The technologies and processes used, including economies of scale.
- The policy framework, not only for metal processing activities, but all policies that affect the activities for designing and operating a recycling chain, or its alternative (like landfill costs).

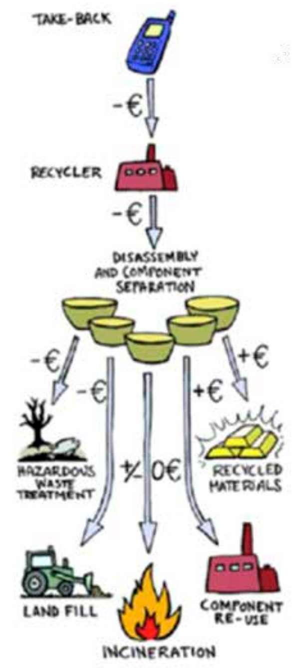


Figure 49:

Process steps of EoL product treatment with indicators of economic gain/cost (Tanskanen and Takala, 2006).

Recycling operations can be highly profitable. For example, where metal prices for the recycled metals, recyclates and resources are sufficiently high, investment can be paid back quickly (Table 16).

Table 16:

A brief overview of earnings and costs for a 1000 tpa NiMH battery recycling facility (Müller and Friedrich, 2006).

	2004	2005	2006	2007	2008	2009
Sales (€)	0	432562	1185280	184405	4134865	6730204
Sales cost (€)	0	297925	775410	1263072	2750048	4514120
Earnings (€)	0	134637	409870	581833	1384817	2216085
Costs (€)						
Labour costs (€)	36300	156090	181500	209378	238564	348190
Non-wage labour costs (€)	13800	33000	34800	34800	34800	38400
Operational costs (€)	11400	22800	22800	22800	22800	22800
Consultancy (€)	18000	36000	36000	36000	36000	36000
Marketing (€)	6000	12000	12000	12000	12000	12000
Further costs (€)	6498	16110	17148	8400	8400	8760
Total cost (€)	**91998**	**276000**	**304248**	**323378**	**352564**	**466150**
EBITDA (€)	-91998	-141363	105622	258454	1032253	1749935
Depreciation, amortisation (€)	1750	4750	48635	163735	166235	166235
EBIT (€)	-93748	-146113	56987	94719	866018	1583700
interests (€)	0	0	4000	150000	0	0
EBT (€)	-93748	-146113	16987	-55281	866018	1583700
Taxes (€)	0	0	0	0	389708	712665
Earnings (€)	-93748	-146113	16987	-55281	476310	871035

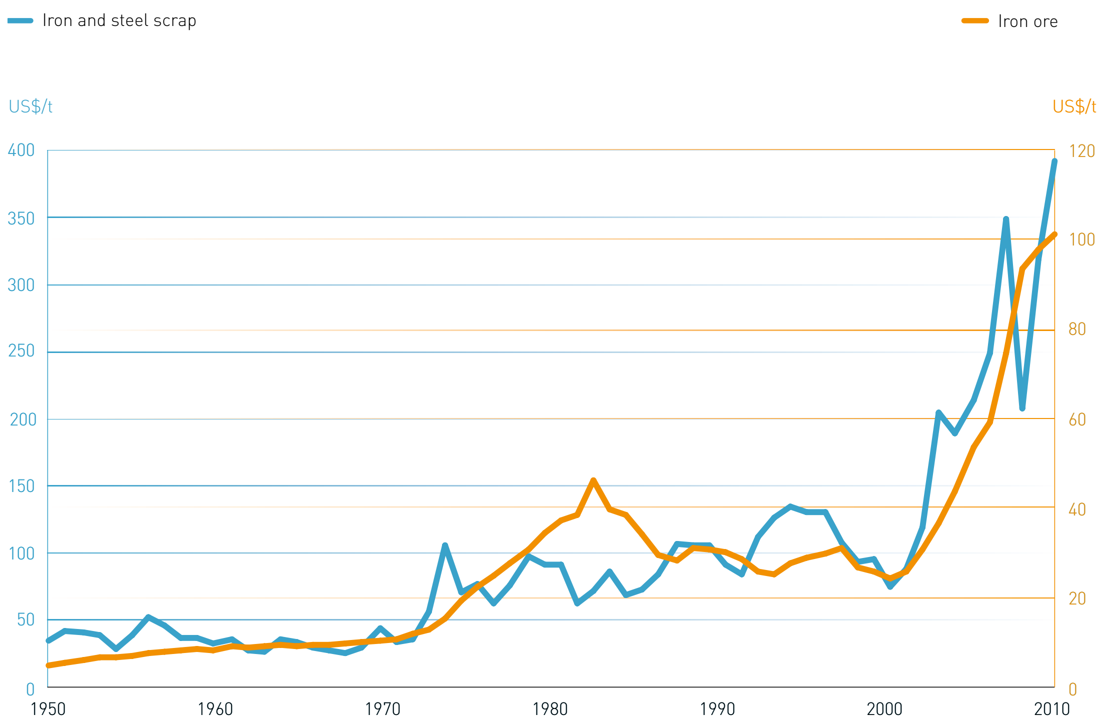
3.5.3 Metal, scrap and waste prices

Metal prices are set at the London Metal Exchange (LME) in relation to supply and demand, and often fluctuate quite strongly. The metal price determines what the smelter can earn from the metal content in recyclates (i. e. potential inputs). The value of the metals coming out of recycling depends upon their purity, which in turn – for reasons described above – is determined by design, material combinations, liberation and sorting efficiency, and recycling routes.

These prices fluctuate, as shown in Figure 50. If the value of the recycled metal is too low due to low metal prices, recycling cannot come to its full fruition. Ultimately, metal price drives recycling: the higher the value, the higher its recycling potential. Unfortunately, commodity metal prices have decreased in real terms over the years. However, recent high prices of various metals – possibly indicating a paradigm shift towards higher metal prices – would generally have a positive effect on recycling.

Figure 50:

Steel scrap prices following iron ore prices (USGS, 2011).



LME prices also influence scrap prices, which are further determined by scrap type, complexity, grade (i. e. purity), and morphology (i. e. turning, sheet, slab, bulk, etc.). The cleaner and closer the scrap quality is to known metal alloys, the higher the prices and thus more scrap collection. Scrap/waste price is further influenced by the cost of alternative uses (or disposal) of the waste. Where the alternative disposal costs are high, more waste is likely to be available for recycling at lower cost. Rising metal prices thus are an incentive for developing BAT infrastructure and advanced recycling, but low LME (and other metal commodity) prices and a corresponding reduction in available input streams, will hold it back.

The variability in metal prices increases the advantages of integrated metal-production plants that can recover and refine many metals at the same time. This helps riding the waves of cyclical metal prices, allowing out-of-sync price fluctuations to be managed by adjusting the balance of metal outputs in a manner that maximizes profit.

3.5.4 The cost of process technology and expertise

Recycling costs also depend on the technologies used, and on the cost of the expertise to run them. Capital investment costs (CAPEX) of metallurgical production plants can be very high, and operating costs (OPEX) will vary. OPEX include labour costs (markedly different in different parts of the world), energy, waste management, water purification, emissions control, occupational health and safety, and consumables. Technological efficiency plays a key role, and is in turn determined by the level of available expertise, and by the degree of innovation in metallurgical and recycling technologies.

Because of CAPEX, smelters require a sufficiently large economy of scale for operating. Profitable recycling smelters run well over 100,000 tonnes/year of diverse feed. The feed can be limited by factors such as the energy balance of the process (certain scrap types may contain large percentages of plastics), aluminium content, the morphology and size of the feed, the range of materials/alloys/compounds in the feed, etc. These affect the thermodynamics and operation of the plant, thus affecting the economics of its operation. The ability of operations to compete for scrap and waste input (where this is scarce) is related to how cost-efficient and expert (BAT) they are compared to other recyclers, including those in other countries whose labour or regulatory costs may be very different.

3.5.5 The influence of the policy framework

The policy framework sets the playing field in which recycling activities compete with other uses of waste, or other potential investments or employment. Waste and recycling policy is only one part of the policy framework, as those that affect innovation, labour cost, availability of trained expertise, transport costs, energy cost, for example, also affect recycling economics. Legislation that places constraints on recycling operations, or use of recycled material, will also affect profitability or feasibility. For instance:

- Land-fill costs affect both scrap price (stockpiling costs money) and costs for eliminating the residues from recycling processes as special ponds and areas have to be constructed and managed.
- Transport costs affect collection costs, whilst energy costs affect operating costs.
- Import or export tariffs, or restrictions for waste, affect potential routes and costs for recycling or residue disposal.
- Labour costs relative to energy costs affect technological choices and the balance of profitability between the use of new and recycled inputs.
- Supporting innovation in technological development or commercial applications can help bringing new and more efficient technology into use.

3.5.6 Obtaining financing and bankable feasibility

Construction of an integrated plant for recycling many metals is a very large investment, and will only be undertaken where it has 'bankable feasibility', i. e. where the desired return on investment is reliable and not subject to strong risk. The predictable availability of reliable scrap-input streams is a key determinant for how plants are set up. For example, over the past 14 years the Umicore facility in Belgium has invested around € 400 million in a brown-field upgrade of their long-established metallurgical operation, setting up a world-class recycling facility that produces many metals on the basis of lead and copper metallurgy (Hagelüken et al., 2009). Boliden have recently started up their new Kaldo e-waste expansion (from 45,000 to 120,000 tpa e-waste) with a total investment of SEK 1.3 billion (ca. € 145 million) in Skellefteå, Sweden (http://www.boliden.com/Press/News/2012/New-facility-makes-Boliden-world-leader/).

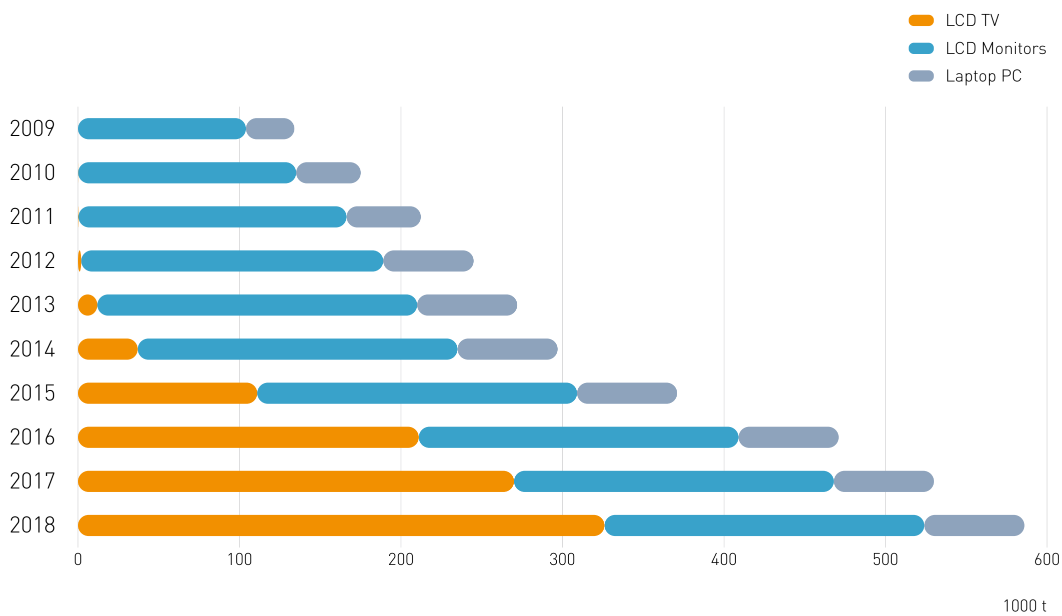
Where bankable feasibility is shown, financing is often available, especially for proven technology. However, finding money for introducing new and innovative technologies, not commercially proved before, can be difficult due to the perceived financial risk and the multi-million-dollar nature of such projects, which holds back technological development.

Box 12:

The influence of economics: Indium in LCD screens

Indium is a critical material used in flat-screen liquid-crystal display technology (indium tin oxide, ITO, 90 % by weight In_2O_3 + 10 % by weight SnO_2), which represents 84 % of indium's total demand (Umicore). Figure 51 shows that a vast quantity of LCD screens will be required in the near future. The metallurgical infrastructure for recovering indium exists in certain places, such as KoreaZinc, Umicore and other copper- and lead-based metallurgical complexes. Hence, the main source for the recycling system lies in the collection and recovery of ITO (Boni and Widmer, 2011).

Figure 51: Past and projected growth in available EoL appliances with LCD screens in EU25 (Salhofer et al., 2011).



Box 12: b

Today, indium extraction from EoL screens is economically unattractive, as treatment and refining costs are higher than the metal value. The indium concentration in screens is very small, as the ITO layer is very thin (125 nm), or about 234 mg indium/m^2 (though a wide range in values is given in the literature). Organic LEDs have about half of this concentration, so they are even less of an economic actuator for extracting indium.

However, extraction from EoL goods could become economically feasible in the future, if indium scarcity drives prices high enough or if new technology becomes available. New methods for recycling flat screens are currently under investigation; while the EU is stockpiling screens awaiting this appropriate technology. Here, the stockpiling cost is weighed against the alternative of incineration, to determine the real cost of intermediate storage.

Note that indium is connected to tin and possibly numerous other elements and compounds. For this reason and as discussed in this document, the recovery metallurgy of indium must be considered in connection with these other elements. These issues are discussed and illustrated in more detail in Appendix F: Physics of Extractive Metallurgy. Also refer to Li et al. (2009) for further information on LCD recycling.

4. Consequence of Limiting Factors

Recycling is a chain of activities. The volume, quality and value of the metals produced by recycling are determined by the combined stages in that chain. With each stage dependent for its success on the preceding ones, the final result is profoundly affected by the weakest link in the chain. Here, we illustrate the cumulative effect of limiting factors, mainly by reference to one metal: gold.

Concepts and processes applied in the recycling chain can vary considerably in different regions and countries. Figure 52 indicates the differences in net yields of gold from printed wire boards that are dependent on efficiency levels in different stages of the chain. The main differences exist between OECD countries, with a prevailing formal sector, and developing countries with a dominant informal sector. The data would be very different for other metals and other input sources, however still shows great variations.

4.1 Collection

In contrast to Europe, where consumers pay for collection and recycling, in developing countries usually the waste collectors pay consumers for their obsolete appliances and metal scrap. Informal waste sectors are often organized in a network of individuals and small businesses of collectors, traders and recyclers, each adding value, and creating jobs, at every point in the recycling chain (Sinha-Khetriwa et al., 2005). As many poor people rely on small incomes generated in this chain, this results in impressive collection rates of up to 95 % of total generated waste. This shows how strong economic stimulus for collection is a key factor in successful collection, a point that occasionally may be missing in today's formalized take-back schemes (United Nations University, 2007).

Figure 52: Recycling efficiency between a common formal system in Europe and the informal sector in India for the gold yield from printed wire boards.

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 %

4.2 Pre-processing

Pre-processing methods affect the outcome. A comparative study by Wang et al. (in preparation) of pre-processing scenarios shows that recovery efficiency improves with better manual dismantling. Purely mechanical pre-processing leads to major losses of, especially, precious metals in dust and ferrous fractions (Meskers et al., 2008; Chancerel et al., 2009). As labour cost is the main denominator for deciding between manual and mechanical treatment, the latter is mostly used in developed industries, accepting lower recovery efficiency, while the cost of manual dismantling is balanced by gains, and strongly influenced by metal prices. In developing countries, where labour costs are usually low, manual treatment is the preferred option, with the double advantage of low investment cost and job creation (UNEP, 2011a).

However, manual dismantling has its limits; at some point in the process, semi-mechanical treatment of the remaining fractions becomes the better option, from both an economical and an eco-efficiency perspective (Gmünder, 2007). For more information, see Appendix E: Models and Simulation in Recycling.

A model by van Schaik and Reuter (2009, 2010a; van Schaik and Reuter, 2012), calibrated with industrial liberation data and experimental work, estimates that only about 15 % of the gold is recovered by industrial pre-processing, though, depending on the processing method, it can also be close to 100 %. Figure 53 shows how different pre-processing methods change the balance of recycling rates between various metals.

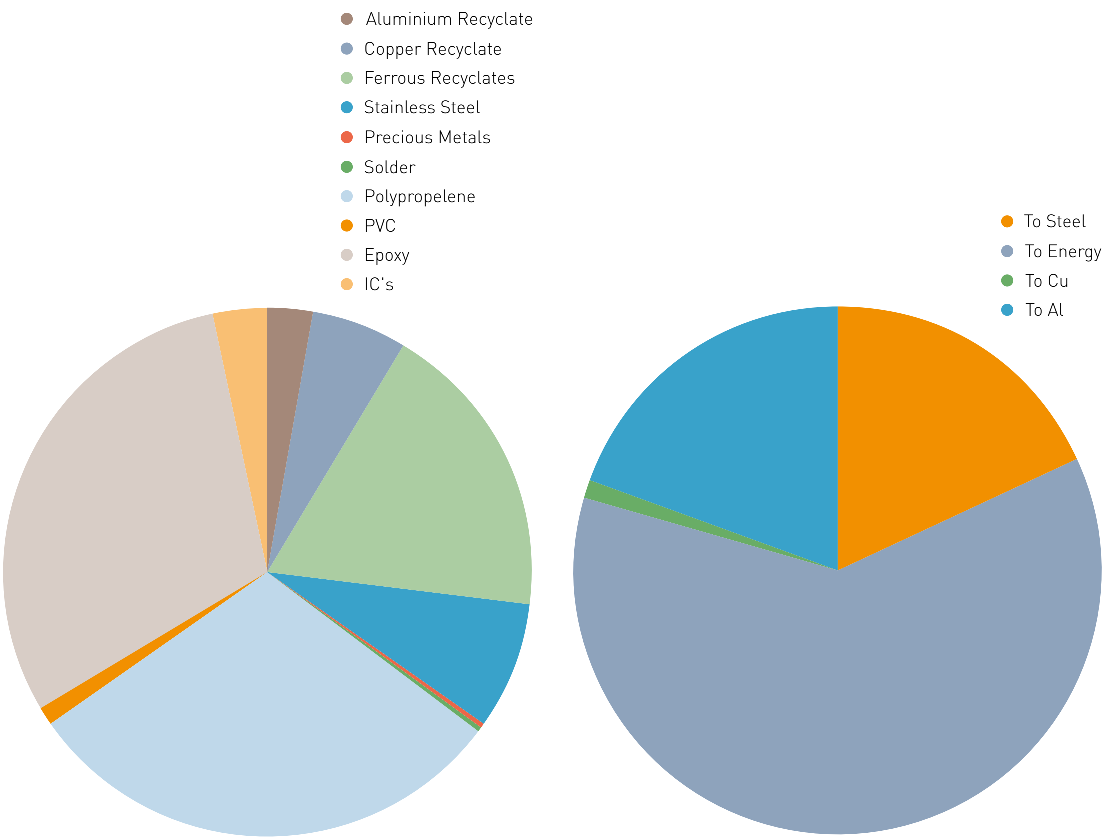
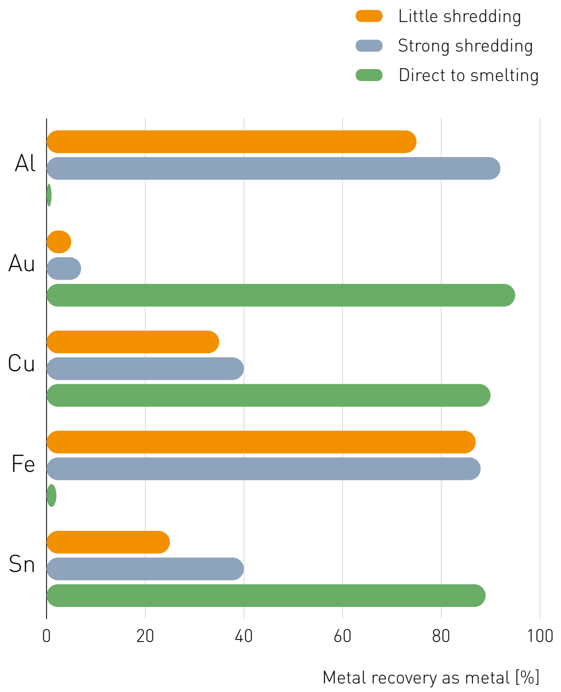


Figure 53:

Metal recycling rates predicted by the recycling model for different metals for disassembled Printed Wire Boards (PWBs) either directly fed into a copper smelter or shredded with varying intensity. Note the low recovery of gold and copper for shredding and the high recycling values if the PWBs are directly recycled to furnace without shredding (van Schaik and Reuter, 2010a).

Figure 53:_b



4.3 Final processing

The recovery efficiency of metals from recycled sources can vary hugely with the sophistication of the metallurgical processes used, being highest when using integrated BAT systems. Informal processes do not achieve this, and, importantly, typically lead to loss of valuable elements in the waste stream, often into the environment, where they can cause human and environmental health problems. Several authors (Table 17) estimated the precious-metal recovery rates for WEEE entering the formal sector largely to exceed 90 %.

Table 17:

Recovery rates for gold and palladium achieved by recovery processes of the formal sector (Chancerel, 2010).

Reference	Recovery rate for gold	Recovery rate for palladium
Huisman (United Nations University, 2007)	> 99 %	> 99 %
Deubzer (2007)	98 %	99 %
Hagelüken et al. (2009)	> 95 %	–
Hagelüken (2005)	–	94 %[a]

[a] 5 % is lost in the copper smelter, and 1 % during palladium refining.

4.4 Net recovery rates

Figure 52 shows some estimates of net yields from different recycling systems. Other estimates also illustrate the cumulative effect of limitations at different stages. According to Hagelüken (2005), in Germany only 37.6 % of the platinum-group metals contained in WEEE are recovered. The losses are due to insufficient collection (50 %), pre-processing (10 %), copper-smelting (2 %) and final refining (0.4 %). Saurat and Bringezu (2008) reported that 13,945 kg of the 22,563 kg of platinum-group metals contained in electronics in Europe were recycled in 2004. Deubzer (2007) assumed the worldwide recycling rates for gold, palladium and silver to be 7 % for low- and medium-grade WEEE, and 9 % for high-grade WEEE.

In contrast, Keller (2006) carried out a substance-flow analysis for investigating the processes of recovering gold from printed wire boards (PWBs) during informal precious-metal recovery in Bangalore, India. He compared two different processes, both starting with manual dismantling of PWBs to remove the parts containing apparent gold, which later was recovered by cyanide leaching and gold stripping. Between 40 % and 84 % of the contained gold was lost during pre-processing (dismantling), mainly because of poor visual recognition of apparent gold. The recovery of gold through chemical processes caused further losses, so that, in all, only 8 % to 18 % of the gold was recovered. In both processes, palladium was not recovered.

4.5 Distributed recycling rates

Table 18 shows that, depending on economic and other boundary conditions, the total recovery of materials and energy can change significantly. The various scenarios simulated by the multi-parameter optimization model included:

- **Scenario 1:** Optimization of a flowsheet for end-of-life vehicle (ELV) processing without limitation of the thermal treatment stream.
- **Scenario 2:** Optimization of an ELV-processing flowsheet with limitation of the thermal treatment stream restricted to 10 % of the input (as required in the European ELV Directive).
- **Scenario 3:** Maximum material- and metal-recovery scenarios with limitation of the thermal treatment stream restricted to 10 % of the input (as required in the European ELV Directive).
- **Scenario 4:** Minimum waste scenario without limitations for thermal treatment.
- **Scenario 5:** Maximum aluminium-recovery scenario, limiting the thermal processing input to 10 %.

It is obvious that there can be no single recycling rate, but only a distribution of recycling rates. Different car models, different recycling scenarios, different recycling infrastructure and routes, etc., all create different recycling rates. It would be best, therefore, to focus on the economics of these processes to create a playing field in which recovery of materials and energy can be maximized.

Table 18:

Various recovery rates for end-of-life vehicles (ELVs) depending on the objective function of the system optimization model (Ignatenko et al., 2008).

Scenario	1	2	3	4	5
Total recovery	**0.95**	**0.91**	**0.91**	**0.97**	**0.88**
Metal recovery	**0.74**	**0.74**	**0.72**	**0.63**	**0.73**
Physical separation	0.73	0.74	0.72	0.63	0.72
Thermal processing	0.003	0.001	0	0	0.01
Material recovery	**0.11**	**0.11**	**0.14**	**0.24**	**0.12**
Plastics	0.02	0.03	0.05	0.02	0.04
Silica	0.004	0.05	0.05	0.03	0.05
From thermal processing	0.05	0.03	0.05	0.19	0.03
Energy recovery	**0.1**	**0.07**	**0.05**	**0.1**	**0.04**
Zn-rich dust (from thermal treatment)	**0.003**	**0.002**	**0.002**	**0.005**	**0.002**
Waste	**0.06**	**0.09**	**0.09**	**0.03**	**0.12**
Physical processing	0.01	0.03	0.05	0.002	0.06
Metallurgy plant	0.05	0.05	0.05	0.03	0.05
Thermal processing	0.001	0.001	0	0	0.01

Recovery results for chosen scenarios

5. Infrastructure for Optimizing Recycling

5.1 Stakeholder infrastructure

A wide range of decision-makers influences the outcome of a recycling system and its infrastructure. Those most strongly affecting the physical nature of global metal chains are shown in the top half of Figure 54:

- **Product designers** decide which metals to incorporate into which products, and set in motion metal flow into plants and from there into society. They decide how accessible metal (sub)components are in their products for dismantling (design for disassembly). Manufacturers (OEMs) and retailers of consumer products determine how products are distributed in the market, what kind of business models they adopt (e. g. sale, deposit, lease, etc.), and what kind of supported or offered take-back infrastructure will affect the collection and recycling results.

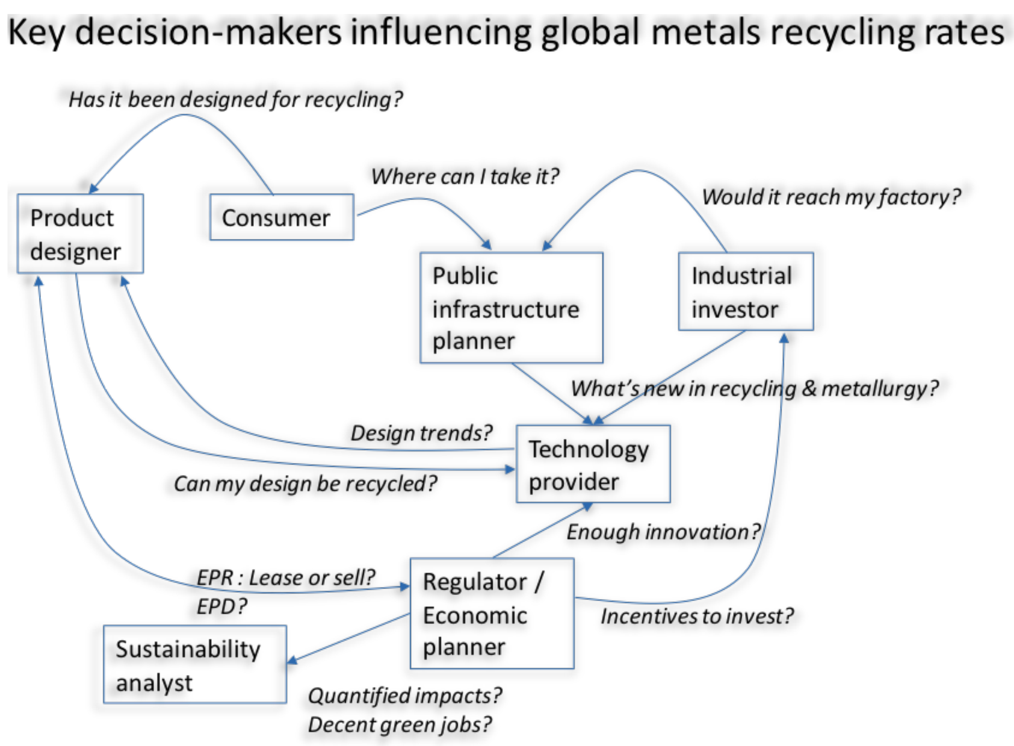
- **Consumers** use metal-containing products and can exercise choices in acquisition, maintenance or disposal of metal-containing products, which then activate and direct metal flows.

- **Public infrastructure planners** plan waste-management infrastructure and they play a key role in recovering and concentrating goods that have too little value for motivating recycling by private enterprise. They most often are affiliated with local government or public enterprises.

- **Industrial investors** or **plant operators** decide where to build smelters or refineries, for which metals and at what size. They provide the physical structures in which metals are separated and refined, but need reasonable secure supply streams.

Figure 54:

The various stakeholders of recycling in a two dimensional simplified representation of a multi-dimensional complex product centric approach (Harro von Blottnitz, 2011).



In addition, there are three more classes of stakeholders, who can enable or regulate the decision-making of the above four classes of direct stakeholders. Indicated in the bottom half of Figure 54, they are:

- **Technology providers** of metallurgical and related technical knowledge most often create and enable innovations in metals production or use.
- **Regulators and economic planners** (at national and international level) encourage, discourage or forbid forms of recycling, through industrial support, regulation of other forms of waste disposal, waste collection requirements, as well prohibiting pollution of the natural environment.
- **Sustainability analysts** increasingly provide vital knowledge of the complex system described thus far. As an example, economic and environmental regulatory concerns in the past were often in conflict, because of apparent trade-offs based on partial views of the economic system. In the transition to a "green economy", such conflicts should disappear through sophisticated analysis that combines environmental, social and economic sustainability considerations with science-technical constraints.

Greater recycling will result when these classes of decision-makers will fully understand the framework of a sustainable use of materials and the role technology can and must play in closing metal cycles. Not every stakeholder needs the same information, but their decision-making can be facilitated by providing them with systemic and cross-discipline insights. After all, though they may have a broad understanding of the systems, they often lack a detailed knowledge of the underlying sciences. Where they take on work in a specialist area, such as the question of metals use and recycling, they must be aware that specialist knowledge is needed for ensuring they make realistic and reasonable assumptions and conclusions.

Not every stakeholder holds all the information he needs, but he must know where to find this information. Good decision-making comes from knowing which questions to ask from whom, as shown in Figure 54. Nobody in the materials and recycling – or any other – field can work in 'ivory tower' isolation anymore. For example, industry, knowledge institutes and government consortia are starting to guide the regulation coming out of governmental waste agencies to provide the groundwork for enhanced metal recycling.

This schematic picture does not explicitly cover the small private enterprises that are crucial to the formal and informal economies of recycling. Recent Brazilian experience with the organizing of waste pickers into cooperatives with government support suggests that the reach of micro-scale private enterprise in resource recovery can be significantly extended through support from public infrastructure planners (Ferrão and Amaral, 2006), and that this may become a major component of green-economy programmes. Such stakeholders respond primarily to the financial value of many metals in EoL products and, as such, can be seen as extensions of the "industrial investors" grouping.

Better recycling will result from having an infrastructure that supports cooperation between the different stakeholders in the recycling chain. Each of them has his own interests and incentives; to improve the system, we need not only an effective route for information exchange, but also a set of incentives making it worthwhile for the stakeholders to cooperate.

Financial gain is the main way that stakeholders influence each other. This may be enough to induce informal collection, but when improvements rely on doing something differently, such as an unusual collecting method, financial incitement may not be enough, and information is needed about potential benefits. The best improvements in recycling will come when more than one stakeholder changes his behaviour at the same

time, so that each change is complemented and reinforced by the other.

These cooperative changes require a degree of trust that both (or all) stakeholders will "play the game". Time lags in the system increase this need for cooperation: a metal processor receiving EoL waste generally can do little to influence the design of the products reaching him.

Improving the system more than incrementally also requires that all stakeholders understand the recycling system as a whole, i. e. beyond their specific task, and that they can evaluate the importance of preceding and subsequent stakeholders for the overall recycling success. Performance jumps in the system need more than the optimization of single steps; focus has to be put on interfaces and interdependence. It may be that more efforts in collection and pre-sorting, or less in-depth pre-processing treatment with additional efforts in subsequent metallurgy, will lead to overall better system performance. Obviously, the current recycling chains and stakeholder interactions are a result of historic development, where old-fashioned waste management with a focus on mass products and flows, and on the elimination of hazardous substances, has been the long-time driver. This approach no longer fits the new focus on recovery of critical metals from complex products, and the overall approach needs re-inventing, best starting from a visionary brainstorming exercise among key stakeholders. Questions to answer could be:

- What should a recycling system ideally look like under the new conditions and objectives, regardless of where we stand today?
- How far is society away from this target situation and what is needed to get there?
- What are the opportunities and limits of recycling, as measured against the rigorous limits based on and estimated by physics?

It is clear that this target cannot be reached "overnight", but, without a vision and "mental reset", it will be hard to make the quantum leaps needed to move towards a real circular economy.

Box 13:

Predictability of input streams
Investment in recycling is facilitated by more reliable prediction of recyclate input streams, based on (time-varying) product type and product design. This helps calculating statistically and fundamentally reliable recycling rates as well as their economic rate of return. Consistent policy and modelling of the factors that can modify the streams will help, but both rely on accurate information from product manufacturers on the variables affecting these streams, such as:

- Product composition, coming from consumer demand (e.g. functionality), policy change (e.g. banning CFC in refrigerators or lead-free soldering), product trends (e.g. SUV cars), changing technology (e.g. hybrid cars).
- Monitoring of collected materials along the entire recycling chain.
- Varying and changing product purchasing, affecting future waste streams.
- Life time (usage) product distribution (determining the distribution of EoL products over time) driven by consumer behaviour (e.g. shifting trends from mobile phones to PDA/smart phones).
- Disposal behaviour, including consumer hoarding of old unused products (e.g. mobile phones).
- Collection schemes or informal collection activities.

5.2 Cognitive infrastructure

The importance of a crosscutting education mirrors a more fundamental piece of the infrastructure for greater recycling. This is a cognitive, rather than physical, infrastructure. The way in which people think has a significant positive or negative effect on recycling success. The more people know about the relationships and interconnections involved in the recycling of complex materials, the more successful it will be, as the recycling industry is often held back by outdated beliefs and mindsets of its stakeholders.

5.2.1 Product-Centric versus Material-Centric views of recycling

Until now, a commonly held way of conceptualizing recycling has been to focus on the recycling of a particular material (a **Material (&Metal)-Centric** view), which is suitable for the recycling of very simple products. It focuses on individual Carrier Metals, considering all other elements as a "hindrance". For example, iron (steel) recycling traditionally views copper, tin and antimony as well as zinc and lead as quality problems, as they affect steel quality and create residues of low economic value that must be dumped. In other words, it tries to operate within the bounds of only one segment of the Metal Wheel.

A very different perspective on recycling lies in considering the requirements for optimally recycling any particular complex product, called a **Product-Centric view**. This considers the complex metallurgy of all elements at the same time, optimizing both the metallurgy and recycling infrastructure in order to minimize losses, but also addressing the related issues, such as liberation, sorting and consumer recycling.

A Product-Centric perspective requires an ability to comprehend the interconnected sys-

tem of design, collection, sorting, and processing that determines the performance of a product's recycling. A Product-Centric view of recycling integrates all policy issues and legislation around products and their recycling. Very importantly, it optimizes recycling, considering processes (and economics) for more than one Carrier Metal, thus optimizing the recovery of several metals (alloys and compounds) from complex products. To illustrate the nature of this view, Figure 48 shows the link between metals for a relatively simple product: galvanized steel (about 50 % of all zinc is used for galvanizing, where it protects steel from corrosion).

Taking a Product-Centric view of recycling in the way described above is a form of 'systems thinking' – considering all factors that affect a system's outcome, in an attempt to improve this outcome. Recycling is a system, or rather – for complex recycled sources – a mesh of related systems. Optimization of this system is best started from a Product-Centric view as this links the product design's complex "mineralogy" to the recycling outcome. The Material (& Metal)-Centric thermodynamic and economic knowledge of the processes involved is also taken into account by this system.

Conceptualizing recycling in this way is helpful for all decision-makers involved in recycling, in industry as well as in the public sector. It helps them understand what actions will affect recycling, and that changes to one part of the recycling system (e. g. collection volumes or the mixing of different product categories) without consideration of the other parts of the cycle may not have the desired effect. Considering the full industrial system of which recycling is a part, also helps private and public decision-makers in understanding the important role of recycling for shaping a global "sustainable" future. A better appreciation of how recycling can provide some of the scarce materials needed for sustainability-enabling infrastructure and products, and of how it can significantly reduce fossil-fuel use, will provide the recycling and metallurgical industry with the economic and political visibility and attractiveness that it merits.

Appreciating the great benefits of systems-thinking for optimizing complex industrial and physical interactions, has grown into a body of expertise called 'industrial ecology'. It is very helpful to see recycling operations as part of 'ecology', affected by many parts of a system. This is particularly valuable because most metal-value chains are international, and metal-containing products are often marketed globally. Thinking this way transforms an over-simplified, linear, 'extract-refine-manufacture-consume-dispose' economic model into a circular one (Ayres, 1997; Allwood et al., 2011). Taking a perspective of metals as 'stocks-and-flows' within a system (Cowell et al., 1999; Graedel, 2003) helps to see recycling's true nature: infrastructural nodes (mines, smelters, factories, our built environment, scrap yards) become apparent, and one can account for the flows of metals between these nodes.

5.2.2 Innovating recycling in a Product-Centric world

A clear understanding of the challenges of recycling complex metal streams will help innovation. It clarifies the likely future demands placed on recycling, defines the appropriate characteristics of new technologies, and supports the economic case for innovation, intended to push back the boundaries of recycling. Just as important is that recycling and metal processing operations adopt new processes.

In developing countries, new technology bypassing OECD practices can be rapidly adopted. Locally, highly adaptive manual sorting will further facilitate this. Without innovation, recycling metallurgy stagnates and cannot keep up with ever-changing product design. Innovation provides the solution to the question: "Is the technological playing field sophisticated enough and ready for handling all the complex recyclates now coming on stream, and for producing high-grade metal products?" Innovative technology can increase the overall recovery rate, including:

- Ways to set up better collection systems.
- Means to trace and track EoL products or fractions thereof along the recycling chain.
- Alloy-specific sorting technologies (where products, scrap, etc., are not too complex).
- Improved and adapted liberation methods.
- Identification and separation of metal-containing components, though complex products with complex material linkages may make this superfluous and impossible.
- New mechanical, chemical and thermal separation and concentration techniques for metals, complementing the large body of existing metallurgical separation know-how.
- Additional final-recovery processes for end-refining metals and metal products, in case these are not yet available or being developed and implemented at this moment.

Table 19 summarizes some of the strategies, relating them to specific metals.

Table 19:

A table of challenges in separation still required in WEEE recycling.

Legend:
- Not relevant
- State-of-the-art at high recovery rates
- Existing but improvement required
- Not existing, improvements required
- Unknown

	Fe	Al	Mg	Cu	Ni	Ag	Au	Pd	Ru	Sb	Ga	Ge	In	Co	REE	Ta	Be	Te	W	Nb	Sn
Increasing overall collection rate	State-of-the-art at high recovery rates	Existing but improvement required	Existing but improvement required	Existing but improvement required	Existing but improvement required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required
Alloy-specific sorting technologies	Existing but improvement required	Existing but improvement required	Existing but improvement required	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not existing, improvements required	Not relevant	Not existing, improvements required	Not relevant	Not existing, improvements required	Not existing, improvements required	Not relevant
New liberation technologies	Not relevant	Existing but improvement required	Not relevant	Existing but improvement required	Existing but improvement required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Unknown	Unknown	Not relevant
Identifying metal containing components	Not relevant	Not relevant	Not relevant	Existing but improvement required	Existing but improvement required	Existing but improvement required	Existing but improvement required	Not existing, improvements required	Not existing, improvements required	Not relevant	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not relevant	Not existing, improvements required	Unknown	Unknown	Not existing, improvements required
Separating metal containing components	Not relevant	Not relevant	Not relevant	Existing but improvement required	Not relevant	Existing but improvement required	Existing but improvement required	Not existing, improvements required	Not existing, improvements required	Not relevant	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not relevant	Not existing, improvements required	Unknown	Unknown	Not existing, improvements required
New concentration technologies	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Not existing, improvements required	Existing but improvement required	Not existing, improvements required	Not relevant	Not existing, improvements required	Not existing, improvements required	Unknown	Not relevant
Final-recovery processes[a]	State-of-the-art at high recovery rates	State-of-the-art at high recovery rates	State-of-the-art at high recovery rates	State-of-the-art at high recovery rates	State-of-the-art at high recovery rates	State-of-the-art at high recovery rates	State-of-the-art at high recovery rates	State-of-the-art at high recovery rates	State-of-the-art at high recovery rates	Existing but improvement required	Existing but improvement required	Existing but improvement required	Existing but improvement required	Existing but improvement required	Existing but improvement required	Not existing, improvements required	Not existing, improvements required	Existing but improvement required	Not existing, improvements required	Not existing, improvements required	Existing but improvement required

a) Even after mixed waste disposal metals can be covered in other waste treatment facilities.

Exciting innovation already takes place, such as:

- Innovative smelters that have come up with ingenious ways for expanding their traditional core competence into a capability of processing complex scrap and a multitude of metals, alloys and compounds of modern products. For example, Umicore and Rhodia recently developed a process for recovering REE from NiMH batteries (Pietrelli et al., 2002; Bertuol et al., 2006; Umicore, 2011). Silmet (2012) is also a rare earth element producer.

- The main separation tool for extracting aluminium from Municipal Solid Waste, the Eddy Current machine, is increasingly (re-) designed for extracting non-ferrous metals from specific-size grains in incinerator bottom ash. This should result in higher aluminium extraction levels within the fine fraction (<5 mm). Further development of sensor-ejector sorting systems will also improve yield.

- Several major adjustments in processing plants are being applied on an industrial scale: strong magnets for removing all ferrous material (in addition to iron/steel) ahead of the Eddy Current machine; washing of bottom ash during the classification process; and dry cooling of bottom ash instead of using a standard water box for cooling. This will lead to better quality and extraction of the non-ferrous metals.

5.3 Recycling infrastructure

Here we describe the physical and knowledge components of an efficient recycling infrastructure, performing according to sustainable development principles.

5.3.1 Collection

Increasing collection and pre-sorting of post-consumer and industrial waste is a key way of improving recycling. Collection that produces technically and economically viable processing streams is a prerequisite for high returns from the rest of the process. Mixing incompatible materials and compounds in a waste stream will have a negative effect on the recycling. Many collection systems therefore aim for separate collection of different waste types (This is less of an issue for the recycling of industrial residues).

Increased collection of suitable input streams plays an important role. Because successful recycling plants often run on high volumes to offset high initial investment costs, the availability of high input volumes is important. This is one reason why most recycling of scarce, valuable and precious metals takes place in primary-production plants. A new plant will only open where the volume of recycled products is of sufficiently high value to cover the costs. For example, the volume of REE production is rather low and only few plants will be built for their processing. The small amounts of REE in recycled waste will most likely have to be processed either in existing facilities that are almost all in China, or in new centralized plants elsewhere (for example, one in Europe) where regional input can ensure the necessary economy of scale.

5.3.1.1 Collection infrastructure

Recycling starts with a collection infrastructure. This can be set up by the authorities (often as part of their waste collection), by product manufacturers and retailers (taking responsibility for the EoL stage of their products), or by companies, individuals or charities wishing to earn money from the value in waste or to reduce environmental impact. A crucial part of that infrastructure is the capability of the people (or organization) collecting the waste. For newly started collection schemes, the responsible people (for example local authorities) will be successful when they have sufficient support in setting up the knowledge base, motivation and physical infrastructure for dealing with separate streams of collected waste.

Another part of the infrastructure is the incentive structure for collection. Some collectors may act out of ethical or environmental considerations, but nearly all work because they earn money from collection, or face pen-

alties for failing to collect. Creating the right incentives will boost recycling and thus can be closely connected to the business models under which (consumer) goods are distributed on the market.

Box 14:

Recycling of aluminium in Brazil - income generation as the main motivation

In contrast to other materials, aluminium can be recycled infinitely without losing its value in the process if pure aluminium is recycled. However, when contamination occurs it leads to downcycling. It can be recycled either from EoL scrap, or from remnants of the production process. Household items, beverage cans, window frames, automotive components, among others, can be melted and reused for making new products. This recyclability is one of the main attributes of aluminium and generates many benefits, as summarized in Table 20.

Table 20:

The benefits of recycling (International Aluminium Institute and Brazilian Association of Aluminium www.abal.org.br).

Social and Economic	Environmental
Generates jobs and income for thousands of workers involved in the chain of recycling aluminium.	Provides significant savings in electricity and greenhouse gases emissions – only 5 % of the energy required and emissions of greenhouse gases when compared with the production of primary aluminium.
It is the main business for more than two thousand companies among cooperatives, retail centers, transporters and processors.	Reduces the consumption of raw materials such as bauxite and alloying elements.
Funds injected on the local economies through job creation, tax collection and market development.	Decreases volume of materials discarded post-consumer and industrial waste, returning to the productive chain as raw material and saving space in landfills.
It is an activity that moves millions in the national economy, at all stages of the process.	Promotes development of environmental awareness in society.
Encourages other businesses, demand for new activities related to the recycling chain.	Encourages recycling of materials.

The world average of recycling aluminium is 27 %; with the highest figure for the United Kingdom (57.3 %) (Figure 55). However, when considering only aluminium beverage cans, Brazil has been the leader for ten consecutive years (Figure 56).

Box 14:_b

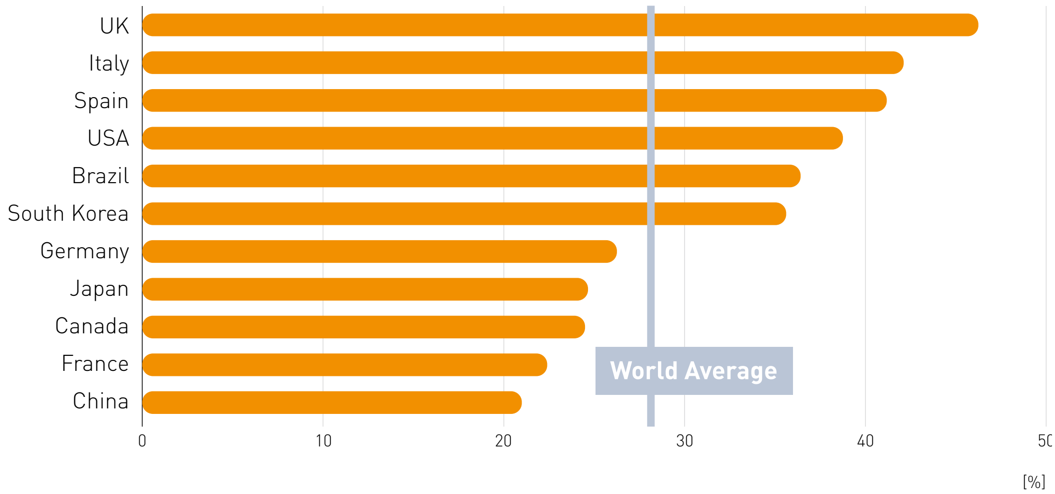


Figure 55:

Ratio of scrap recovered and domestic consumption (%) – 2009 (The Aluminium Association www.abal.org.br).

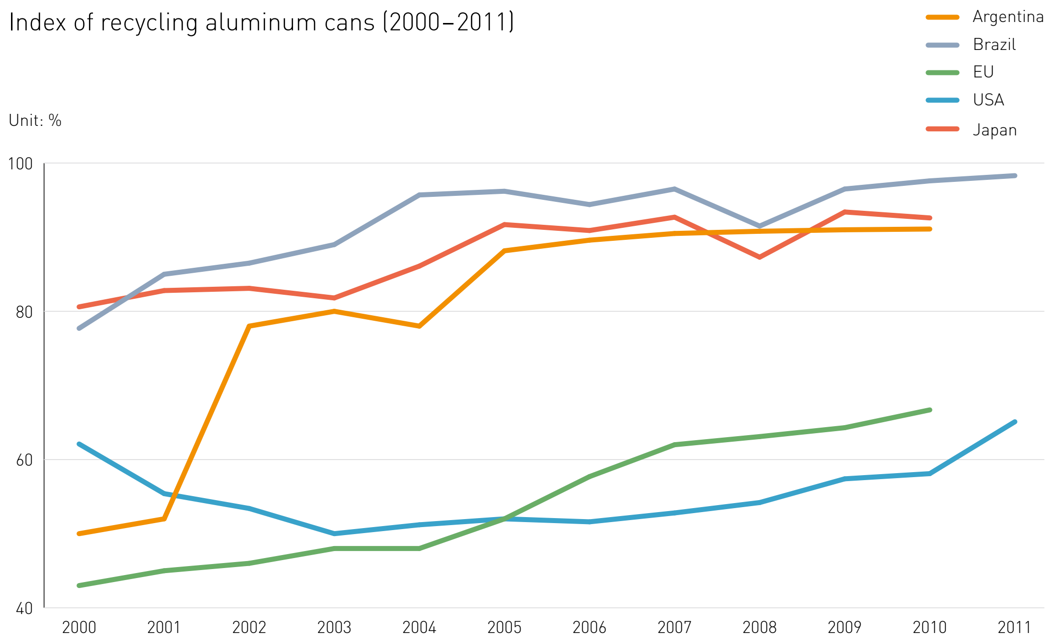


Figure 56:

Recycling rates for beverage cans (Sources: Brazilian Aluminium Association, ABAL, who collected data from: Brazilian Association of Highly Recyclable Cans, The Japan Aluminium Can Recycling Association, Camara Argentina de la Industria del Aluminio y Metales Afines, The Aluminium Association, and European Aluminium Association).

Aluminium cans are important in recycling because they have a high volume and a much shorter life cycle than other aluminium products. In 2010, with a recycling rate of 97.6 %, Brazil again beat the world record with 239,100 tonnes of scrap cans (17.7 billion units, 48,500,000 cans/day, two million/hour). Currently, it takes about 30 days to buy, use, collect, recycle, remanufacture, refill and return an aluminium beverage can to the shelves. The efforts of the recycling chain – manufacturers, bottlers, cooperatives and recyclers – and the Government, and public awareness, have made the can recycling programme into a successful experience with great social, economic and environmental impact.

5.3.1.2 Collection of Consumer Waste

Managing post-consumer waste faces different kinds of challenges compared to the management of office or factory waste. Consumer behaviour plays a big part in collection, for example, by separating waste into different streams, as long as they know the product differences. If, for instance, the consumer has no idea what is in different batteries and is not given clear guidance on the fact that there are different types, these can potentially all land in the same battery-recycling bin and create a metallurgical nightmare.

Educating and changing the behaviour of individuals can thus lead to better recycling. One way is to encourage people to return their old products for recycling when they no longer need them. Currently, many consumers keep redundant products at home, or throw them into mixed waste. If more consumers would offer their mobile phones for recycling, the increase from the current 2000 tonnes/year towards the potential 80,000 tonnes/year (Hagelüken et al., 2009) would amply drive the recycling system.

Figure 57 summarizes the different features of consumer behaviour that affect recycling behaviour. The first ring around the consumer describes the direct impact on the recycling decision, such as accessibility and attitude. The next layer shows ways for motivating the recycling behaviour, like transparency of the system or past experience, and the following ring presents the different ways of influencing recycling behaviour by marketing and social media activities. The outer layer shows the future values and social trends that may affect the consumers' recycling behaviour, communality and downshifting being examples of those trends. As seen from the figure, many factors affect recycling behaviour, from personal attitudes and experiences to the quality of the existing recycling systems.

The most important factors for enhancing recycling behaviour are convenience and awareness of where and how to recycle. Inhibiting factors are an emotional attachment to the old products. Making the consumer aware of the opportunities of recycling, and changing his mindset and disposal habits are the true keys to any successful programme. Again, consumer education is of vital importance.

Different cultures offer different opportunities. Recycling is a global theme that needs local execution, appropriate to existing cultural norms. Different ways of communicating, providing incentives and motivating consumers, are effective in different countries.

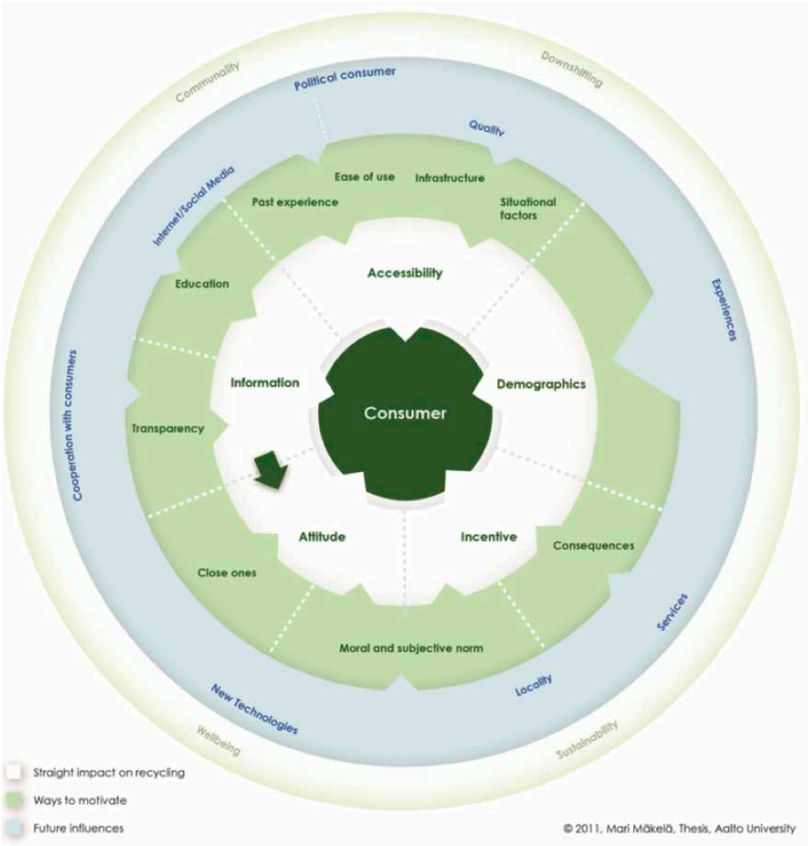


Figure 57: Features affecting consumer recycling behaviour (Mäkelä, 2011).

Box 15:

Mobile-phone recycling in India and China

In India, no recycling infrastructure (collection places or recycling companies) existed in 2008 for mobile phones. There was very low awareness of the benefits of phone recycling, the roles of the different stakeholders were not defined, and there was no regulatory framework.

Phone producer Nokia started a recycling programme, making it easy for consumers to recycle. The new phone collection infrastructure included recycling bins and information material for consumers, reverse logistics, an IT system, a recycling company that fulfilled corporate requirements, and training of employees. The programme was launched as a pilot in four cities, Bangalore, Delhi, Gurgaon and Ludhiana, for a 40-day period in 2009. A key challenge was overcoming the scepticism of trade partners and retailers, who believed that Indian consumers were not ready for recycling. A second phase expanded the programme to a further 28 cities. Marketing methods included billboards, radio and print media, Bollywood celebrities, road shows and a commitment to plant a tree for every phone recycled.

During the first 2.5 years of the programme, more than 50 tonnes of old phones and accessories were collected, with the collection increasing every year. Success depended on several factors, including the use of a very short and simple, emotional and social message to consumers about recycling, rather than a rational one (Singhal, 2010).

In China, operator China Mobile, Motorola and Nokia started a recycling programme in late 2005, with six other cell-phone manufactures joining the year after. The programme has grown every year, from 40 cities (1500 recycling points) to 300 cities. By late 2009, more than 150 tonnes of phones, batteries and chargers had been collected.

5.3.1.3 Pre-processing expertise

Recycling operations are more effective where a good pre-sorting infrastructure exists for scrap, with accurate scrap specifications that are based on material composition. If some valuable metals slip into iron recycling, for example, they are lost in slag, flue dust and sludge. Such an infrastructure can be informal (Figure 58), or rely on technology. However, the separation will only optimize recycling of valuable metals when it takes the next stage of processing possibilities into account.

Figure 58:

Manual dismantling in the informal sector in China.

5.3.2 Processing infrastructure

None of the processes used by industry for the primary production of Carrier (Base) Metals can deal well with the many elements of man-made recyclates. Usually, the maximum that can be handled is around twenty metals. The Metal Wheel illustrates how industry tends to operate on the basis of one Carrier Metal process at a time, metallurgical infrastructure being built around the extraction of elements from geological minerals. It provides an overview of which elements each Carrier Metal process-and-infrastructure can deal with economically. Chapter 3 described how the recycling of complex waste streams requires integrated technologies for recovering a wide range of metals, especially where those metals are thermodynamically related. Those that are incompatible may go to streams where they are lost, mainly for economic reasons.

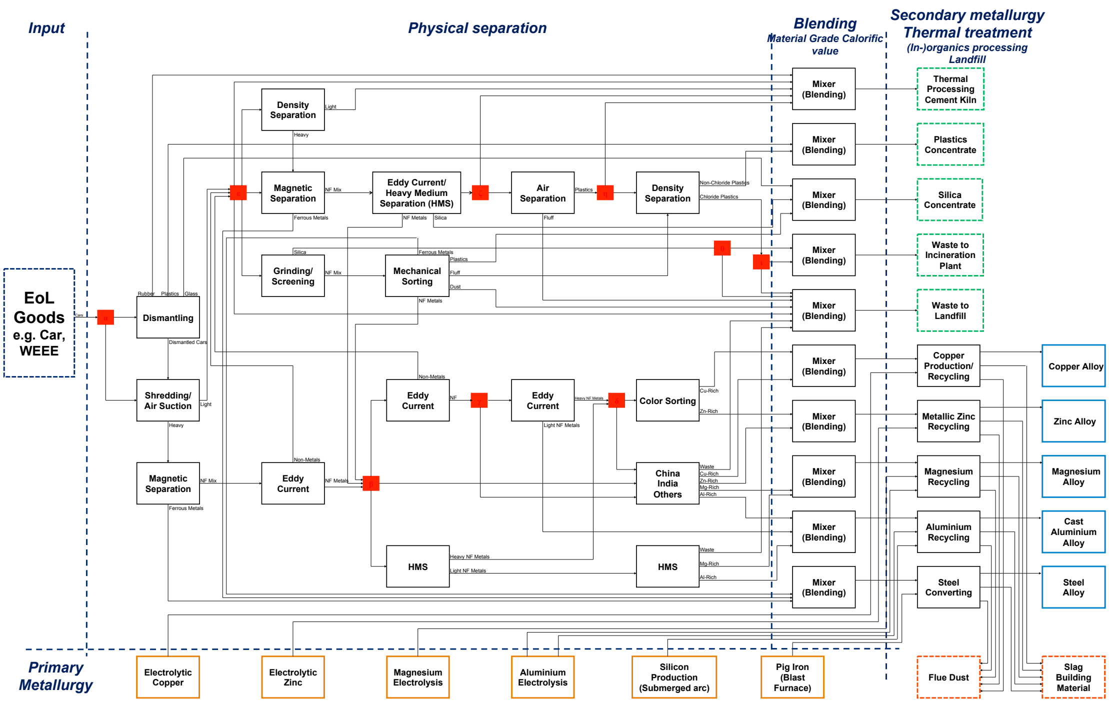
Figure 59 shows a complex flowsheet used for the optimized recycling of EoL products, illustrating that this requires an entire metallurgical network. This must consider constraints for technology, particle-size distribution, breakage and connection, metals, alloys, compounds, and metallurgy (van Schaik and Reuter, 2004a; 2004b; 2007; 2010a; 2010b; van Schaik and Reuter, 2012; van Schaik, 2011). Therefore, a successful WEEE processing facility is based on technologies for two or more Carrier Metals, such as practiced by the metallurgical recycling plants of Boliden, Umicore, DOWA, or Aurubis, all of which combine deep-rooted lead/zinc/copper primary-smelting expertise and the necessary infrastructure.

The ideal situation is a system that connects scrap to all Carrier (Base) Metal processes, and that can be seen as the centre of the Metal Wheel. Scrap then flows, as determined by thermodynamics and economics, into the appropriate Carrier Metal technologies (Metal Wheel slices), with links between the technologies (or slices) for processing the residues from each technology. This ideal cannot be achieved with existing technology, but its conceptualization helps understanding the system required for recycling.

Figure 59:

Product-Centric recycling of EoL goods with a networked structure of technologies for dealing with the various streams. This Figure shows the complex network of technologies that can be applied to manage resource efficiency. (van Schaik and Reuter, 2004a; 2004b; 2007; 2010a; 2010b; van Schaik and Reuter, 2012; van Schaik, 2011; Reuter et al., 2005; Reuter, 2009; Ignatenko et al., 2008).

Zoom



In addition, recycling operations of future products and material combinations will need the development of even more smelting competence in different Carrier Metals, making the right inter-linkages between processes. This type of response to new products already exists for some of the waste streams that recently have become valuable. For example, Umicore have developed a process for recycling rechargeable batteries, recovering nickel and cobalt. A rare earth oxides fraction can now be created and processed at Rhodia (Rhodia; Umicore, 2011; Eurometaux, 2010).

5.3.2.1 Depth of expertise in Carrier Metal processing

Detailed techno-economic metallurgical know-how and recycling capability is most commonly found among primary-metals producers, partly because this is where they focused efforts in the past, and partly because current economies of scale mean that much recycling occurs together with primary production. This means that one of the keys to successful recycling, anywhere, is access to and the maintaining of this core competence of primary metal production expertise.

By extrapolating past trends, we can predict that future products will have a different composition from current products, and that new uses will be found for metals. This will lead to a surge in the use of certain valuable elements that, with time, will arrive in the waste stream. However, it is hard to predict which of these elements will arrive, and thus which types of metallurgical expertise will be most needed in future. Lessons might be learnt from the recent situation with REE, where much expertise was lost worldwide, holding back recycling. Once such metallurgical know-how is lost within a sector or region, it is usually very hard to recover it, so maintaining a broad infrastructure of expertise within industry may be prudent.

5.3.2.2 Expertise in scarce/valuable/ critical metals recycling

A challenge for the recycling of complex multi-material and simpler products is to ensure the existence of a Carrier Metallurgy infrastructure for separating the complex linkages between commodity metals, valuable elements, plastics and other materials. This requires a keen understanding of the physics of separation and an ability to innovate and optimize. For example, indium and tin can appear as various different chemical species when processed from their oxides found in flat-panel TV screens, though the usual form is indium tin oxide, ITO. Their thermodynamic stability has a direct effect on their recovery and recycling rate. Understanding these thermodynamics within the technological and economic context determines how well indium and tin will be recovered in the appropriate phases for further processing.

To prepare the infrastructure for increased recycling means greater information exchange within the metal industry, including the development of further Carrier Metals knowledge. Usually, BAT operators do this very well, but the mainstream of industry still focuses its expertise on single Carrier Metals. Such increased knowledge can come from process engineers (metallurgists, chemical engineers, etc.), who have sufficient understanding of different Carrier Metal processes to profit from each other's more detailed expertise.

5.3.2.3 Increasing industrial expertise through education

The expansion of recycling answers a changing societal need, whereby the educational system can play an important role by adapting to this need. Education is pivotal in providing society with the skills and expertise to increase recycling. As an essential aspect of humankind's answer to the challenge of materials and metals management, metal-recycling technology must be given greater priority in the educational landscape. Engineering programmes in general and materials-engineering curricula in particular, may take the lead in addressing this challenge. Under the umbrella of resource management, a curriculum of specialist courses can build the physics-based expertise that will drive innovation in recycling. These efforts could be particularly successful where industry and government are involved as well.

Universities have the roles of being an educator, knowledge keeper and knowledge seeker. In the area of sustainable metals management, a critical mass of universities has the opportunity of making the strategic choices for safeguarding knowledge and fostering innovation in the field of process metallurgy. As an academic discipline, metallurgy has been in rapid decline in the OECD countries during the past decades, but is now in urgent demand for supporting the transition to sustainable metal production.

In addition, cooperation between metallurgy and other disciplines in science and technology, including non-technical disciplines, would lead to an increase in the transverse skills needed for expanding recycling. Recycling multi-material recyclate sources is an area where the quintessential characteristics of the engineer as an innovative, ingenious thinker, who can conceptualize and optimize a system as a whole, will be extremely valuable. Sustainable-metallurgy engineers of the 21st Century will use their knowledge of the importance of interconnections to help industry break out of its straightjacket. Today, talented students in OECD countries tend not to choose metallurgy, but they are needed for the challenges of recycling. Emphasizing the key role of recycling in the sustainability of our society, may be one way to attract young talent back into the field, which is pivotal to enabling sustainability. There are positive signs that this transition in education and research is happening. University programmes are embedding metallurgy in an industrial ecology framework. Intra- and inter-university consortia, some in cooperation with industry, are set up in the area of sustainable metal production. Forward-thinking companies in the field of metal production invest in educational programmes at all levels. These early signs of educational adaptation are promis-

ing, but will need further amplification and acceleration.

5.4 The optimization toolbox

The potential recovery of materials from society is not fixed, but changes as a function of time, products, components, product mixture (input to recycling systems) and recycling routes. Wherever in the world recycling occurs, the infrastructures for all stages can be improved for achieving higher recycling rates.

Recycling takes place as a system. As each part of the system affects the success and viability of the others, the limits of recycling performance depend on the optimization of each of these related factors, recycling being a truly complex multi-dimensional dynamic problem. Hereafter we discuss the physical and organizational infrastructure toolbox for optimizing recycling rates.

Maximizing resource efficiency requires a detailed understanding of the complete recycling chain, for recovering the maximum amount of metals in hydro- and pyro-metallurgical processing facilities. This is only possible through a holistic systems approach, starting with product design and optimizing the technical and organizational set-up of dismantling, shredding and separation technologies. Only then can the relevant material fractions be directed to the most appropriate metallurgical end-process. Figure 60 reflects this system, showing that any mismatch between the different steps produces unwanted residues, losses and ultimately leads to a lower overall resource efficiency.

In summary, policy should stress the building and maintenance of a suitable metallurgical processing infrastructure and of well-channelled preliminary pathways, to ensure a maximum recovery of metals. See also Appendix E: Models and Simulation in Recycling for more details on all of the above aspects.

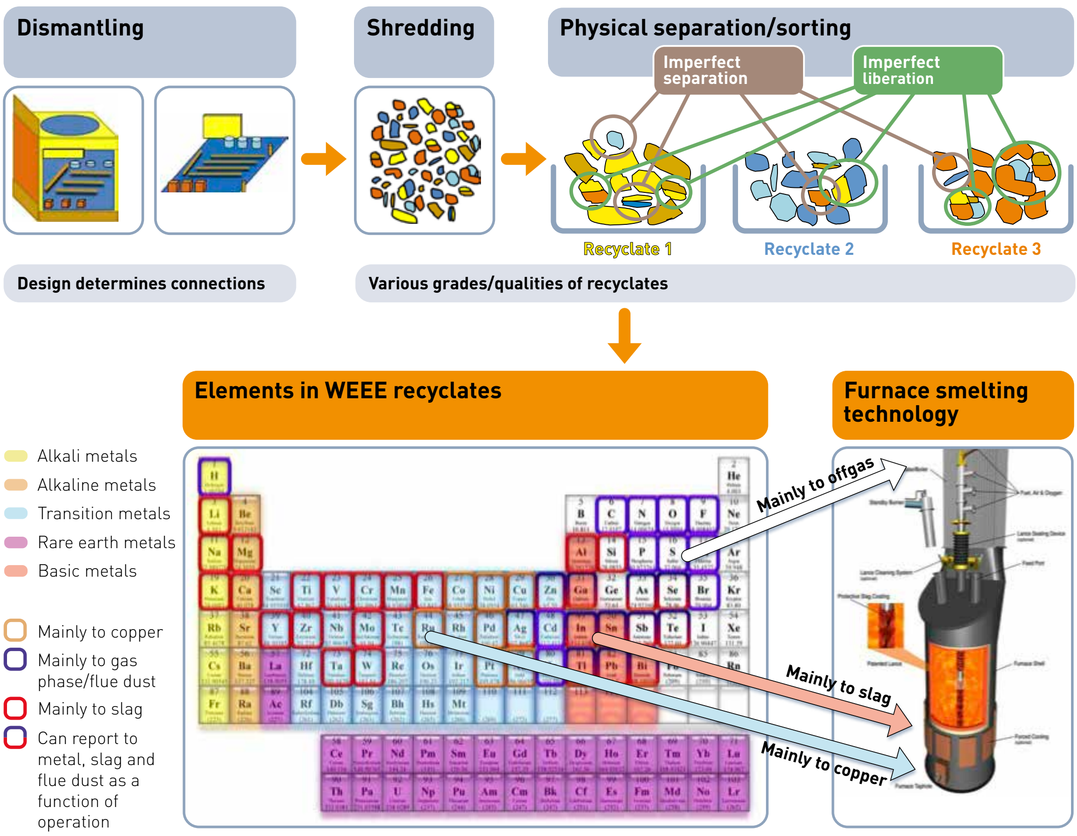


Figure 60:

A key message concerning Product-Centric recycling: Product design must be linked to liberation, separation efficiency, and quality of both recyclate and of final output streams, based on the thermodynamic limits of recycling (Reuter et al., 2005; Reuter and van Schaik, 2008, 2012a&b; van Schaik and Reuter, 2012).

5.4.1 Product design for resource efficiency

The three steps of the recycling chain as shown in Figure 52 are a simplification. Recycling starts with collection, but product design determines the mineralogy of the recyclates and thus their economic value. The purity and constituency of the material entering metallurgical processing determines recycling output. As sorting and pre-processing can only physically separate some elements and compounds, this purity depends on the design of waste products entering recycling. Figure 60 summarizes this for a Product-Centric recycling approach. Design for Resource Efficiency refers to the design of the whole system linked to the product design ensuring that losses are minimized.

This means that designing products for better recycling can have a significantly positive impact on recycling results. Designs can be improved when considering the complex physics of separating their metals and compounds, while recognizing that design for good functionality may still make liberation impossible. Where product design considers this, it is called "Design for Recycling", or DfR.

If product design can keep thermodynamically compatible materials close together, then metallurgical technology can deal with them. For example, the recycling of printed circuit boards is often carried out with copper metallurgy. This means that silver and gold can be easily recycled, but aluminium will be lost. To reduce this loss, designers could avoid the presence of aluminium with copper, or could plan a design that facilitates the removal of aluminium during pre-processing. For example, heat dissipaters are often made of aluminium and could be designed for easy manual extraction. This is called "Design for Disassembly". For other parts containing precious materials, the recovery ratio during dismantling or sorting could be increased by visually identifying such components.

It is not easy to make a LED, fluorescent lamp, car, electronic product, etc., any simpler, as the metals in close proximity create their functionality. This will always be at the heart of product design, but designers often have some leeway in the choice or arrangement of materials. Continuous innovation in materials can aim at delivering similar functionality with other, thermodynamically compatible, materials. In short, it is a truly complex challenge to design products for optimal recycling. However, what is good for DfR could, and most likely will, defeat functionality, especially that of a complex product.

Design for Recycling thus needs a supportive infrastructure. Fortunately, the tools now exist that provide designers with the information they need about recycling outcomes from different designs (see Chapter 6). These are based on the opportunities and limitations shown by the Metal Wheel, and allow the assessment of different designs. Where these are widely known and used, recycling outcomes can be improved. The other part of a supportive infrastructure for Design for Resource Efficiency is the creation of an economic or policy framework that motivates designers to consider recycling. This might be the case where consumers reward good design by preferring products they know to have high standards. More commonly, public policy can require, or influence, product manufacturers to take recycling into account, thus encouraging material innovation without constraining functionality.

Another aspect of design for recycling relates to supporting markets for recycled metal products. When recycling produces metals, or other compounds, that have the same purity (or grade) as primary metal, they can easily be sold at equivalent prices. This applies in most cases where state-of-the-art processes are used. Where recycling produces metal with impurities, this might fail to find markets, even when it has the physical or chemical properties needed for use in specific products. Manufacturers may not choose to use such recycled metals, either because they do not know the precise mix of elements and compounds on offer, or because they are unsure of the quality or consistency of the re-

cycled metal on offer. These are not technical but marketing issues, which nevertheless influence the success of recycling. Designers can help to create markets by being willing to take up suitable recycled material.

5.4.2 Establishing routes of influence: Life Cycle Management (LCM)

A starting point for any cooperation can be Life Cycle Management (LCM). This approach allows decision-makers, for example in companies, to enhance the sustainability of their products, and specifically their recyclability. An LCM perspective means assessing the cost and environmental impact of a design choice over the whole life of the product, and then trying to increase the benefits and reduce the product cost over that lifetime. It includes assessment of the manufacturing process, the use phase of a product, and the end of life treatment. Modelling tools – called Life Cycle Costing and Life Cycle Assessment (LCA) – have been developed to help with this assessment, as described in Chapter 6.

When adding a detailed simulation of recycling 'best-practice' to the design and disposal stages of a product, an even more useful LCA is obtained. This helps decision-making about design and innovation, and about how to resolve tradeoffs, for instance, where a product change increases recyclability, but reduces life-time environmental performance. This moves 'Design for Recycling' to 'Design for Sustainability', a major step within a Life Cycle Management approach.

An further benefit comes from including information on recycling BAT in the LCA. This can help producers to understand the positive impact of recycling and what opportunities this presents for their brand. For instance, Figure 61 shows the LCA of a personal computer, which traditionally was based on a standard impact of one metal. Though this is helpful, it cannot show how different recycling processes for a product will affect the product's sustainability. Discussion with recyclers will enhance a standard LCA, showing how a different arrangement of components within a product for aiding recyclability can improve a product's environmental performance. Equally, for the LCA to show how using recycled metal in a product improves its sustainability, it needs data on the environmental impact of recycled, rather than primary, metal, again sourced from recyclers.

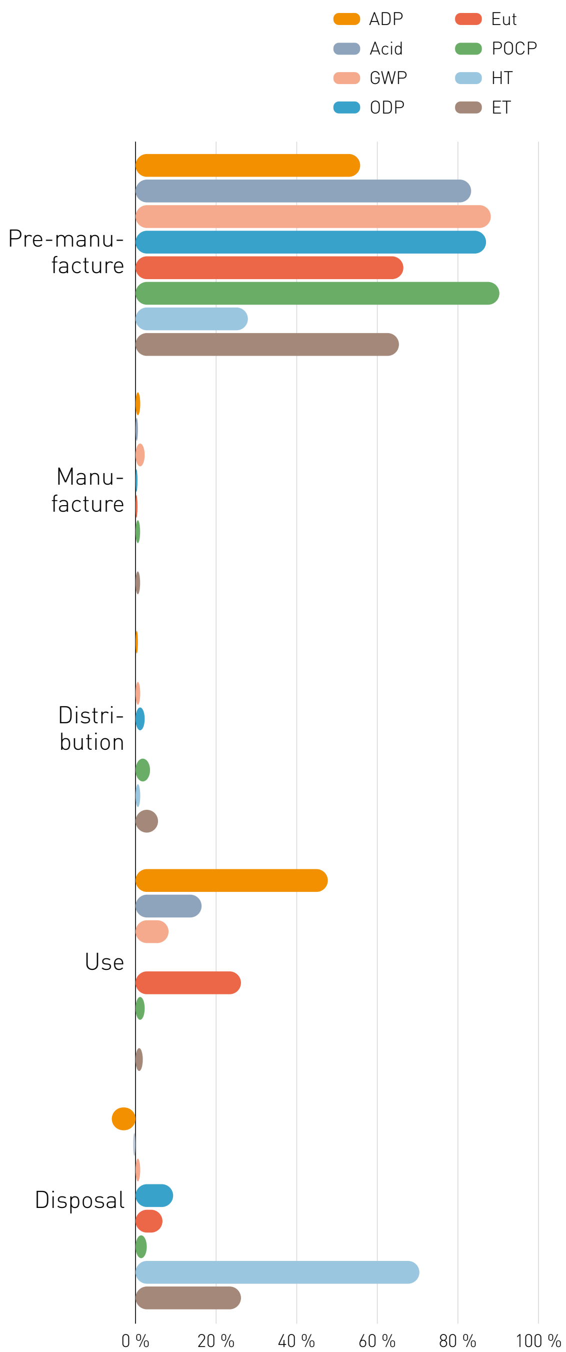


Figure 61: LCA of a personal computer (Choi et al., 2006).

Using LCA information can help companies change their working practice from clearly separated areas to interlinked ones. Figure 62 shows that, for Life Cycle Management to

Figure 62:

All functions in a company play an important role in Life Cycle Management (adapted from UNEP, 2007a).

be successful for companies, different departments need to work closely together for considering the sustainability aspects (UNEP, 2007a). For example, product designers benefit from cooperating with engineers, to ensure that the design is compatible with the metallurgy they seek to apply.

5.4.3 Value chain management

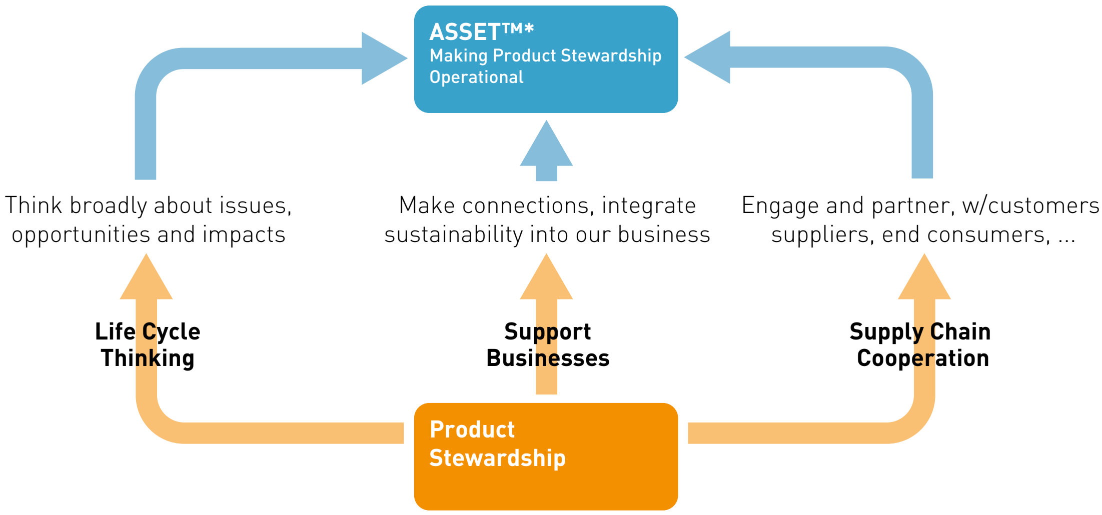
Life Cycle Management also promotes stakeholder outreach along the entire value chain of different stakeholders, or Value Chain Management. By working with stakeholders both up and down the value chain, businesses can influence design, collection, disposal, recycling processes and the market for recycled metals, as shown by Figure 63.This includes steps to influence consumer collection.

5.4.4 Industrial strategy

Another way to operate recycling is combined positive action by industry stakeholders. This can be action by industrial associations or through individual partnerships, for developing technology and new practices. This gives greater power and resources for influencing the recycling system than would otherwise be possible for an individual operator and can be part of a strategic view of an industry's future. The creation of a strategic view can also help matching new equipment to future changes in waste composition.

Figure 63:

Life-cycle management within ALCAN, engaging and collaborating with stakeholders in the value chain (Balkau and Sonnemann, 2010).



* ASSET (Alcan Sustainability Stewardship Evaluation Tool) is a trademark of Alcan Inc. and/or its affiliates, patent pending.

However, value chain management usually only happens when a stakeholder has a sufficiently strong incentive for working along the value chain. It also relies on the managing stakeholder to be in a sufficiently strong economic position for influencing the value chain. For instance, equipment manufacturers can influence their suppliers (and their supplier's suppliers) through negotiation of what they wish to purchase, using either the incentive of paying more, or the threat of buying parts from elsewhere. In contrast, a collector or recycler is rarely in a position of economic influence over a product manufacturer.

Box 16:

Steps by the aluminium industry for recycling non-ferrous materials from Municipal Solid Waste (MSW)

The aluminium industry, acting together, could increase recycling from MSW through:

- Disseminating technical information on improved technologies and process flow-charts within the industry sector, which, due to its fragmented nature, might not be fully aware of this potential.
- Encouraging use of de-metallized recycled bottom ash as a raw material for road construction, cement making, etc. Today, standards and/or specifications differ strongly between countries and even cities. One way to open up new markets is to achieve greater harmonization in these standards for creating larger international markets.
- Developing and promoting sampling and testing methods for untreated bottom ash from Waste-to-Energy plants and bottom-ash processors. This will clarify the benefits of non-ferrous metals extraction and/or of optimizing the whole plant.
- Contributing to a coherent development of the statistical data needed for monitoring progress in non-ferrous metals extraction.
- Cooperating with incineration associations, sorting-equipment manufacturers, and Waste-to-Energy engineering companies, for developing and disseminating best-available technology and practice.
- Contributing to reducing aluminium feed into MSW. Bottom-ash processing certainly can be improved, but should remain a "scavenger process". The primary target should be to keep aluminium out of MSW streams, and to separate these beforehand for direct treatment by Al smelters (optimization within a wider system boundary).

5.4.5 Summary: tools and models

In summary, a whole set of tools is available to help decision-makers understand the recycling system, assess how they can best increase recycling, and facilitate the information exchange between stakeholders. The Life Cycle Assessment tool is one example. Each of these tools provides an easy way for decision-makers to access the detailed information usually held by industry-sector experts.

Such tools enable decision-makers in one part of the recycling system (for example, designers or metal processors) to arrive at a better prediction of the likely final results of the system of any changes that they would make, such as investments in new technology.

A final observation: true Design for Recycling can only take place with tools that are based on a rigorous application of physics, thermodynamics and process technology, as reflected by, for example, Figure 5.

6. Tools to Aid Decision Making

Chapter 6 provides an outline of some of the best tools for helping decision-making in the recycling field. These include the Metal-Wheel, Grade Curves, Liberation Performance modelling, Systems Engineering modelling, Economic Outcomes modelling, Design for Resource Efficiency modelling, Life Cycle Assessment modelling, and Design for Sustainability modelling. These models condense and describe technical and scientific information, providing user-friendly predictions of results. This helps recycling stakeholders in visualizing the complex aspects of recycling on a technical and economic basis, and to translate the results into simple facts, as well as helping industry and policy-makers to improve the recycling system.

Finding ways for optimizing recycling as a system is much easier with the development of several specific tools, as discussed in Chapter 5, some of which help in understanding the thermodynamic drivers of recycling. Detailed models provide specific estimates of how changes in design, collection or processing, will alter economic and environmental recycling results.

6.1 Tools that help conceptualizing results on a physics basis

6.1.1 The Metal Wheel – An overview tool

The Metal Wheel (Figure 15) is based on the economic recovery and recycling capability of elements from hydro- and pyro-metallurgical processing. It visualizes current BAT for metallurgical processes (implicitly covering thermodynamics and physics), showing how different metals can be dealt with within technologies that were developed for the primary production of Carrier Metals, but which, when economically viable, can also separate complex modern waste materials into metals, alloys and compounds.

It also shows where innovation can improve current technology, identifying which metals cannot be dealt with in a Carrier Metal process and will be lost to the environment (the green, outside, band of the Wheel). Innovation can lead to recycling more of the metals by minimizing such losses. The understanding reflected in the Metal Wheel forms the basis for all the tools described hereafter. However, there are also some very useful "niche" technologies, e. g. for de-coating galvanized steel, producing high-grade zinc powder that can be directly reused for galvanizing.

6.1.2 The Element Radarchart – A reactor specific tool

Thermodynamics can assist in product design, by showing which metals can be metallurgically removed when found together in complex input or scrap. The "element radar chart" indicates how metals are separated in different Carrier Metal processes (Nakajima et al., 2009; 2011; Hiraki et al., 2011). It shows how metals and their compounds split between metal, slag and flue dust, and thus whether they can be recovered by that process, or will serve as useful alloys of the Carrier Metal. It also shows that removing impurities and extracting valuable metals is much more difficult for aluminium and magnesium than for the other metals on the chart, and can help decision makers in choosing the recycling products and identfying the probable outcome.

6.1.3 Grade curves – physics of separation tool

The use of grade curves is straightforward. They clearly show the tradeoffs between purity of the metal obtained ('Grade') and its rate of recovery as a percentage of the maximum potential stream from a mixed metal input (Figure 35 and Figure 36). However, it is difficult to obtain a grade curve of statistically acceptable quality, with the data coming from

separation tests or sampling on mechanical separators. The curve represents the theoretical value obtainable, but real mechanical separators are less efficient and efficiency further changes with time, feed grade, wear-and-tear of separators and with different plant settings.

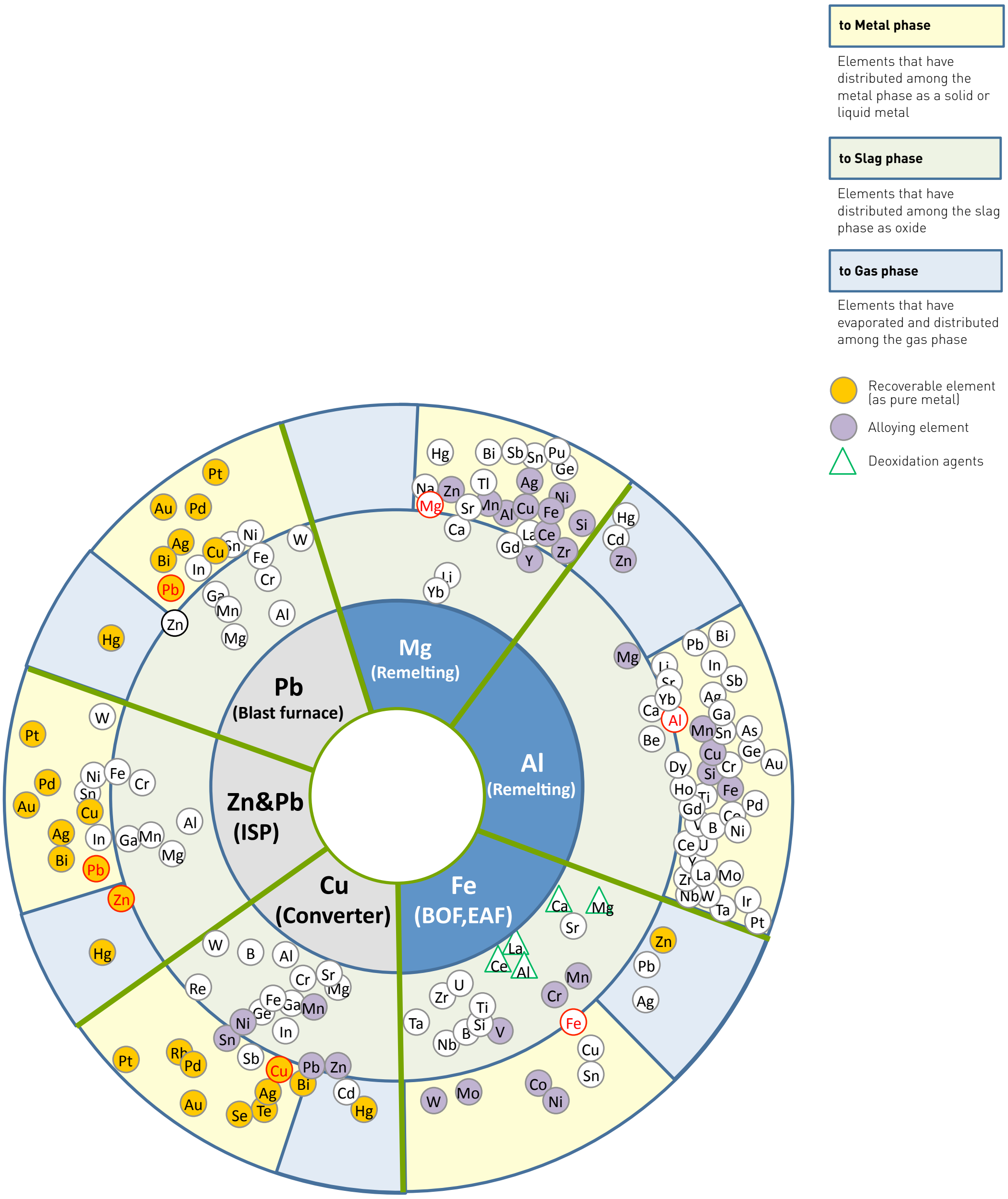


Figure 64: Element radar chart for metallurgical processing of selected metals, showing element distribution in metal, slag, and gas phases based on thermodynamic analysis and metallurgical data of specific single reactors. (Nakajima et al., 2008; 2009; 2011; Nakamura and Nakajima, 2005; Nakamura et al., 2007). The copper Peirce Smith converter of Figure 44 represents the Cu (Converter) segment here.

6.2 Advanced modelling and process simulation tools

Highly developed modelling tools provide detailed calculations based on BAT physics and thermodynamics. These are used in flowsheet design and simulation software for determining the optimal combination and arrangement of recycling processes, and include the following aspects:

- Liberation designs of complex products.
- Separation physics, including automated sorting technology.
- Chemistry and thermodynamics of metal production and recycling systems.
- Physical and chemical recyclate and recycling-product quality, as a function of product-design choices and the calorific values of (intermediate) recycling streams.
- Losses and emissions to water, air, residues, slags, etc.
- Optimization and selection of plant- and flowsheet architecture with changing product design (see flowsheet for all processes in Figure 59).
- Predictions of composition and volume of future recycling streams.
- Economic Outcomes.

These engineering- and industry-friendly simulation models define and provide the essential metrics for measuring, controlling and improving recycling. They also help determining recycling concepts as well as facilitating product design for high recycling and energy-recovery rates while advising policy makers. The distinguishing factor of these 'multi-level models' is their basis on the physics behind recycling systems. Reuter (2011a) discussed several of these commercially available tools.

Box 17:

Available tools for constructing multi-level recycling models
Reuter (2011a) listed several models that can be used for simulating processes and their outcomes, all of which are well known and freely available. They include ASPEN (1994 – 2013), HSC Sim (HSC Chemistry 7, 1974 – 2011, Figure 5) and several others that can be found in the publications by Mellor et al. (2002), Geldermann et al. (2006), and Basson and Petrie (2007). In addition, we should note Green Chemistry and Engineering software (Anastas and Breen, 1997; García-Serna et al., 2007; Manley, 2008), while multi-level simulation for industrial ecological systems was described for metal systems in 1999 (Reuter et al., 2011b). These software packages can also be linked to environmental assessment work, as in LCA tools (HSC and GaBi 4&5, 1989 – 2009, Figure 5; IChemE, 2001; Dewulf et al. 2010; Jeswani, 2010; Reuter, 2011a). Nakamura and Kondo (2002, 2006) developed a hybrid type LCA tool called Waste Input–Output, WIO, that includes costs, for evaluating the environmental performance of systems.

Such multi-level dynamic-simulation models reproduce recycling rates quite accurately as they consider all metallurgical interactions, as suggested by a Product-Centric view of recycling. Appendix E: Models and Simulation in Recycling provides a more in depth description of the application of some of these models.

In addition, advanced tools such as computational fluid dynamics (Figure 138, Section 13.11, Appendix F: Physics of Extractive Mettallurgy) and similar tools help optimizing processes within reactors to improve resource efficiency.

6.2.1 Liberation performance

Even in the field of classic mineral processing, it is difficult to model the liberation of multi-component materials (WEEE products). The breakage and liberation behaviour of consumer products fundamentally differs from that of natural ores (Richard et al., 2005), indicating that a different approach is required for predicting the liberation behaviour – and hence recyclate quality – of consumer products (van Schaik and Reuter, 2004a; 2007; van Schaik and Reuter, 2012). In addition, the dispersion of critical, scarce and/or toxic elements over the various output streams, caused by imperfect liberation, separation and design choices, drives the need for improvements in recycling-system performance and for closing material loops. The complex and unusual mix of material properties in many modern products requires some heuristic rules in support of the modelling of liberation behaviour, and for predicting the particle and recyclate composition after shredding. Based on such derived heuristics, trained fuzzy sets can capture these aspects (van Schaik and Reuter, 2010a; 2007), linking product-design characteristics and liberation behaviour in terms of:

- Design tables (input definitions for recycling) that define the mass and material connections derived from the design in real-time.
- Shredder-connection tables (Figure 31) that define the remaining connections of the design after shredding and modelling particle composition after shredding.
- Shredder-liberation tables that define the degree of liberation for the different materials and connections as a function of joint type and shredding intensity.

This can predict the distributed and time-changing recycling and recovery rates for the materials in the product, and the particulate properties, particle-size distributions and recyclate qualities.

In summary, complex particulate recycling systems, as governed by product design, are described on a physics basis that enables practical calibration of the parameters. This highlights the influence of design on recyclate quality, and on recovery and/or loss of materials. This highly detailed approach is critical for pinpointing design deficiencies and possibilities related to recycling performance (both sorting and metallurgical recovery), to improve resource recovery from products such as e-waste.

6.2.2 Modelling on based on the physics of processing systems – system engineering

Liberation models can be linked to modelling the thermodynamics of processing systems. For more precision, rigorous metallurgical-process flowsheeting can be linked to environmental software for producing a specific BAT for metal production, rather than relying on the usual averages from LCA software.

This enables calculating and predicting the dynamically changing recycling and recovery rates of complex waste streams or individual products. These can cover all individual materials in such products for different recycling scenarios and objectives, such as maximum total recycling/recovery, maximum recycling of metals, minimum waste production, legislative constraints, etc., as a function of input. In turn, this allows:

- Predicting the grade of all (intermediate) recycling streams (e.g. iron recyclate, copper recyclate, plastic recyclate, etc.) and recycling products (metal, matte, speiss, slag, flue dust, off gas) (see Figure 60, 5.4).

- Predicting the dispersion, occurrence and appearance (chemical phase) of possible toxic and harmful elements in recycling products.

- Defining the best recycling concept for multi-material designs, such as the SLC concept (recycling plant and flowsheet configurations) for optimal recycling results and/or minimal material losses.

6.3 Modelling of economic outcomes

Liberation modelling, when coupled with modelling of the thermodynamics of a specific processing plant, allows defining recyclate grades and thus the resulting economic value. This gives depth to feasibility studies for building multi-million-dollar plants and systems, providing insight into their opportunities and limits. It also shows when recyclates have sufficient quality to warrant economically viable recycling, or which recyclates turn into waste because of insufficient economic value, and thus where legislation may have to step in. The models' predictive nature also permits analysis of complete systems and products for establishing future systems requirements.

6.3.1 Prediction of valuable metals in scrap streams

Models of product sales, use characteristics, disposal, and collection behaviour can also estimate future composition (not grade!) and volumes of waste streams that will be available for recycling, also known as "Mass Flow Analysis" models (MFA). For example, MFA models can reasonable reflect copper flow as discussed by Ruhrberg (2006), due the relative large fraction of relatively pure scrap, but they cannot predict the complex grade of unliberated and liberated scrap mixtures, the word "prediction" usually being reserved for models that are based on physics.

The "Lifetime Approach" predicts an in-use copper reservoir for Western Europe of about 78 million tonnes of metal and alloys. For 1999, the estimated copper scrap availability and old scrap recovery amounted to about 2.7 million tonnes and 1.6 million tonnes of copper and alloys, respectively. The corresponding recycling efficiency rate for end-of-life copper and alloys in 1999, excluding outflow to other metal loops, was estimated to be 63 % for the EoL approach, 64 % for the lifetime approach, 67 % for the scrap-balance approach, 69 %, 70 %, and 73 %, respectively, including all identified outflows to other metal-recycling loops.

The recycled content of products and the quality-constrained availability of materials are subjects of great importance for sustainable metal management. Nakamura and Nakajima (2005) and Nakamura at al. (2007) developed a novel MFA tool (WIO-MFA) that allows estimating the material composition of a product using information about the fabrication of materials and the inter-sector flow of goods and services provided by a high-resolution input-output table. For instance, the WIO-MFA tool enables estimating the recycled content of final products such as cars, appliances, or buildings, for whatever materials are of interest.

6.3.2 Environmental performance

The quality predictions from recycling-system models also provide the basis for:

- Scientific estimates of the toxicity (and possibly related environmental costs) of each recyclate stream, based on the combination of materials in each particle.

- Assessment of the potential use of slag and/or of the need for its further treatment.

- Assessment of the toxicity of output streams, such as leaching behaviour and/or land-fill costs.

The amount of fossil fuels used also determines the environmental impact of any recy-

cling system. The same applies to any metal-production facility, as each has its own technology. Where impact studies of metal use in many cases are based on average environmental data, a BAT life-cycle inventory (LCI) database of different technologies should be available. New technology increasingly replaces old one, as the metallurgical and recycling industry constantly reduces its footprint.

6.3.3 Integrating water and metals recycling

A very important environmental problem is the potential link between water pollution and mineral/recyclate processing. Because of poor water (quality) management, many metals and their compounds find their way into sludges, precipitates, etc. Figure 65 schematically shows this link between water-treatment residues and the metallurgical infrastructure, as a multi-level-system optimization model describing a particular area of water, here the water south of Rotterdam harbour. By considering the metal/compound-processing and water-treatment/recycling infrastructures together, complex problems can be investigated. This provides sufficient technical detail for improving the system, as well as pinpointing which metals originate where, and what are the technological and policy solutions for maintaining water quality.

Understanding and predicting the recycling residues (the metals going to the green band of the Metal-Wheel) makes it possible to link them to water models, especially for predicting changes in water quality. Since physics-based models can predict the phases and compounds in the residues, leaching models can be calibrated for estimating how much of the metals will actually flow into the environment.

Box 18:

Physics-based simulators

Environmental performance can be visualized with state-of-the-art process simulators, linking them in real-time to environmental impact software for flowsheeting, simulation and thermodynamic modelling, such as Linking HSC Sim (HSC Chemistry 7, 1974–2011), or Outotec with the GaBi LCA tool for benchmarking process designs (GaBi 4, 1989–2009; PE-International). Not only does this approach show the difference between BAT and non-BAT operators, but it also links GaBi to HSC Sim for 25,000 compounds in the database. This gives a more accurate view of which compounds occur in the system, and better evaluates the quality and toxicology of most metal compounds in the system streams.

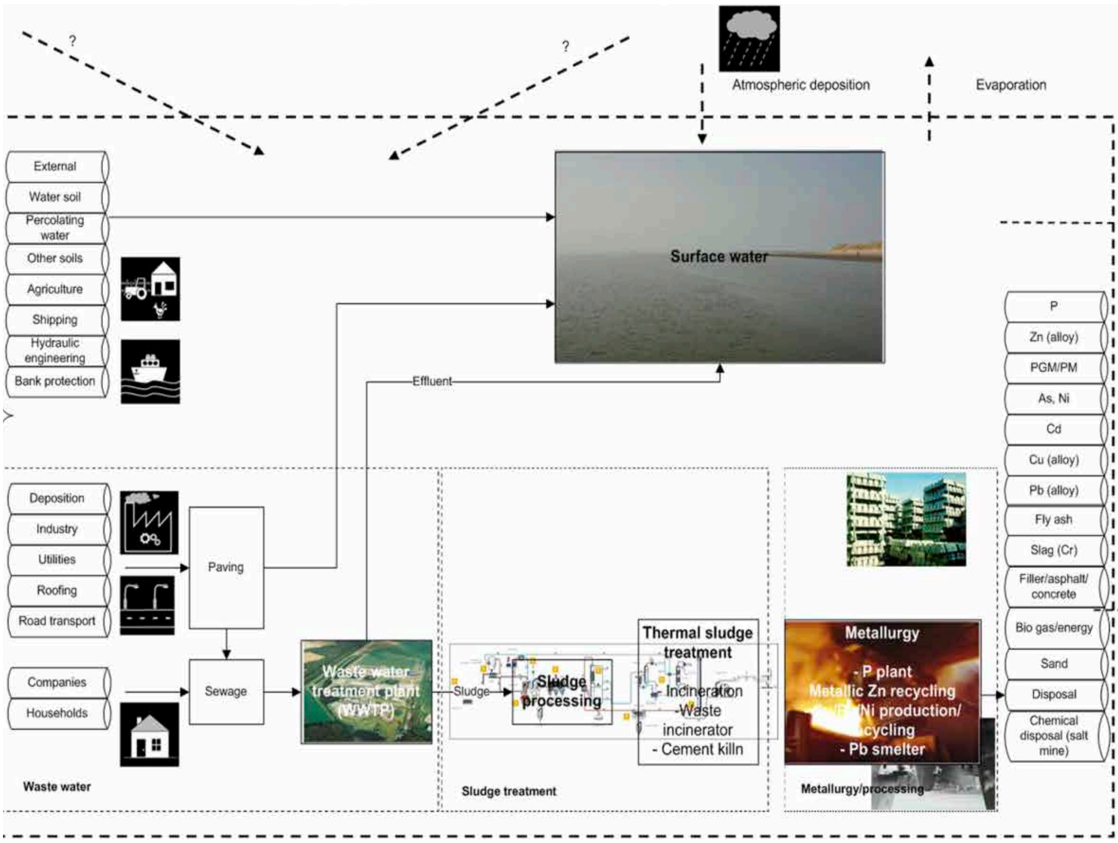


Figure 65:

Water cycle connected to metal and sludge processing, showing that recycling is not linear but complexly interlinked (van Schaik and Reuter, 2010b; Fagan et al., 2010).

6.4 Tools for assisting product designers

Design for Resource Efficiency (DfRE), of which Design for Recycling (DfR) is a sub-set, demands knowledge of liberation behaviour, of the particulate quality of recyclates, of the separation efficiency linked to the compatibility and thus recovery and/or loss of material in metallurgical processing, and of the modelling thereof, all as a function of design choice, connection type and connected materials. Insight into this provides a technology- and industrial-process driven basis for DfR to optimize resource efficiency and closure of material cycles for both commodity and critical and scarce elements in complex consumer products, such as cars and e-waste/WEEE products. Available tools can help with this, as shown by Mathieux et al. (2008), Kim et al. (2009) and Kuo (2010), and more details are given below.

6.4.1 Design for resource efficiency and material compatibility matrix

A 'Material Compatibility Matrix' (Table 1) (Van Schaik and Reuter, 2012) and the Design for Resource Efficiency Metal Wheel (Figure 4, Figure 38; Reuter and van Schaik, 2008) were developed as preliminary DfR tools for designers, which capture the physics of recycling. The simulation models and the Wheel are based on system models that link product design to the complete recycling system as shown in Figure 59.

DfR should be considered when designing products so that functional groups within the product can be separated more easily during the dismantling phase. By providing these pre-selected parts into the right segment of the metal wheel, the most resource efficient recycling process can be achieved. Obviously each functional group may have metals that are incompatible, but these will then be the loss from the system. Thus DfR should be guided by the possible metallurgical infra-

structure that can recover metals economically.

Table 21 shows a DfR compatibility matrix for various materials in a car, including critical, scarce and valuable elements. This shows how recycling factors for various combined materials may be limited, based on liberation, sorting and thermodynamics. It indicates the possibilities and limits of the recovery of (critical) materials by pinpointing the (in)compatibility of different materials on the basis of metallurgical recovery.

6.4.2 Modelling the results of changes in product design

The multi-level modelling of recycling outcomes described above can be linked to Computer Aided Design (CAD) packages, providing designers with all the predictive power they need for designing products with optimal Life Cycle costs and minimal environmental impact. A collaborative-design platform using CAD collects all data, enterprise resource planning, and product life-cycle management systems.

Table 21: Compatibility matrix for materials in a car, showing compatible and incompatible metals in terms of recovery (Castro et al., 2004, 2005; Reuter et al., 2005).

Car components (kg)

Input streams	battery 13	body 520	bumper 5.5	electronics 2	engine 90	exhaust 10	fuel tank 0.1	gear box 27	grille 0.8	wheels 30	lights 1.4	others 93	rubbers 7.7	seats 6.5	tires 28	windows 25	wiring 5
Aluminium (cast)		Minor			Major			Major		Major							
Aluminium (wrought)		Minor							Minor								
Copper alloys				Major							Major						Major
Lead alloys	Major			Minor													
Magnesium alloys					Minor			Minor									
Pt-family alloys				Minor		Minor											
Stainless steels		Minor			Minor	Major											
Steel + Cast Iron		Major	Minor		Major	Minor	Major	Major						Major	Major		
Zinc alloys		Minor				Minor											
Glass											Major					Major	
Elastomers		Minor										Major	Major		Major		
Natural Fibers		Minor										Major		Major			
Natural Rubber		Minor															
Porcelain					Minor	Minor											
Thermosets	Minor	Minor									Major	Major		Minor			Minor
Thermoplastics	Minor	Minor	Major	Major					Major		Major	Major		Major	Major	Minor	Major

Industrial streams (metals)

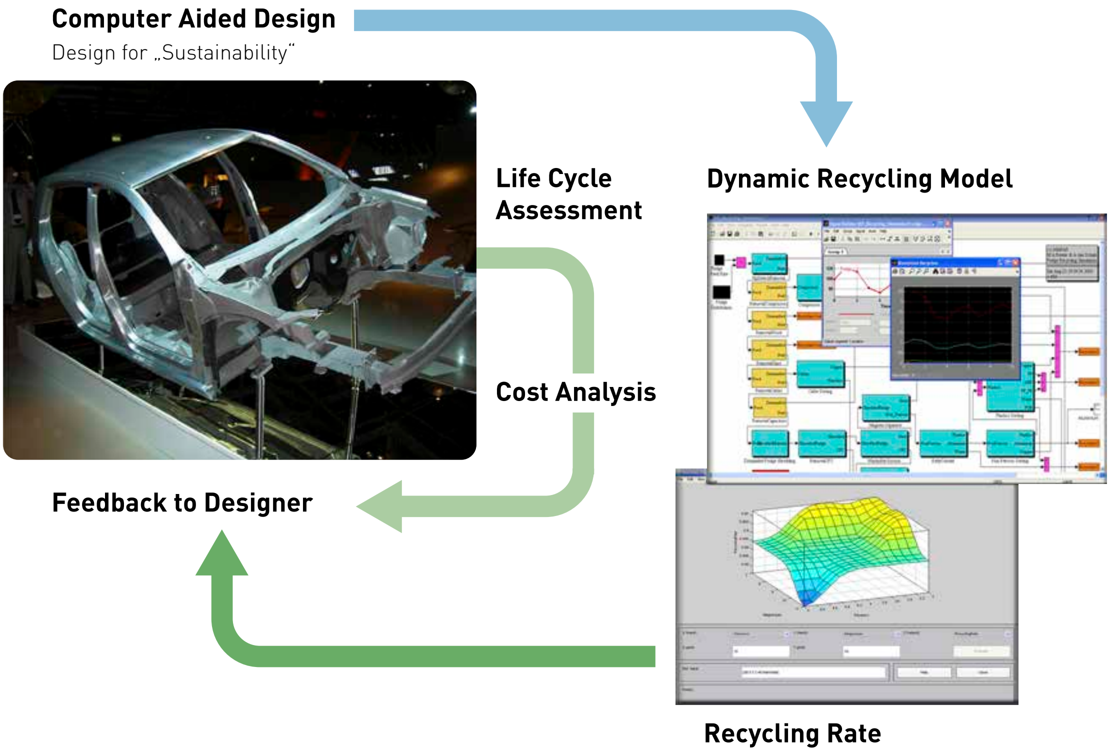
Input streams	Aluminium (cast)	Aluminium (wrought)	Copper	Lead	Magnesium	Pt-family alloys	Stainless steels	Steel + Cast Iron	Zinc
Aluminium (cast)	2	0	1	0	0	1	1	1	0
Aluminium (wrought)	1	2	1	0	0	1	1	1	0
Copper alloys	1	0	2	1	0	2	0	0	2
Lead alloys	0	0	2	2	0	2	2	2	2
Magnesium alloys	1	1	1	1	2	1	1	1	1
Pt-family alloys	0	0	2	2	0	2	1	1	1
Stainless steels	0	0	1	1	0	1	2	0	1
Steel + Cast Iron	0	0	1	2	0	1	1	2	2
Zinc alloys	0	0	2	2	1	1	2	2	2
Glass	1	0	1	0	0	1	1	1	0
Elastomers	1	1	1	1	0	1	1	1	1
Natural Fibers	1	1	1	1	0	1	1	1	1
Natural Rubber	1	1	1	1	0	1	1	1	1
Porcelain	1	0	1	0	0	1	1	1	0
Thermosets	1	1	1	1	0	1	1	1	1
Thermoplastics	1	1	1	1	0	1	1	1	1

Minor component (kg)
Major component (kg)
0 – MUST separate, avoid mixing
1 – SHOULD separate, problems can occur
2 – DON'T separate, good combination

6.4.2.1 Example: Designing car-bodies: the Super-Light Car Project

The Body-In-White (BIW) shown in Figure 66 for the EU's SuperLightCar project, is a novel construction of steel, light metals and polymers reducing the weight by 35 % for a substantially lower manufacturing cost per kg (SuperLightCar, 2005-2009; Krinke et al., 2009). The ultimate objective was to reduce not only weight but also fuel consumption, creating the basis for future passenger-vehicle power trains.

The project created a tool that links CAD to a costing and LCA tool. Due to the EU's ELV legislation (95 % material recycling and energy recovery by 2015), a major aspect of the project was to calculate the recyclability of the BIW. This was done with the ELV recycling model developed by Reuter et al. (2006) and van Schaik and Reuter (2007), linking the different tools between product design and recycling (Figure 66). This DfR/DfS tool, incorporating the recycling model's input, provides environmental-impact data for different designs, while the costing tools provide the cost of each design.



Recyclability optimized as a function of technology, economics, material recycling and energy recovery.

Figure 66: Linking design with sophisticated recycling tools drives innovation and improves resource efficiency through DfR for the SuperLightCar project (Goede et al., 2008; SuperLightCar, 2005 – 2009).

This can facilitate Design for Dismantling of parts of the equipment, where factored into design choices.

6.4.3 Life Cycle Assessment (LCA)

Life Cycle Assessment or LCA (Rebitzer, 2004; UNEP, 2010) is a tool that facilitates understanding and quantification of the ecological and human-health impacts of a product or system over its complete life cycle. We identify the following steps:

- Compilation of an inventory of relevant inputs and outputs of a defined system.
- Evaluation of the environmental impact associated with these inputs and outputs.
- Interpretation of the results of inventory analysis and impact assessment based on the set goals.

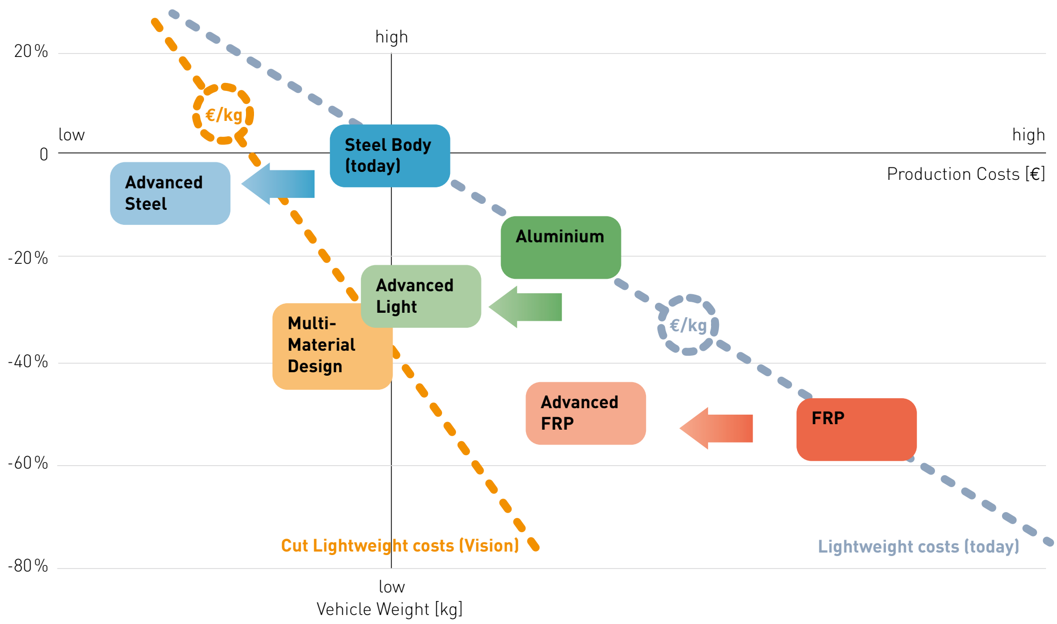
Box 19:

The SuperLight Car

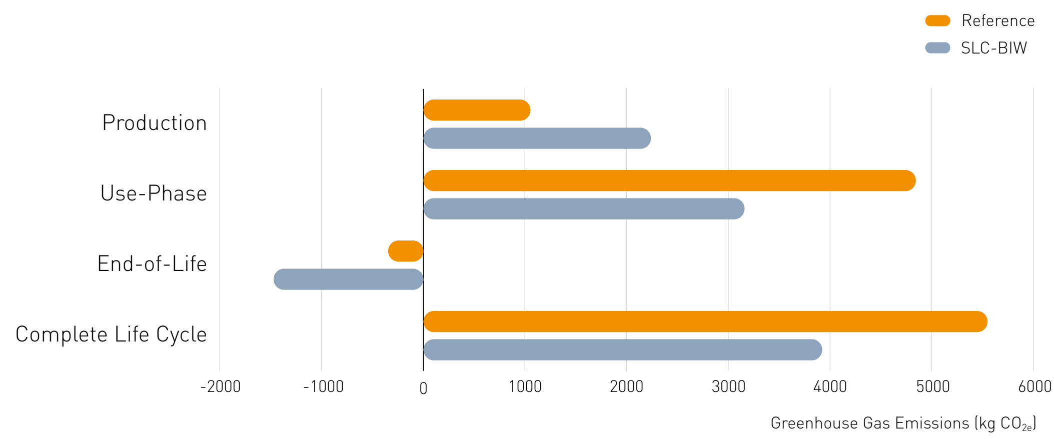
The SuperLight Car project provides an example of using LCA. Through application of the data shown in Figure 67, we can calculate the environmental footprint of the SuperLight Car design and the materials used in the concept body-in-white (BIW) as summarized by the right of Figure 67. The LCA modelling showed the SuperLight Car to have a substantially lower carbon footprint than a reference vehicle, although materials are used during production that require more energy. As it is also recyclable, it also brings a higher CO_2 credit with it (the negative bar, see Box 19_b).

Figure 67:

LCA visualization of the SuperLightCar concept (Goede et al., 2008; Krinke et al., 2009).



Box 19: _b



Within recycling systems, LCA can be applied to a comprehensive assessment of WEEE recovery systems, as was done for Swiss WEEE (Hischier et al., 2005; Wäger et al., 2011). It uses different environmental indicators whose selection is a factor for choosing methodology. For example, the following midpoint indicators[a] are used by Guinée et al. (2001): Acidification Potential, Global Warming Potential, Eutrophication Potential, Photochemical Oxidation Potential, (Stratospheric) Ozone Depletion Potential, Abiotic Resource Depletion, Freshwater Aquatic Ecotoxicity Potential, Human Toxicity Potential, and Terrestrial Ecotoxicity Potential. Other potential endpoint indicators[b] according to the Eco-Indicator '99 methodology (Goedkoop and Spriensma, 2000) are ecosystem quality, human health and resources.

a Midpoints in the cause–effect chain (environmental mechanism) of a particular impact category lie somewhere between stressor and endpoint.

b Endpoints are elements of an environmental mechanism that have a societal value, such as human damage to plant or animal species or natural resource depletion.

6.5 Design for Sustainability (DfS)

Design for Recycling, as outlined in the previous section, focuses entirely on the recyclability of a product and disregards, for example, energy-efficiency considerations. These and others are crucial to the Design for Sustainability approach. This approach requires product designers to assess which material promises the best sustainability performance, for example with regard to energy efficiency combined with other factors like recyclability, durability, etc., by taking a life-cycle perspective.

Any changes to a product generally lead to tradeoffs. A lower cost or environmental impact in one area may lead to a cost increase in another. The LCA helps revealing these tradeoffs, so that the different outcomes can be understood and compared. In some cases, Design for Recycling will not be appropriate, because of other impacts at other stages in the life cycle, for example, in energy efficiency. Such a tradeoff is shown in Figure 68, comparing a steel and a carbon-fibre-reinforced-plastics (CFRP) basic car 'body-in-white'. Carbon-fibre production has a high environmental footprint, but, because the car body will be lighter, the environmental footprint over the use phase will be smaller. Whether the CFRP or the steel car has a

bigger impact will depend on how far the car is driven; after the break-even point around 135,000 km, the steel car accrues more (negative) eco-points.

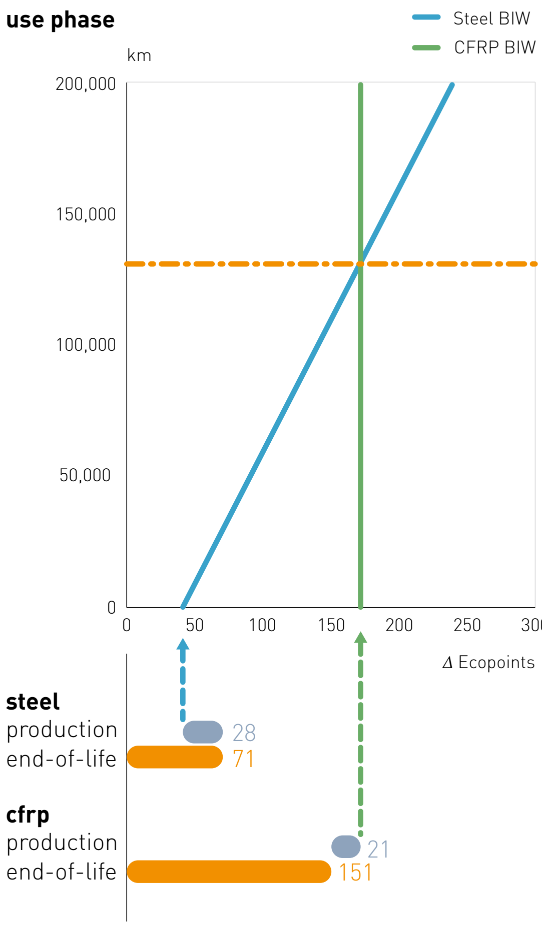


Figure 68: Total life cycle impact of a CFRP body in white (BIW) compared to a conventional steel BIW. Only the difference in fuel consumption is considered in the use phase (van Acker and Verpoest, 2011; Duflou et al., 2008, 2012).

This moves Design for Recycling to Design for Sustainability, an important step within a Life Cycle Management approach. Assessing the overall energy efficiency thus includes considering the energy needed for producing the material in question, as well as the energy the product would require during its use-phase. Finally, the energy needed for recycling of the product needs to be considered as well.

In conclusion, while Design for Recycling enables high recycling rates, Design for Sustainability focuses on more than just one issue and is better suited for improving the overall sustainability performance of a product. Such tradesoffs with regard to various issues, in particular environmental impact, is generally made transparent by applying Life Cycle Assessment (see Appendix E: Models and Simulation in Recycling).

6.5.1 Life Cycle Management (LCM)

Life Cycle Management, LCM, is a business approach that can help companies achieving sustainable development. It helps reducing, for instance, a products' carbon, material and water footprints, as well as improving its social and economic performance. It is used for targeting, organizing, analysing and managing product-related information and activities toward continuous improvement throughout product life. LCM is about making life-cycle thinking and product sustainability operational for businesses that aim for continuous improvement (UNEP, 2007a). These efforts ensure a more sustainable value-chain performance of companies. The resulting benefits can include long-term value creation, better corporate credibility and stakeholder relations, and higher shareholder value, both locally and globally.

LCM facilitates Design for Sustainability, and resolves tradeoffs in choosing material combinations, in life-cycle costing and LCA across the value chain. This helps especially where many of the decisions affecting a product's life cycle lie outside the direct control of one stakeholder, including the use phase (impacted by design) and the end-of-life phase, impacted by the recycling infrastructure, legislation, consumers, etc.

6.5.2 Recycling indicators

Recycling indicators serve to guide decision makers, many of which have a Material (& Metal)-Centric outlook with an imperfect understanding of multi-material recyclates as explained before. Material (& Metal)-Centric indicators are based on material flows of either pure metal and/or alloys. For the much more common multi-material recyclates, the recycling product depends on the physical separation of mixed waste before it enters metallurgical processing. As described above, the degree of physical separation often displays a strong degree of randomness,

which means that the recycling outcome will also have a degree of randomness, instead of being a set of predictably separated discrete metals.

Approaches based on an understanding of the physics of recycling are freely available. They can help in rendering the Material (& Metal)-Centric indicators more Product-Centric, to reflect the complexity of products and their large diversity of rapidly changing compositions.

6.5.3 A note on data, data structures and quality

Well-collected and formatted data, including information on their timelines as well as on standard deviation and average values, are important for evaluating recycling systems. Although some data are available, not many have a thermodynamic basis, and thus will be of little use for models based on that fundamental starting point. Many data are measured in such totally different ways that there is insufficient information for closing a mass balance, and certainly for producing statistically sound recycling-rate calculations, predictions, etc. While data compilations such as the Review of Directive 2002/96 (United Nations University, 2007) give a snapshot of the "now", they are of little use for calibrating physics-based models that are needed for understanding and innovating recycling. Therefore, special attention should be paid in the future, that good data are collected for a meaningful contribution to better resource efficiency.

To perform dynamic modelling and simulation of recycling systems requires data sets with at least the following characteristics:

- Metal, alloy and compound details.
- Identified connections between materials.
- Standard deviation values of the composition of each metal, alloy, compound, and of total flow rates.
- Thermodynamic and physical properties.

6.5.4 The future of design for recycling and recyclability indexes

Useful Design for Recycling tools must be based on the rigorous methods discussed here. Simplistic linear methods without any physics basis will be of no use in guiding product design. The more complex the products are, the more rigorous the methods must become for capturing all non-linear thermodynamic and physics interactions between materials, for a clear prediction of recyclability and resource efficiency.

In summary, recyclability indicators will only be of use if they are based on rigorous physics (Figure 5), as otherwise they can mislead decision makers and consumers.

7. Policy Drivers and Recommendations for Recycling

More than 25 years ago, Lidgren (1986) made a statement that still holds true: "It stands to reason that society wants to impart the most correct possible dimensions to the recycling sector. That, however, requires knowledge of the mechanisms that govern this sector and should be allowed to govern it." Government policy can have a very significant positive or negative impact on increasing recycling. It can:

- Influence the economics of any part of the recycling chain, changing the economic viability of the whole chain or of any part of it.
- Provide the incentives and means for stakeholders in the recycling chain to exchange information and cooperate to increase recycling.
- Act as a stakeholder in the chain – public organizations (often local authorities) are frequently part of the recycling industry – providing waste-collection services and recycling or disposal infrastructure.
- Set framework conditions that enhance recycling, such as setting certified standards.

Rather than looking primarily at recycling rates, policy could much more usefully focus on creating a robust BAT platform for recovering metals and helping industry to do this. A BAT infrastructure, once in place, will operate by itself to maximize the recovery of all valuable elements with an economic incentive to do this.

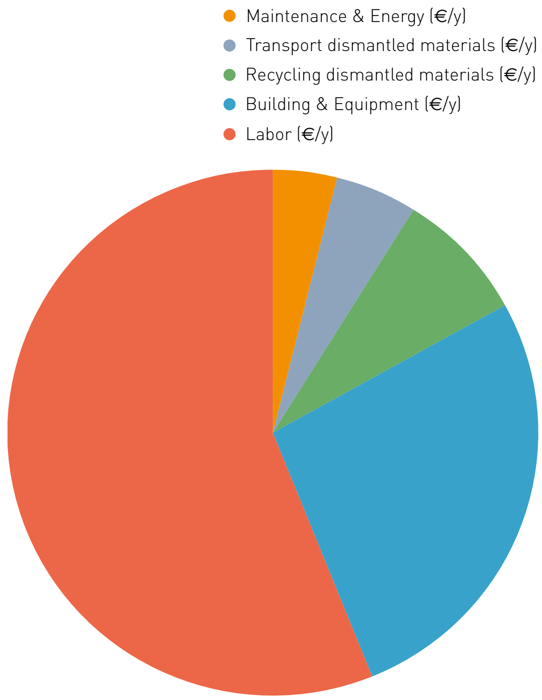
7.1 Influencing the recycling chain economics

Many of the world's existing recycling policies have grown out of environmental policies, and are often still under the control of environmental ministries. This reflects the potential environmental benefits and harm from increased recycling or insufficient waste treatment. However, it can also obscure the fact that recycling is primarily an economic industrial activity, and is strongly affected, for better and for worse, by all of the policies that influence the costs and benefits of recycling.

Waste- and recycling policies directly affect the cost of recycling processes (e. g. where environmental requirements change such processes) as well as the cost of alternatives to recycling (e. g. of waste disposal). These policies also influence the availability and composition of waste streams for recycling. Relevant, too, are trade restrictions on waste or metals, and all policies affecting industrial activity such as taxation, labour regulation and energy costs. The balance of costs and benefits from these policies determines whether recycling is more or less profitable than alternative disposal of recyclate materials, or even to what extent individual substances are recovered from complex products. For example, Figure 69 shows labour costs to be a large part of the cost of an industrial shredder that pre-processes End-of-Life vehicles. This is partly because policy promotes some manual dismantling of cars to increase the recycling rate, as well as the removal of hazardous oil and fuel for environmental and health reasons.

Figure 69:

Rough cost-breakdown for a typical shredder, where manual dismantling contributes up to 80 % of the ELV recyclate (Ferrão and Amaral, 2006).



Policy promoting the industry, for example through subsidies or a suitable tax regime, also changes the economics. Such policy tools can both target innovation and the recycling of particular strategic metals. Taxation policy, often seen as just a tool for raising revenue, has a major influence on investment and consumption decisions, and is probably the most important tool that a government has for aligning economic incentives with the transition to a more resource-efficient, low-carbon economy. In the context of recycling, differential taxation can play a role, either through energy-price controls or by favouring recycling processes or materials. The balance of taxation between energy, materials and labour cost further affects the viability of the collection of EoL goods.

Due to the links between the metal-supply chain and recycling systems, public policy may inadvertently damage the infrastructure for recycling (Verhoef et al., 2004). Policies that affect one part of the industry may have knock-on effects elsewhere. Policy-makers can help by being cognizant of such pitfalls. One example comes from the EU policy for reducing the use of lead in products, so that less toxic lead will escape into the environment at the end of product life. One of the elements planned to be used as a substitute for lead was bismuth. The policy was effective at removing lead, but caused an inadvertent reduction (rather than increase) in bismuth production as bismuth and lead are mined and produced together, and lead production had decreased due to the lower demand.

Establishing weight-based product-recycling rates for all individual trace- and critical elements is impossible, hence policy should focus instead on well developed BAT Carrier Metal-recovery systems. The critical elements will then be recovered if there is an economic reason for doing so.

A prime factor for investment is the security of its future economic rate of return, helped by knowledge of secure material streams of known composition. Stability in government policy affects the economics of recycling, and timely announcements of any future policy changes will help investment. Creating supply security for investors also implies stimulating collection and preventing illegal outflows such as theft.

7.2 Providing the incentives and means for stakeholders to exchange and cooperate

The previous section described how coordinated change to different parts of the recycling system often is the best way for increasing recycling, and how this requires exchange and cooperation between the stakeholders who are the key players in the recycling system. The lessons from recycling policies used around the world suggest that the effectiveness with which policy promotes these interactions between stakeholders is one of the most important factors in increasing recycling rates.

For example, the continuous evolution of battery chemistry, the use of manufacturer-specific formulations, and extremely high quality requirements, makes the recycling of rechargeable batteries very difficult, unless one-to-one business-to-business (B2B) relationships between a manufacturer and a recycler are developed. Though critical today for geopolitical reasons, lithium and rare earths for example will require increased battery collection volumes for creating the economies of scale that render recovery of the contained metals economic. However, the wrong combination of rare earth waste streams, e. g. mixing batteries with other REE-containing recyclates to boost scale effects, will greatly complicate the subsequent refining process, as different REEs are used in different batteries and some do not contain REEs at all. Partnerships in the recycling system can provide solutions to these issues, if all of these intricacies are to be understood and economically fully exploited.

Government policy can facilitate information exchange between stakeholders, either by providing the information itself, or by convening meetings or increasing trust in information, for example by setting and monitoring standards for quality labels. Through education, it can influence the ability of different sectors to work effectively with each other. However, experience suggests that recycling stakeholders respond more strongly when there are economic incentives for cooperation.

These incentives can come from allocating the responsibility for a product life cycle to the most influential stakeholder in this life cycle. For most products this is the producer, who can influence design and suppliers, and can raise any funds needed for recycling from consumers through increasing the product's sale price. This is one of the primary ways in which existing Extended Producer Responsibility policies work. Yet, even where producers directly feel the net benefits and costs of recycling, and thus have economic incentives for maximizing the value of the metals that result from the recycling process, they frequently do not focus on recycling. Just as primary metal producers tend to focus on their core Carrier Metal business, product manufacturers often do not have the expertise to start recycling and so choose not to engage.

Policy has to overcome this reticence by placing quantifiable recycling obligations on producers, for example the weight percentage of the product that must be recycled to meet legal compliance. This provides a stronger motivation for producers to cooperate with recyclers than the prospect of economic gain. Section 7.5 below examines several examples of Extended Producer Responsibility worldwide.

Governments can also bring people together around innovation projects. Here, the incentive to participate comes either from subsidized innovation development, from the potential savings that innovation may have for future revenues, or from benefits of working together with other stakeholders on a joint solution.

7.3 Government as a stakeholder in the recycling chain

Public authorities commonly are stakeholders in the recycling chain, where they exert a direct influence on the outcomes of recycling, or cooperate with other stakeholders. Many local authorities are responsible for waste collection and processing, which often includes the ownership and construction of infrastructure for separate collection or treatment. Such public investments, either in physical infrastructure or in expertise, are often long lasting in view of the large capital costs. Local authorities can seek ways to benefit economically and environmentally from new or existing waste streams.

In deciding on infrastructure location (whether their own or that of private stakeholders), government indirectly affects the economics of recycling. Just as the mining industry runs optimally if the concentrates are processed close to the mine site, leaving residues in well-controlled ponds, recycling production capacity should ideally be close to the "urban mine" that delivers the modern post-consumer "ore", for lower collection and transportation costs. Such input costs, when high, can lower the attractiveness of recycling. In view of the common 'not-in-my-backyard (NIMBY)' desire to move industrial sites away from urban areas, care must be taken to protect the recycling industry close to large "urban mines", ensuring that BAT prevails so that the general public trusts what industry is doing.

Where local authorities are responsible for collection, they may lack the commercial incentive for separating waste so that its most valuable constituents can be recycled. Policy can help with this. Again, where public authorities have no expertise in recycling or collection, they can productively work with partners ensuring downstream cooperation with reliable and efficient companies and stakeholders.

Public authorities, and related public bodies like health providers, are both significant generators of waste and product buyers. In the former capacity, authorities with good waste-separation policies can have a significant influence on recycling potential, and, through public procurement processes, they may boost the market for products containing recycled materials, thus supporting recycling. Green public procurement should also provide guidance for end-of-life, ensuring that public devices find their way into a certified recycling chain.

7.4 Interactions between policymakers that facilitate decision-making for recycling

Government policy will produce better results when it considers the interconnections in the recycling system. Taking a Product-Centric view will help, as it makes use of the available tools and looks to minimize conflicts between policies from different parts of government. Conflicts between policies can arise out of a lack of communication between different government departments working in different policy areas, or even between colleagues in one part of government (e. g. the environmental department.)

For example, in China good recycling occurs where governmental responsibilities for solid-waste and recyclable-resource management are linked. The authorities in charge of comprehensive resource utilization set economic policies for waste and recyclable resources, practicing economic stimulation measures. The competent authorities for environmental protection are responsible for pollution control during the recycling process. Moreover, urban construction authorities are responsible for household-garbage management and treatment, commerce authorities supervise the collection of recyclable resources, customs look after customs-clearance and inspection of imported recyclable resources, and industrial-management authorities have some functions in recyclable resources. Such dual functions

improve recycling efficiency and productivity of solid waste and recyclable resources.

Although there is no perfect organizational structure for ensuring better cooperation between government arms, policy making can be improved where specific responsibility is allocated for recycling capacity as a whole. This can shape policy to enhance the key expertise of industry, making individual policies that take a narrower view into a success. One way is to create government structures that adopt a holistic approach and deal with interdependencies (recycling, energy efficiency, climate impact, emissions, etc.).

7.5 Common forms of policy designed for better recycling

7.5.1 Extended producer responsibility and take-back-systems

Extended Producer Responsibility (EPR) facilitates recycling by creating partnerships along the recycling chain. It induces the producer to take part in waste-collection schemes, and engage in partnerships with recycling processors. Both can push back the boundaries of innovation, promoting information exchange (for example, on how design facilitates or limits recycling.) EPR policies have been adopted across the world and, in practice, can consist of different aspects, from voluntary to mandatory (OECD, 2001; Table 22).

Table 22: Possible approaches to EPR and examples (OECD, 2001).

Type of EPR approach	Examples
Take-back programmes for products	Mandatory take-back Voluntary or negotiated take-back programmes
Regulatory approaches	Minimum product standards Prohibitions of certain hazardous materials or products Disposal bans Mandated recycling
Voluntary industry practices	Voluntary codes of practice Public/private partnerships Leasing and “servicing” Labelling
Economic instruments	Deposit–refund schemes Advance recycling fees Fees on disposal Material taxes and subsidies

The only formal WEEE take-back systems, based on sustainability and extended producer responsibility principles, are almost exclusively found in OECD countries (Sinha-Khetriwa et al., 2006, 2009; Ongondo et al., 2011). The European WEEE Directive (European Union, 2003), based on the EPR concept, sets the global pace in regulating WEEE management. It has its origins in environmental policy, so in addition to the extended pro-

ducer responsibility, it also sets some design standards and prescribes certain environmental standards for the recycling processes.

As the European WEEE Directive had to be implemented by national laws, it showed how different arrangements for implementing EPR could lead to different outcomes. It also showed how important it is that regulation gets all the economic incentives right, as well as relying on mandated action. The design and enforcement of the EU WEEE Directive led to insufficient collection rates in many EU member countries, an issue now being tackled by a legislative revision (European Commission – 2008 – Questions and answers on the revised directive on waste electrical and electronic equipment (WEEE) – Press release MEMO/08/764 – http://europa.eu/rapid/press-release_MEMO-08-764_en.htm). Only the best performing European countries, which had started to implement WEEE management policies before the EU WEEE Directive came into force, now achieve collection rates higher than 80 % of waste generated.

Box 20:

EU WEEE and WEEE-2 Directive
The 2005 EU WEEE legislation required producers to ensure that all of their products were recycled to certain environmental standards when they became waste. Producer-funded collection schemes were set up to deliver on this goal. However, a review of the destination of EU WEEE found that around 50 % of the WEEE available for collection still disappeared into grey or illegal channels. Some was being processed in the EU, but much was illegally exported despite regulations banning its shipment.

The explanation was that illegal waste operations were informally out-bidding regular recycling schemes for the valuable WEEE, ignoring recycling standards, causing corresponding environmental harm and avoidable metal losses. The producer-collection schemes had the financial resources (from fees added to the purchase price of new goods) to out-bid the illegal sector, but chose not to because it did not align with their economic incentives. Instead, they mostly aimed at achieving the significantly lower collection estimates that were part of WEEE legislation. Enforcement had, in the absence of data on potential collection, focused on the achievement of these targets (EC9).

It appears likely that, if the legislation had instead created requirements or incentives for the collection schemes to bid sufficiently high prices for waste, this would have stayed with regular operators applying stricter monitoring and enforcement. The WEEE directive now has been revised and on June 11th, 2012, the WEEE-2 directive was published.

One of the oldest legislative frameworks is the Swiss "Ordinance on the return, taking back and disposal of electrical and electronic equipment" (ORDEE) of 1996 (Schweiz. Bundesrat, 2004). Its principles of defining stakeholders' obligations are presented in Figure 70.

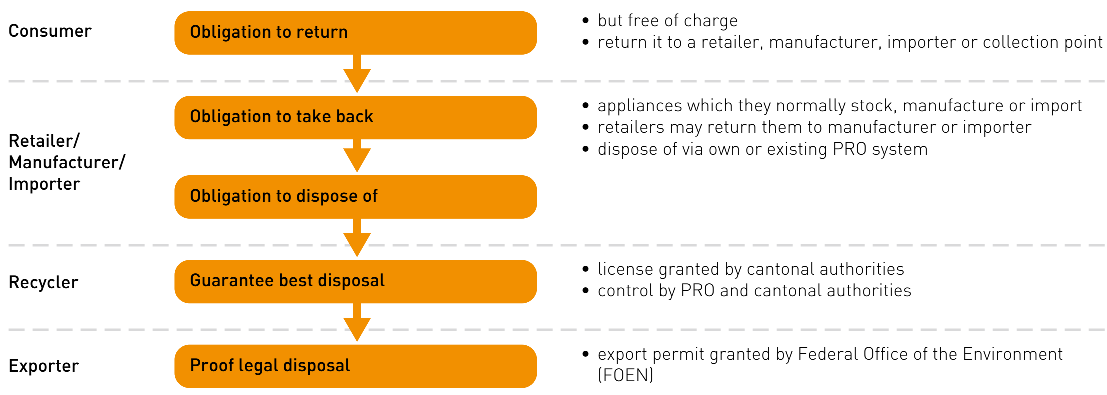


Figure 70: Schematic explanation of the stakeholder's obligations according to Swiss WEEE legislation ORDEE (Widmer et al., 2008).

In the USA, Canada and Australia, implementation of the EPR mechanism by industry is voluntary, but emphasis is put on the fact that the responsibility is shared between the producer, the packaging manufacturer, consumer and the retailer. Current take-back initiatives either have come in late or are not comprehensive enough (Ongondo et al., 2011). Probably the biggest issue is that current take-back systems often only cover a few products and ignore the comprehensive Product-Centric aspects of recycling.

Emerging economies and developing countries generally face very different challenges to OECD countries. Their challenges highlight the main issues related to the implementation of take-back systems, such as defining responsibilities, securing financing, setting up the logistics, ensuring compliance, and restricting monopolies (Sinha-Khetriwa et al. 2009). However, the general goals of e-waste management need not differ from the EPR approaches taken in OECD countries. Experience from the latter and cooperation initiatives in developing and emerging economies countries have shown that a few overarching principles should be followed for the implementation of successful take-back systems (Widmer et al., 2008). These include:

- Shared Responsibility: Manufacturers and importers commit to the recycling of their products and to ensure that the recycling operates safely and smoothly. Retailers participate in collecting WEEE (and if necessary fees) from consumers. The relevant government bodies ensure a workable legal framework. Recyclers recycle or otherwise dispose of discarded equipment in an environmentally sound way, using the best available technique and users return end-of-life equipment to dedicated collection centres.

- Economic Feasibility: The financing of WEEE recycling as well as its collection, transport, and other costs associated with its proper disposal are guaranteed, either through self-financing, or by means of a transparently imposed recycling fee on new equipment, if the system is not fully cost recovering.

- Operational Simplicity: The system is convenient for all stakeholders. Most importantly, consumers can return any used EEE free of charge to retail stores, collection points, and/or manufacturers. The system allows for an easy and low-cost administration.

- Enforced Accountability: Independent external auditors and regular checks ensure that the system is transparent and competitive. Well-defined roles, rules and standards prevent any misunderstandings.

7.5.2 Recycling rates, targets and their physics-based rigour
Legislative requirements for the size of waste streams to be recycled have been used in combination with EPR policies to promote increases in collection and recycling. At best, these will stimulate innovation and partnerships within the recycling system, increasing the possibilities of recycling beyond what stakeholders can do individually. To do this, testing targets have to be set for a date several years in the future, so that partners have time to work out solutions. This is particularly important where products have long use periods, as any design changes to help recycling will take years to affect the EoL product.

The EU's ELV legislation successfully stimulated several partnerships. In order to meet recycling targets, car maker VW formed a partnership with metal-processing specialists Si-Con, and French manufacturer Renault set up a joint venture with waste specialist SITA and the car recycling specialist INDRA Investissement.

Defining the system boundaries for which targets are stipulated is of critical importance. Furthermore, weight-based targets hinder rather than promote recycling of the many critical elements in complex products, usually present in very low concentrations. In addition, priorities have to be set between different metals, such as base metals, special metals, critical-technology metals, etc. This further highlights the dilemma of defining recycling targets for metals that are present in small quantities in products.

However, targets that go beyond what is thermodynamically possible for recycling will fail and lead to excessive energy consumption caused by efforts to meet the recycling target. Policy makers can set appropriate targets by drawing on the expertise and tools available within the recycling industry.

The empirical one-dimensional recycling rates for metals given in UNEP's previous report on Metal Recycling Rates provided useful indications of the overall recycling rates for various metals, based on available data and a linear and sequential Material (& Metal)-Centric perspective, shown in Figure 71.

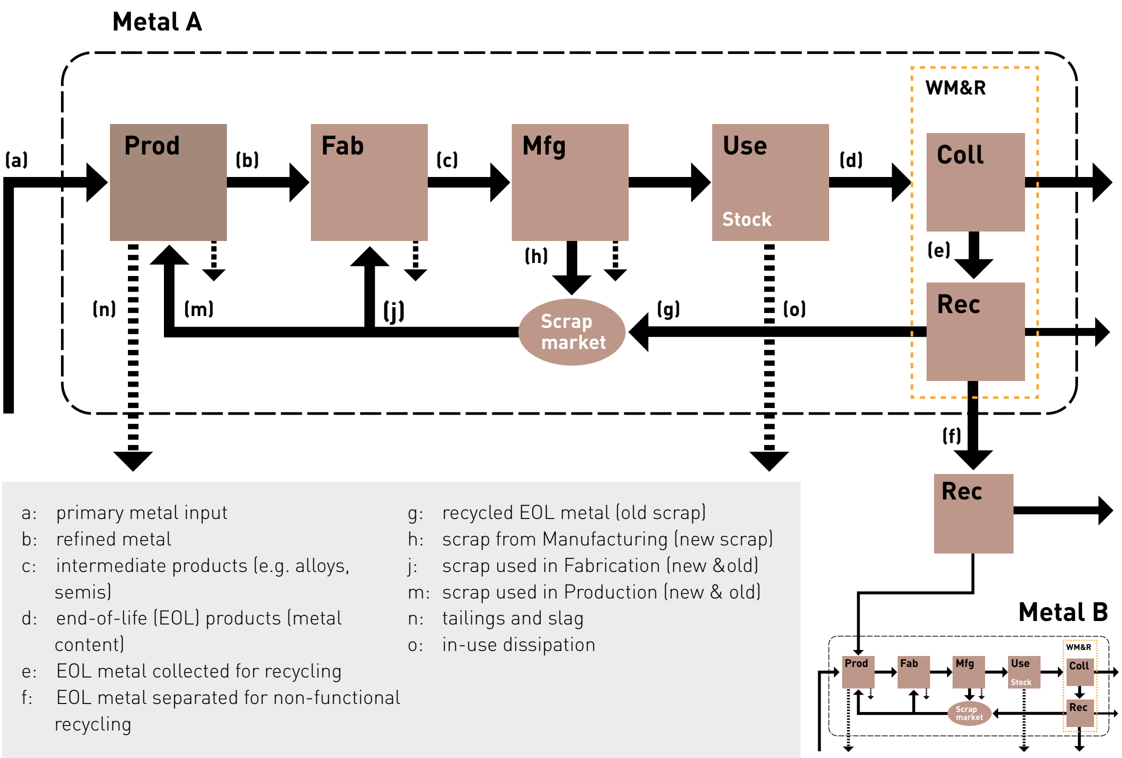


Figure 71:

A Material (&Metal)-Centric view of recycling: Linear and sequential representation of recycling for non-complex metal applications such as in construction, packaging etc. (UNEP, 2011b). This recycling-rate definition is one-dimensional and lacks the required non-linear predictive qualities for successfully driving a recycling system.

To generate appropriate recycling rates for multi-material products with large amounts of different elements in functional proximity, a Product-Centric view is more appropriate (Reuter et al., 2005; Reuter and van Schaik, 2012a&b). The models they developed (e.g. for ELV recycling) provide a clear insight into the critical parameters of a recycling system, and can be used for setting recycling and recovery targets.

A Product-Centric view helps understanding the tradeoffs between achieving very high recycling targets of a particular product (and its contained metals) and natural-resource depletion, in this case the energy needed for running the recycling process. A wider consideration of recycling systems, including such natural resource impact, can help verifying that the recycling/recovery targets imposed by legislation support the preservation of natural resources, in technical terms, that they make thermodynamic sense.

If this complexity of products is understood to its fullest, not only will the recycling of valuable critical and scarce elements improve, but the recycling rates of the commodity metals as well. The right indicators help with this understanding, and focus.

Above all, rather than focusing primarily on recycling rates and their measurement, much better metrics for success are found in ensuring that sufficient collection and good pre-processing efforts exist close to the "Urban Mine". This should provide sufficient high-quality recyclates for optimal and economic BAT recovery of the multitude of metals in complex EoL products. Physics- and economics-based legislation would help much in creating a resource-efficient recycling system and infrastructure that must be measured on performance rather than on achieving recycling-rate quotas.

However, for the strategic elements in complex product mixtures, the thermodynamics and physics of separation often are so complex – due to complex linkages and interactions – that it is almost impossible to define realistic recycling rates. Also, the dynamically changing use of individual elements in specific applications (such as Ga, REE and W needed to provide lighting) may complicate things even further.

In summary, economic targets for the BAT chain as a whole should focus on maximizing resource efficiency, and should be based on understanding the physical properties and destination of all materials.

7.5.3 Information tools and eco-labelling

Consumers can affect recycling rates through their choice of products and disposal behaviour. This works well when they have effective information tools that provide them with facts they can act on, such as labelling, which is one of the simplest tools though making it truly effective requires expertise. By labelling a product as recyclable, or as containing recycled materials, consumers can choose products that promote recycling. The producers must be careful not to create a recycling expectance, as the absence of a recycling infrastructure for capturing EoL goods might be perceived by consumers as "green washing". However, when product manufacturers can source their materials from BAT recycling with its environmental benefits, they may well be rewarded by higher profits from consumers. Eco-Labelling is also useful for separating goods for recycling, for example, advising consumers not to discard WEEE in domestic waste.

Eco-Labelling is most effective when used in connection with other information tools, raising awareness about recycling benefits and opportunities. The example of recycling mobile phones illustrates that, the more convenient such opportunities are, the more likely people are to recycle them.

Many labelling schemes were set up by non-governmental organizations. Policy is not necessarily required for a successful label, but it can be helpful for creating trust in a label. Government can play a useful role in bringing stakeholders together to agree on design and meaning of the label. Government

information on labels can also have positive effects and provide guidance when too many labels could confuse consumers.

7.6 National examples of government policy

7.6.1 Japanese mineral resource policy, recycling and research and development

The Japanese approach demonstrates willingness to secure a metallurgical infrastructure for safeguarding metal availability, notably those used in high-tech applications. Japanese mineral-resource policy defines 'critical' metals for society in a similar way to the US and the EU. In the Japanese context, these are base metals and precious and platinum group metals that are either "geologically rare" or "technically and economically difficult to recover", and/or have a predicted "strong demand in industry today and in the future." Japan stockpiles the following metals:

- Co, W, V, Mo, Ni, Cr and, Mn (steelmaking alloys) since 1983.
- In and Ga since 2009, due to their use in various modern technologies.
- It carefully monitors Pt, REE, Nb, Ta and Sr.

Where an urgent risk exists of mineral-supply shortages, the government uses subsidies for promoting investment in industries and R&D projects. The following are examples of subsidized R&D projects:

- Recovery of critical metals such as indium from small home appliances (mobile phones, digital cameras, portable gaming machines, MP3s, pads, etc.).
- Recovery of cerium and other rare earths from glass polishing processes.
- Recovery of rare earth elements from used motors in EoL goods.
- Recovery of rare metals from EoL batteries (Li-ion), mainly Li and Co.

Japan has started to explore a systems approach for "Rare-Metals" recycling. Though difficult to collect, small home appliances (SHA) are known to contain high concentrations of critical metals. The relevant Japanese ministries jointly carried out a pilot project for SHA collection and technology R&D for metal recovery from SHAs. The project showed that the whole system of collection, dismantling/separation, and material recovery, is financially feasible as a whole, but that the "collection" stage was not financially viable by itself. Considering this, the Japanese government started discussions for implementing a recycling scheme for these SHAs in a working group under the central environmental council.

7.6.2 China

In China, a set of policies supporting the whole system is being established for recyclable resources. This includes a tax preference for the recycling of waste materials to reduce the operating costs of recycling. China has promulgated "The Circular Economy Promotion Law" to promote the resource recycling; see also section 3.1.1.1 of this report.

Policy steps have included the creation of suitable government units and, in recent years, the central government also promoted "City Mineral Pilot Units". China has promulgated "Regulations for the Administration of recycling and Treatment of Waste Electrical and Electronic Equipment" that govern the whole cycle of product design, materials use, collection, dismantling and treatment. The Regulations also set up a recycling fund for subsidizing the processing cost of WEEE, funded by manufacturers and importers, and thus, indirectly, by consumers.

This fund is used for steering WEEE flow to regular enterprises rather than illegal recyclers, thus improving human safety and environmental protection. From June 2009 to June 2010, China built more than one hundred regulated enterprises pre-processing

WEEE. Since then, over 600 million computers, refrigerators, TVs, air conditioners, washing machines and other waste were collected and treated mechanically. However, the informal sector still manually dismantles WEEE in parts of China, such as Guiyu Town, Shantou City and Taizhou City. Often, such waste is illegally imported into China, where these informal processes cause serious health problems and environmental pollution. Local governments find it hard to close this illegal dismantling, particularly as part of this activity is moving to more remote areas.

7.6.3 European Union (EC1 to EC9 and European Commission)

The European Union has several policies that relate to raw materials and recycling. The Waste Framework Directive includes, among others, the Battery Directive, End of Life Vehicle Directive and the WEEE Directive. It is implemented and relates to specific legislation concerning waste handling and treatment. Recently, the European Union developed the Raw Materials Initiative, a long-term strategy based on three pillars: 1) Ensuring a level playing field in access to resources in third countries, 2) Fostering a sustainable supply of raw materials from European sources, and 3) Boosting resource efficiency and promoting recycling. Fourteen critical (groups of) materials are identified: antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, platinum group metals, rare earths, tantalum and tungsten. The Directive also includes actions in the areas of diplomacy, trade and development, and R&D, among others, via the European Innovation Partnership on Raw Materials, Resource Efficiency and Recycling. The EU Strategic Energy Technologies plan is also relevant, as it includes materials for energy technologies. In addition, many European countries also have their own policies on resources and recycling.

7.7 Policy recommendations

Three major factors determine the recycling results: 1) The processes used in recycling operations and the two other major influences on the mix of metals and other materials going into processing; 2) The way waste streams are mixed during collection; and 3) The physical properties and consequences of design and material linkages of the EoL products in such waste streams. These three factors interrelate in ways that make it impossible to optimize one without considering the others. To get the best results out of recycling, the participants in the recycling system need to know what is happening in the other parts of the system. This suggests that, for optimizing recycling, the following conditions must be fulfilled:

- **Waste streams for recycling must go to operations that use certified Best Available Techniques (BAT) throughout the complete recycling chain**. These techniques differ between regions, and need not be high technology, but include well-regulated hand sorting. When they go elsewhere, value will be lost.

- **Policy goals for the recycling system must dovetail with the economic drivers**. With so many operators in the collection and recycling industry, regulation enforcement is unlikely to be sufficient by itself for determining the destination of metal-containing waste-streams. Policy is essential for creating the economic conditions for sending waste to BAT operations, rather than into illegal or 'grey' recycling.

- **The metals recycling industry must have the human talent and metallurgical knowledge needed for linking up different BAT processes, for recovering large proportions of valuable metals**. Producers benefit from producing a range of valuable and critical metals, rather than focusing on one or two.

- **Rapid innovation in process technologies motivates and supports new solutions for sorting and separating metals in mixed waste streams**. This must be promoted by Policy.

- **Incentives must exist for all participants in recycling to cooperate with the other participants for improving the system's recycling performance**. Practical ways must be promoted for transmitting the data between the different stakeholders. For example, a Producer Responsibility law will motivate a manufacturer to innovate in recycling-process technology so as to meet recycling targets. Such incentives can be purely legislative or purely economic, but work best as a combination of policy and profit.

- **Policy targets set for recycling must be set in ways that account for the loss of metals due to mixing, must not exceed physical, technological and thermodynamical limits, and should not prioritize one or two metals at the inadvertent expense of other metals found in the input stream**.

- **Computer-based-modelling of the recycling performance of products helps guiding product design that facilitates more recycling**. It should be based on the realities of how products and their constituents break up and separate in BAT recycling processes.

7.7.1 Creating the right conditions for optimal recycling

Several actions can help creating the right conditions, with policy playing a key role. They depend on participants and policy makers taking a wider, systemic view of recycling, one that looks at the industrial and economic factors driving recycling and can cope with complexity. Simplified approaches to recycling will not adequately support the drive to resource efficiency. Policy that only specifies desired recycling outputs will not be sufficient for attaining that result. Linear, one-dimensional, approaches cannot deal with complex interactions between metals, mixing of waste streams, and the economics behind processes.

A Product-Centric approach to recycling is based on a good understanding of the physics of materials in products. This allows simultaneous consideration of the interactions of such materials, how and when they dynamically vary, and the resulting economic value of recycled materials. This leads to the points enumerated in the following sections.

7.7.2 Industrial infrastructure and technology are essential

- **The use of certified BAT for the complete recycling chain is a key factor for positive results**. The physics and economics determining what is achievable with combinations of BAT, create the limits of what policy can aim to achieve. Quantitative computer models, based on the physics and economics of BAT recycling, can serve for resolving complexity and guiding policy, superseding more simplistic material-flow-analysis approaches.

- **The infrastructure and expertise for processing waste into recycled metal is often the same as that for primary metal production**. Therefore, the health of primary production in a mining region is of vital importance for recycling goals, fostering the required metallurgical systems knowledge. This balance will also help mitigating any cyclical disturbances affecting the primary-metals industry.

- **The strength of the basic industries – the fabric of our society – is the foundation for maximizing resource efficiency as it contains the expertise that can provide solutions**. To attract expertise and investment, the significance of these industries for sustainability must be explained with a suitably inspiring narrative, supporting the sometimes dry and difficult physics underpinning recycling. Public policies, whose cumulative effect makes any part of the basic industries uneconomic, will block the

achievement of recycling and resource efficiency goals.

- **Technology and know-how should be adaptive for dealing with the changing complexity of society**. For instance, current pre-processing technology is often inappropriate for increasingly miniaturized technology. The recycling system constantly needs new dismantling, cutting, sorting, and whole-product smelting technologies. As the change in products is much faster than the change in process equipment, processing must use much more adaptable technology (which includes highly adaptive manual sorting). The modularity of recycling systems and product design can help here, as some pre-processing equipment could be moved to where scrap is being generated.

7.7.3 Economics of recycling

- **As recycling is an industrial activity, economics are the main determinant for results**. **Policy plays a key role in shaping the economic incentives**. Experience shows that where the economic incentives for collection by private (or public) operators do not align with policy goals, significant resource volumes can be lost to illegal or informal recycling, such as 'cherry picking'. Generally, this causes environmental problems – damage to health, water or climate – as regulatory standards are ignored.

- **A certified BAT recycling processing infrastructure, supported by metallurgical expertise, will operate by itself for maximizing the recovery of all valuable elements it receives**, optimizing tradeoffs between quality and volume of metals in the output. Though the economic incentives usually already exist to do this, BAT is frequently not in place, thus harming resource efficiency.

- **Policy can improve results if it focuses on promoting the adoption of BAT along the material and metal chain**. It can provide the framework and innovative business models that lead to adopting BAT in recycling systems, which can include help for offsetting losses from parts of the treatment process for EoL products.

- **Increasing the willingness of product manufacturers and their customers to use BAT recycled materials boosts the recycling market**. It has the added advantage of consuming the least resources in their production.

- **For various minor elements, cross-boundary transport for processing at a "central" plant of sufficient size may be the answer** when, at home, the economies of scale for recycling are not fulfilled.

7.7.4 Collection as part of the recycling system

- **Optimizing recycling requires secure and large volumes of waste, collected (or sorted) in ways that facilitate its metallurgical processing**. Experience points to two factors as essential for better and sorted waste collection: 1) A capable collection infrastructure, and 2) Economic incentives for delivering waste to BAT operators, rather than to informal or illegal operators.

- **Where economic incentives exist, private operators often form collection infrastructures**. In some cases, public-policy intervention may be needed to assist the creation or capacity building of such infrastructure, for example when setting up recycling systems for cell phones.

- **When waste ends up in areas where no or poor quality recycling takes place, the resources are often lost**. It is thus very important to enlarge the scope of collection and recycling infrastructure to areas where products have their final use, not only those of their first use. Responsibility for collection can then be shared between all stakeholders in the system in ways that best finance and increase the capabilities of collection systems in these areas.

7.7.5 Design for resource efficiency

- For optimal recycling, the **industrial wastes and End-of-Life product streams that enter processing should ideally be economically compatible with the metal-production system**. Their material and physical properties should allow the available recycling infrastructure to separate out different valuable metals into high-purity recycled metals.

- **Product design strongly affects the physical properties of the waste stream**, as do collection methods. Optimal recycling can therefore only succeed through increased physics-based Design for Recycling (DfR) or Design for Sustainability (DfS), which is better covered by the term Design for Resource Efficiency that is more economics based with links to Product-Centric recycling. Here, product design is based on, or at least cognisant of, the limitations of the recycling BAT (as concisely reflected by the Metal Wheel). To achieve optimal designs for recycling and recycling systems demands good understanding of the limits imposed by physics, chemistry, thermodynamics and kinetics, as well as the technological, economic and social barriers and inefficiencies encountered. However, functionality demands mean that this may not be possible, dictating that certain metals and materials must be combined, rendering Design for Recycling inefficient and pushing Design for Resource Efficiency into the place of systemic driving force.

- **Computer models facilitate Design for Resource Efficiency**. Like any engineering-process design model, they need a detailed basis in thermodynamics and the specific recycling techniques likely to be used. They should show sufficient detail and they are best based on predictions of how recycling techniques will separate metals in products, for in turn predicting the quality and economic value of the output.

- **Data structures for the whole system must contain sufficient information to allow calibration of detailed simulation and Design for Resource Efficiency models**. Only then is it possible to estimate grades of materials across the whole recycling chain.

- Currently possible design changes can do much to improve recycling as **many "critical" elements are often intertwined in products to ensure complex product functionality**. Optimizing recycling thus requires radical innovation in IT systems, maintaining functionality while maximizing recyclability.

- **If functionality demands of the product do not permit optimal design for recycling, such constraints should be recognized**. In that case, policy should not set recycling rates that cannot be achieved.

- **Design for Recycling comes out of a design perspective that looks at the impact of products over their life cycle**, (LCM), and policy has a key role in assisting in the adoption of LCM by product manufacturers.

7.7.6 Because of complexity no single recycling-rate values for metals

- **Due to product complexity and the inherent randomness of metals separation in recycling processes, no single optimal recycling rate exists for metals in End-of-Life products**. The same product, put through BAT, can produce different amounts of recycled metal (with differing quality) when driven by economics. Such results often show a statistical spread that is influenced by a host of different effects.

- Picking an optimal recycling rate is, at best, specifying an average recycling rate that might be complemented by a **standard deviation** defining the distribution of expected recycling rates. However, the shape of the distribution curve may be unknown due to this complexity. The distribution can even be multi-modal, questioning whether a standard deviation describes the distributed recycling rates that will, in practice, result.

- **The use of material-based recycling-performance output metrics** (mass, or a percentage of a single metal within a waste stream) **can be counterproductive, as it may ignore the complexity of recycling and its inherent tradeoffs between the different recycled-metal outputs from mixed waste streams**. If used, they may cause the wastage of valuable metals; for example, a system focused on increasing recycled iron output is likely to lose the valuable and scarce metals shown in red in the Metal Wheel. This is particularly the case for more complex waste streams that have a large diversity of rapidly changing compositions, as either product mix or product composition changes.

- **We must reconsider the current practice of using recycling rates of single metals, or of a percentage of product mass, as the Key Performance Indicator (KPI) of the recycling system**. Approaches based on an understanding of the physics of recycling already exist, and can help refine and build on the Material (& Metal)-Centric indicators for rendering them more Product-Centric (with an economic basis). Better results are achieved where this practice is complemented by indicators that better illustrate quality and range of metals resulting from recycling.

- Performance metrics can be based on the use of BAT and the economic value of BAT outputs. **Economic output value is the indicator that best reflects whether the physical realities of the recycling process have been optimized**. Although not a perfect match for social goals, the summed value of recycled metal outputs from a process allows for whether the valuable metals were successfully recycled and for the quality (i. e. purity) of the metals. It complements a Product-Centric approach.

- **The economic value produced by BAT processes should be considered as a performance indicator**. This would be the opposite of a mandated performance target to be achieved by industry. It would on the contrary be an indication whether the policy and industry have successfully created the conditions and incentive structures that facilitate high performance. This would require policy actions across the system to overcome the bottlenecks that currently hold back optimized recycling.

7.7.7 Education and information – high quality people and training

- Research and educational infrastructure is critically important. It must be nurtured to preserve know-how, especially of the processing of the key metals, and ultimately drives innovation for maximizing resource efficiency. A large body of knowledge also exists in tacit form, as the accumulated experience of knowledgeable people. This cannot be traded like a commodity, and is lost when industry sectors become too cyclical and unwisely shed knowledge for profit.

- There is a need for extending the systems based approach to recycling knowledge, described in this document, and for capacity building in the use of BAT combinations for optimizing recycling output.

- Market operations would be significantly helped when recycling operators can estimate future needs for recycling infrastructure, by quantifying the "urban orebody", and defining its location and future waste flows. Policy can stimulate or assist work towards estimating the metals in marketed products. The detailed composition of these products is also needed for use in physics-based process simulation tools that help choosing the best processing route for waste.

7.7.8 Policy processes should match the challenge

- We indicate how the outcome of metals recycling is the result of a system of interactions, with upstream (e. g. design and collection) choices affecting the value of output, and the value of output influencing upstream behaviour. None of the recycling stages can be optimized in isolation. Optimization of the system requires participants to take a wider view of the system, and be motivated and able to communicate and work with other participants in other parts of the system.

- Policy needs to create the conditions that facilitate and motivate this cooperation and communication, for instance between the product manufacturer and the recycling operator. Policy can remove the bottlenecks in a successful recycling system, such as a lack of capability in collection or in recycling.

- This may be a change for some policy regimes. It certainly has implications for how policy is set. Policy makers will have to take into account the economics of the system, the motivations of designers, innovators and collectors, forging a set of policies that deliver the above mentioned conditions.

- This will only be possible where policy sets itself the goal to optimize the system as a whole rather than parts of it, and is formed through cooperation between policy makers with expertise in industrial, environmental, innovation and local-government policy. Within policy circles, working structures would need to be created that bring together such policy makers with common goals.

8. Appendix A: Details on Recovery of Metals from Recyclates

This appendix provides an overview of the technologies used in metallurgical recovery of metals from recyclates and residues, ranging from steel to PWBs as well as TVs and other WEEE.

8.1 Separation methods

8.1.1 Manual sorting

People are probably the best sorters due to the learning capability of the brain fed by all human senses and experience. This is true where there are visual differences between materials and whilst their concentration lasts. However, there are limits, i. e. an eye cannot read an RFID tag or bar code, but a machine can. Product design can prohibit manual sorting, by designing in components that cannot be separated by hand.

8.1.2 Automatic sensor-based sorting

Automatic sorting with different detection systems can substitute for manual sorting. For example, a camera, used as a detector in combination with a computer (Figure 72), scans a product on a belt conveyor before processing each frame by the computer. After processing and identification, for instance based on colour, the computer can activate air valves that shoot identified particles into collection bins.

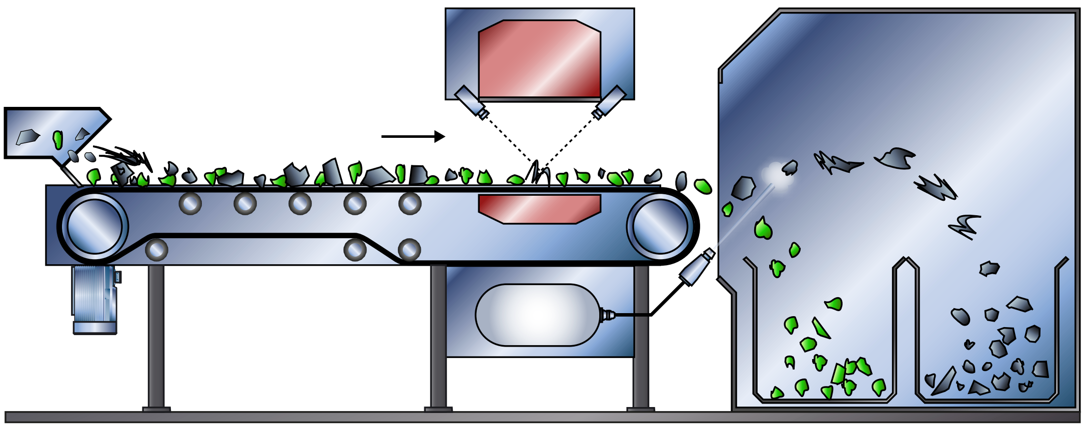
Alternatively, a detector can consist of a transmitting coil, a U-shaped copper rod with pairs of receiving coils in the middle of a transmitter, or an XRT/XRF-device (Owada et al., 2011; Titech, 2012). This type of machine can detect over 99 % of all metal particles larger than 4 mm in an input stream and, depending on the settings, 95 % to 98 % of the metal will be removed. An electrical signal produced by receiver coils can also be processed in different ways to determine metals from non-metallic materials. The difference between stainless steel and non-ferrous metals can also be determined.

8.1.3 Eddy Current separators

Another form of sorting uses a magnetic field for separating materials that move off a conveyor into a magnetic field. In these 'Eddy Current' separators (Figure 73), particles P1 and P2 have different trajectories because of different rates of acceleration in the magnetic field. This variation is caused by the difference in conductivity of the metals, hence creating stronger magnetic fields, or, more precisely, conductivity divided by density separates conductive lighter alloys (Al) from heavier alloys (Cu).

Figure 72:

Sensor based automatic sorting for metal particles from a mixture of glass, polymer, stone, etc. (from HSC Sim 1974 – 2013).



For example, at low frequencies of a changing magnetic field, the acceleration of an aluminium particle will be twice as much as that of a copper particle with the same dimensions. Poorly conducting materials, such as lead and stainless steel, will respond with a low acceleration to a changing magnetic field, whereas non-conductors, such as glass and plastics, will be accelerated at all by the magnetic field. Both permanent magnets or an electromagnet can generate the magnetic field.

8.1.4 Rising-current and hydrocyclone methods

In the rising-current method, a continuous rising water column is projected through a pipe that receives the feed material. Material that sinks faster than the water column is rising falls to the bottom of the separator. The material carried up by the column of water can be separated from the water by a screen or a sieve (Figure 74). A complication is that the water must be constantly cleaned from dissolved compounds.

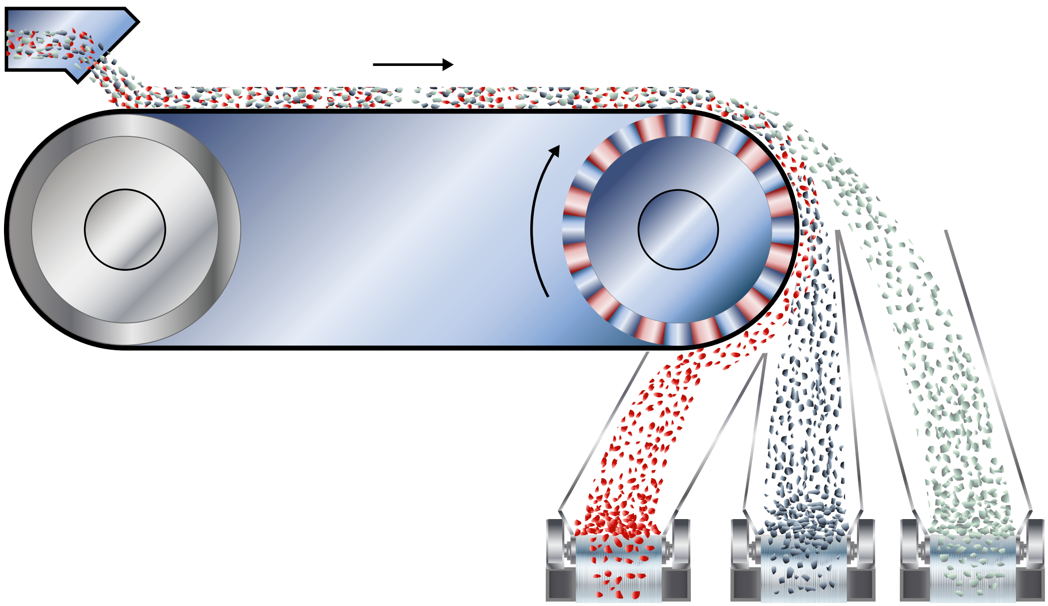


Figure 73:

Eddy Current physics: light grey highly conductive and light, white non-conductive, and black slightly magnetic. Magnetic field strength, rotation speed, and positioning of the two splitters, among others, determine recyclate purity (from HSC Sim 1974 – 2013).

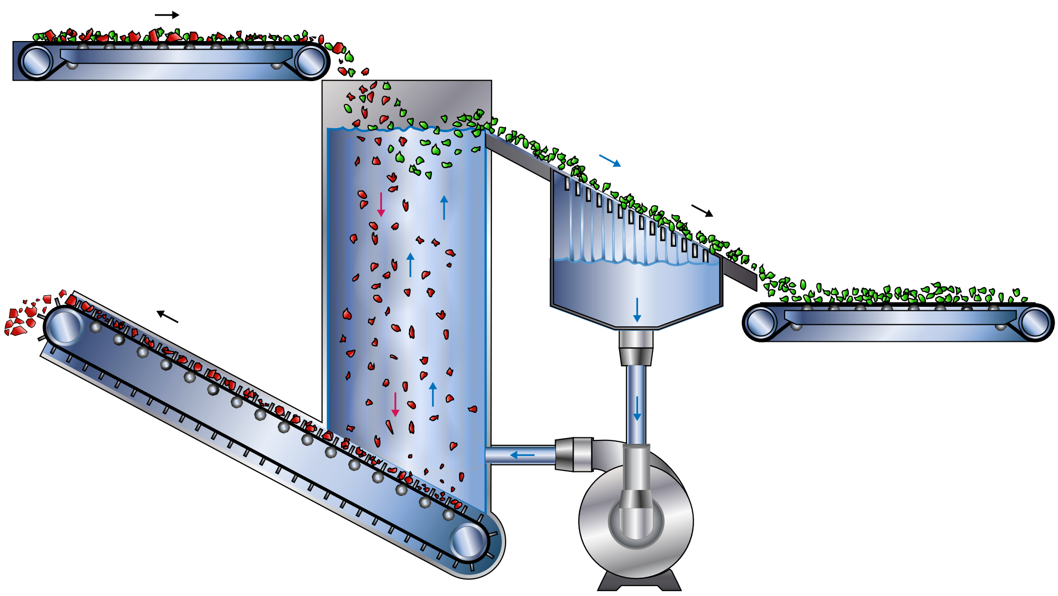


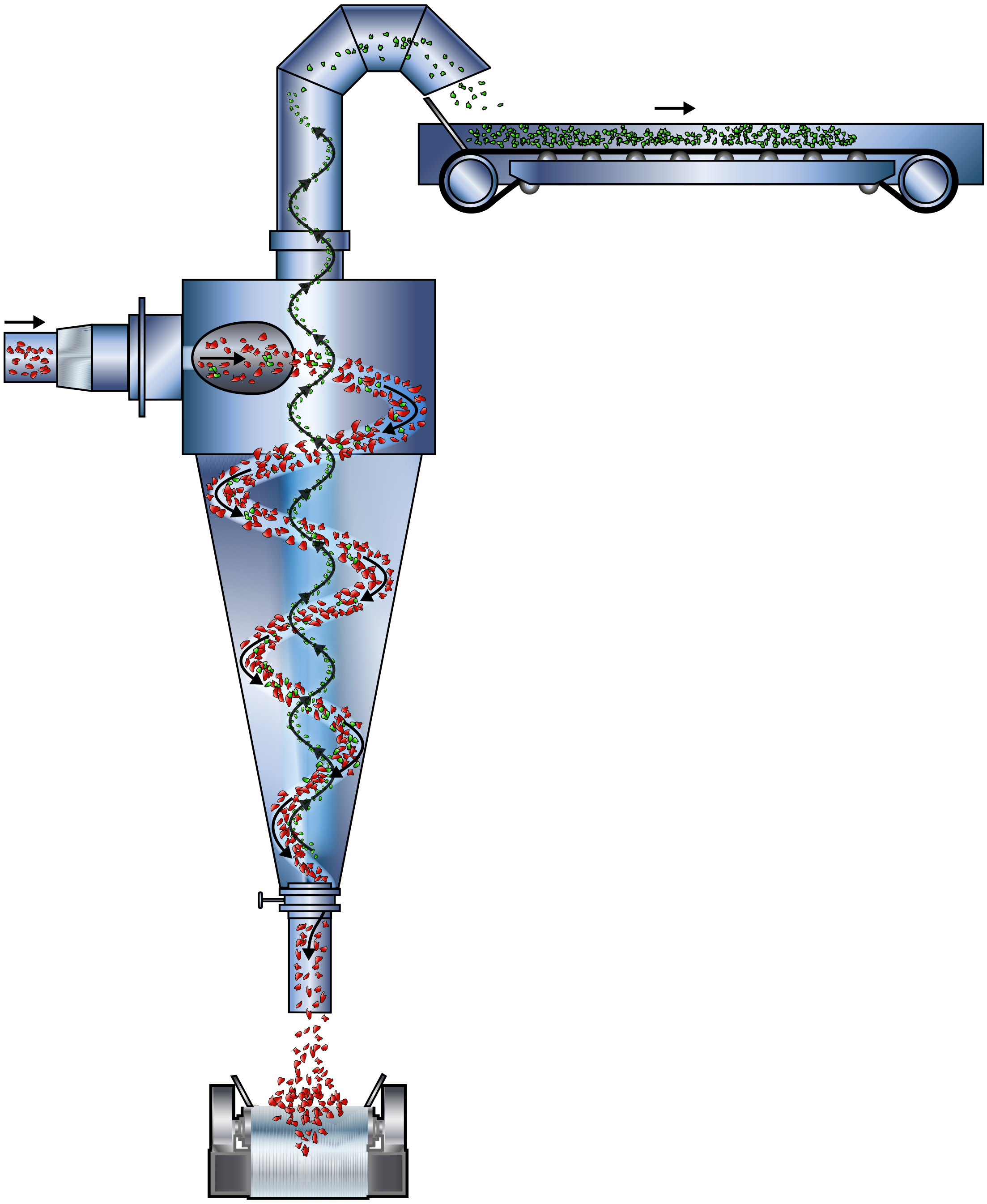
Figure 74:

Rising-current separator using a rising water flow in a column to recover a light floating fraction from a feed also containing heavy material that drops to the bottom of the water column.

In hydrocyclone-separation, water or a heavy media suspension is made to rotate. As a result, the larger and heavier particles move to the wall of the cyclone and then sink to the bottom (Figure 75). Lighter, or smaller, material will remain suspended and leaves the cyclone via the overflow or a vortex at the top of the cyclone. This method is widely used for cleaning coal and has also been adapted for separating metals.

Figure 75:

A hydrocyclone separating feed into light and a heavy fractions.



8.1.5 Sink-float methods

Sink-float methods separate materials based on whether or not they float in liquid. For example, wood, insulation (paper, PUR foam, board, etc.) will float on water, and can be removed from the surface. The method is used in plastics separation, making use of the fact that PVC has a specific weight of > 1 g/cm^3 (heavier than water) whilst other plastic types, such as PE, PUR, PP and PS, usually are < 1 g/cm^3 (depending on whether or not they are in foam form) (Figure 76).

8.1.6 Jigging

Jigging is one of the oldest methods of sink-float separation. In a piece of equipment called a jig, input material is formed into a thick layer (or 'bed'). This is fluidized by pulsating a water current through it. On pulsation the bed of input material is lifted as a mass; then, as the velocity of the water-stream decreases, the particles fall with different speeds to the bottom, depending on their density. When this process is repeated, the different materials will stratify in relation to their density, and can be recovered accordingly.

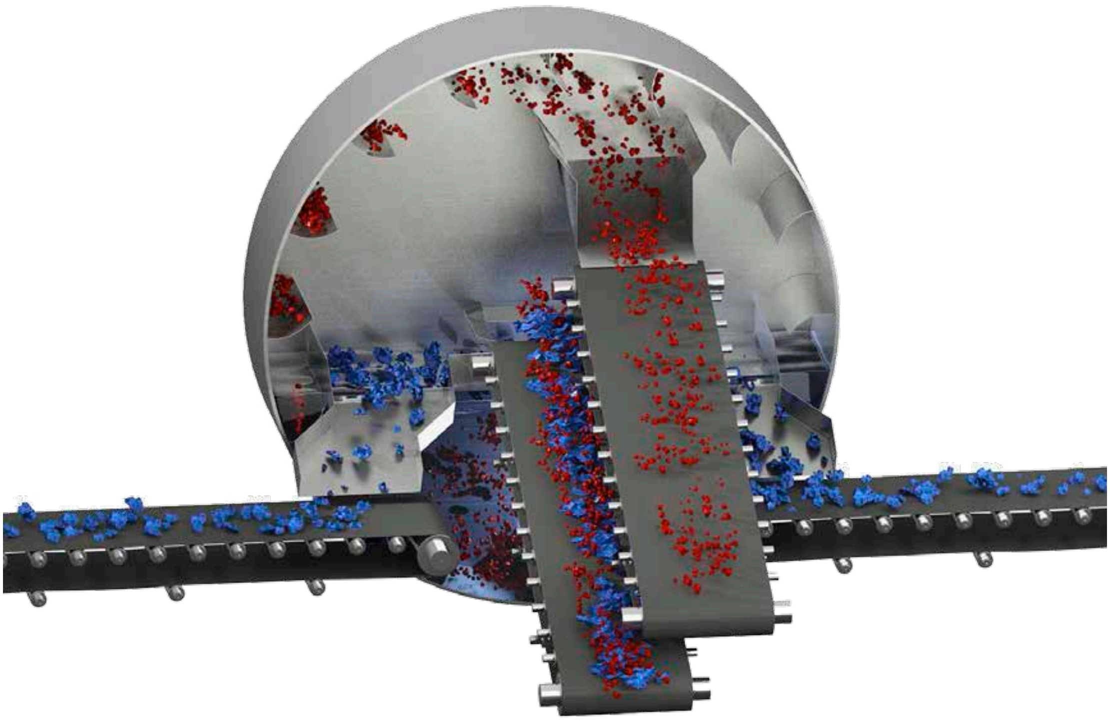


Figure 76: The heavy-medium separator separates feed into a heavy fraction that sinks to the bottom of a rotating drum that lifts it to the top where it discharges onto a conveyor belt. The light fraction floats on the separating medium (water, FeSi slurry, etc.) and is collected and discharged via the floats conveyor belt. Cleaning of the float medium creates a sludge that has to be processed.

Sink-float methods can use water or another liquid, or a suspension of water and a solid material (e. g. FeSi) to vary the density of the liquid and adapting to which materials will float and sink. This variation is used particularly for the separation of shredded aluminium and magnesium from a non-ferrous mix. Sufficient ferro-silicon (FeSi) or magnetite (Fe_3O_4) is added to water for making a constantly agitated suspension with a specific density of anywhere between 1.8 and 3.3 g/cm^3. This enables, for instance, aluminium with a density of 2.7 g/cm^3 to sink and magnesium with a density of 1.74 g/cm^3 to float.

This method is very similar to the rising-current separation process, but here the water jet is projected through the screen in pulses. Jigging is used for separating shredded metals and particularly plastics from metals. The magnitude and direction of the water-jet force can be varied to change the separation result. A jig is generally used for concentrating relatively coarse materials down to 3 mm. When the feed is fairly similar in size, it is not difficult to achieve a good separation at low cost.

8.1.7 Shaking tables

Shaking tables use a controlled vibration and the property of particle density to separate materials.

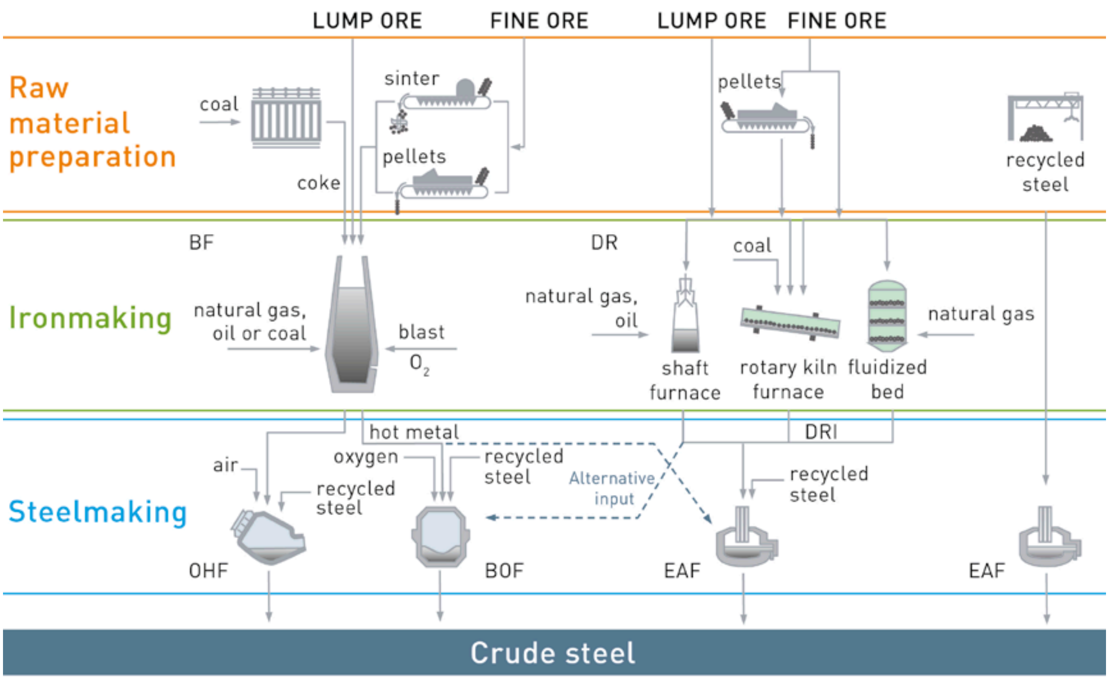
8.2 Steel (Fe-C-X), high-Mn steel (austenitic Fe-Mn-X) and stainless steel (Fe-Cr-Ni-C-X) recycling (X are minor alloying elements for different steel types)

Figure 77 shows the different routes for steel production and recycling. When smelting steel scrap in an Electric Arc Furnace, the energy intensity is reduced significantly. Kepplinger (2009) gave an overview of the present status of bath smelting, such as COREX and other similar technologies that require no coke, while further alternatives that lower the carbon footprint are discussed by Orth et al. (2007).

Figure 78 makes clear that recycling and primary production go hand-in-hand. In some cases, such as Tornio, the BAT ferro-chrome smelter is next to the stainless steel smelter and mill, producing high-grade products. The same situation is found next to the stainless steel smelter in Middelburg (RSA), where a 40 MW plasma ferro-chrome furnace produces liquid-charge chrome for use in the stainless-steel plant, while the AOD converter also accepts stainless steel scrap. See also Nickel (2012) and ICDA (2012).

Figure 77:

Different process routes for steelmaking. A comparison of the energy requirements (GJ/t) of the different routes are given on p. 80 (World Steel, 2013).



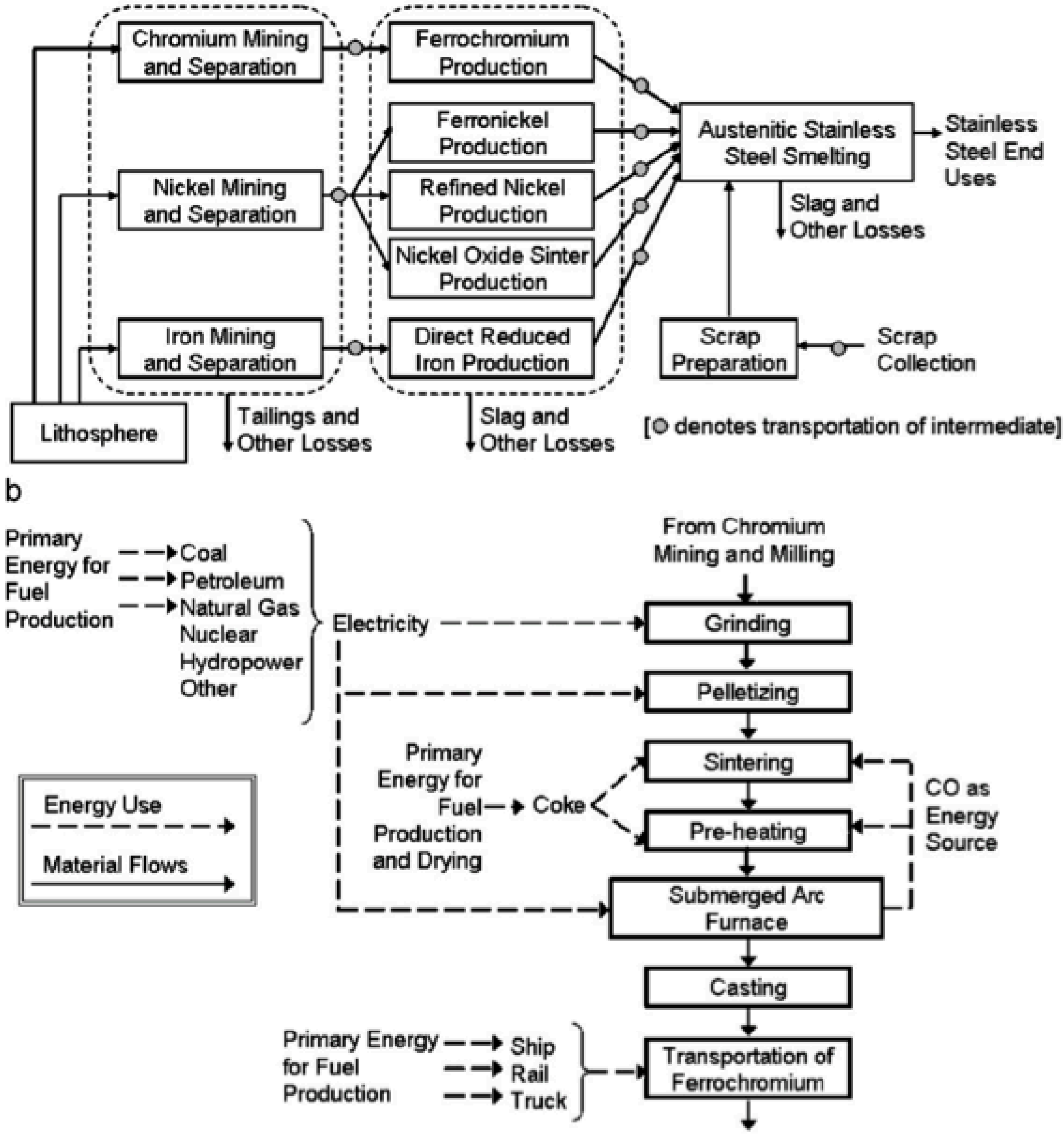


Figure 78:

The technology of stainless-steel production (Johnson et al., 2008).

8.3 Copper-scrap recycling

An example that clarifies the concept of the Metal-Wheel is copper, the infrastructure of which is crucial for recycling many of the elements associated with copper, and which also appear in WEEE. Figure 42 and Figure 79 show that copper recycling takes place in existing primary smelters, while Figure 80 shows some dedicated smelting facilities for recycling copper. The latter are, however, always linked or associated with further refining capability that is based on the core competence of copper smelting and refining knowledge. See Copper (2012) for more information.

Figure 79:

Primary refined production with primary and secondary/scrap feed shown (left) and and World refinery and smelting capacity (right) (Outotec – compiled/ estimated from e. g. Brook Hunt, International Copper Study Group etc.).

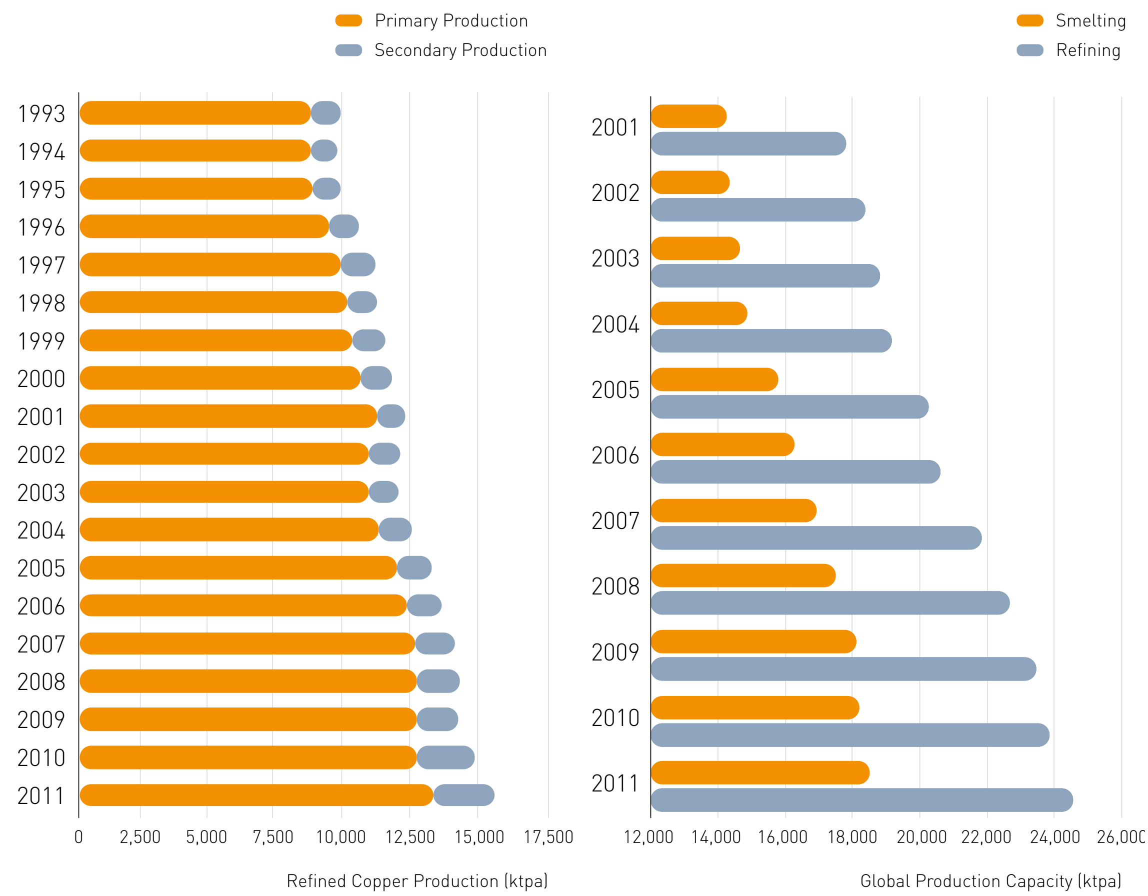
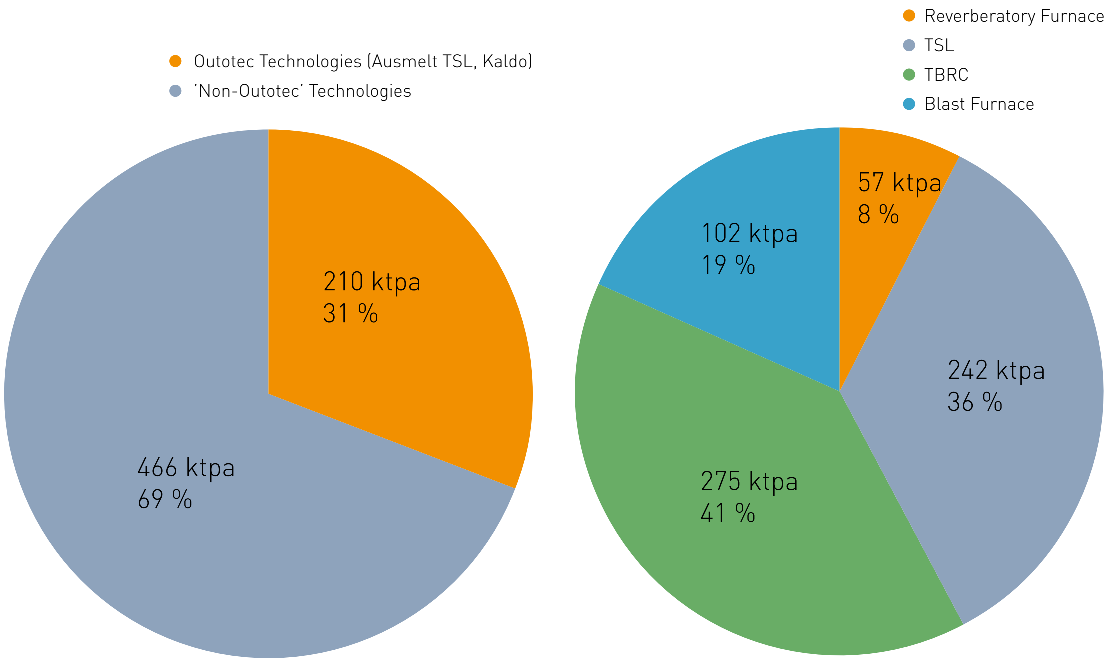


Figure 80:

Dedicated copper-smelting production (Outotec).



8.4 Zinc-containing residues

When zinc metal is produced from primary sources, residues are created that still contain zinc and other valuable metals. Process residues that cannot be treated economically are often dumped or stockpiled, but, as shown in section 2.2 there is a significant monetary value locked up in these intermediate products. Table 23 summarizes the main components of a range of residues. To achieve a maximum recovery of these valuable metals and to achieve a zero discharge of hazardous waste, some of these residues can be regarded as recycled sources of zinc, for example the neutral leach residue and the goethite precipitate.

It is obvious from Table 24 that all the metals and compounds in the zinc concentrate (as also shown on the Metal-Wheel) are recovered in the plant shown in Figure 21. Valuable elements, such as Ag, Co, In, Ge, Sb, etc., find their way among others into intermediate products such as jarosite and goethite. With the technology shown in Figure 21, these can be recovered. Such valuable contents are an incentive to treat old stockpiles and ponds, especially as environmental licenses often are not extended.

Table 23: Typical analyses of zinc residues (International Zinc Association, 2001 – 2002).

Material	Neutral leach residue	Jarosite	Goethite	ISF slag	Vertical retort residue
Zn %	16.9	5	10	6	3.6
Pb %	9.9	5.2	2	0.5	4.9
Fe %	28.9	25	40	35.4	11.2
S %	12.5	13	4	0.3	2.2
SiO_2 %	6.1	3	2.5	17.8	18.3
Cu %	1.1	0.2	1.5	0.1	0.8
Cd ppm	8100	200	500	–	–
As ppm	1800	600	2000	1000	6000
Ag ppm	1800	80	80	5	100
Sb ppm	1700	100	10	10	500
C %	0	0	0	0	32.2

Table 24:

Average composition of zinc concentrates obtained in flotation also showing the mineralogical and thermodynamic basis for the Metal-Wheel (see Zn-pie) (Grant, 1993).

Element	Grade [%]
Zn	53.0
S	32.2
Fe	7.3
Pb	1.6
Ti	1.2
Si	0.8
Cu	0.6
Ca	0.4
Mn	0.4
Cd	0.2
Mg	0.2
As	0.1
Sb	0.04
Ag	0.02
Co	0.02
In	0.02
Hg	0.01
Ge	0.005

Figure 81 summarizes the use of TSL (top submerged lance) furnaces in processing (Alfantazi and Moskalyk, 2003; Piret, 2006). From these sources the following can be estimated for jarosite: 3290 ktpa untreated (100 ktpa contained Zn contains ca. 0.01 % Ag and a similar amount of In), and goethite: 310 ktpa untreated (20 ktpa contained Zn contains ca. 0.02 %Ag and a similar amount of In), or about 1 billion dollars per year of metal value from a rough calculation based on metal prices given elsewhere in this document. However, not everything is recovered, as this is thermodynamically and thus economically impossible.

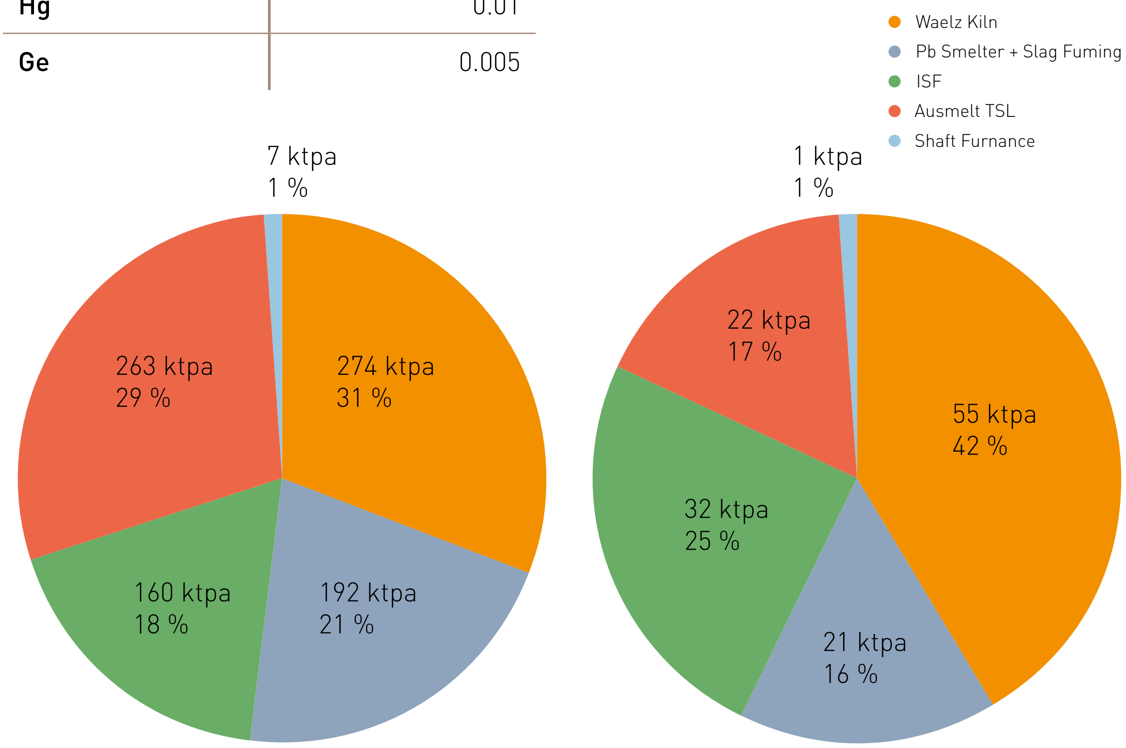


Figure 81:

The share of various technologies for processing zinc-containing residues (Outotec).

Note: The data assume treatment of all residues generated at operations with leach residue.

Of special interest here is the recovery and recycling of indium in the residues as shown in the flowsheet of Figure 21. The economic value of indium (ca. $ 500/kg av 2012 peaking above $ 800/kg mid 2011) renders the recovering indium from such residues a lucrative affair.

8.5 EAF dust and other Pb, Zn, Cu containing residues

When steel scrap is processed in an Electric Arc Furnace, about 15 – 20 kg of dust is formed per tonne of steel, which for the 2010 steel production translates to 5.2 to 7 million tpa EAF dust being produced. Table 25 and Table 26 summarize the composition of EAF dust and other zinc and lead containing residues. Due to economic reasons, relatively low landfill costs of Waelz-kiln slags, and relatively low zinc and lead metal prices, the Waelz kiln (Figure 82) is still the preferred route for processing EAF dust into a Waelz-oxide and other products as shown in Table 26. The produced Waelz-oxide is processed in a zinc plant (e. g. Figure 21) to LME grade zinc. This underlines the fact that metal recycling is optimal if a primary metallurgical infrastructure is available.

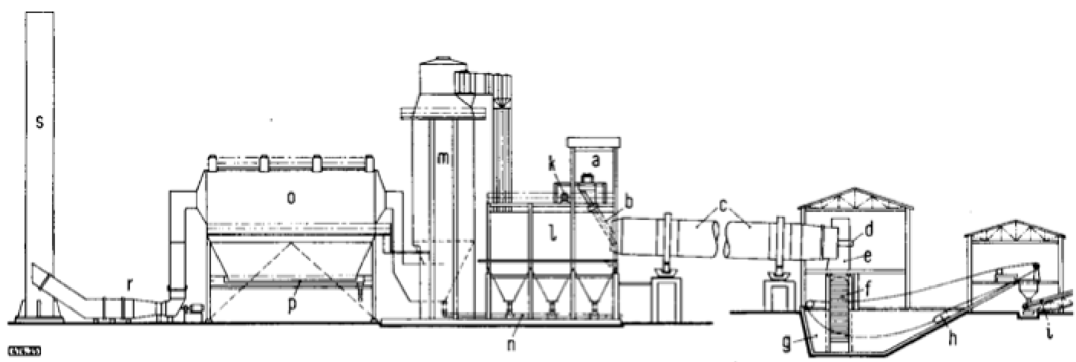
Table 25:

Typical Zn and Pb containing recycled raw materials (Schneider et al., 2000).

	Filter cake Cupola furnace	Dust from copper and brass industry	Dust Cupola furnace	EAF dust	Lead dust	Zinc-lead oxide	Neutral leach residue
Zn	31	43	31	23	2	44	18
Pb	3	20	0.1	1.3	68	15	7
Cu	0.2	3	–	0.1	–	0.4	1.6
C	11	0.6	5	2	2	0.6	0.2
FeO	10	0.6	23	35	5	4	33
SiO_2	15	1	1.3	1	–	1	3
Cl	0.4	5	0.5	0.6	0.2	4	–
H_2O	45	0.3	0.4	10.6	10.4	1.8	30

Figure 82:

Waelz kiln for the processing of EAF dust (Ullmanns, 2005).

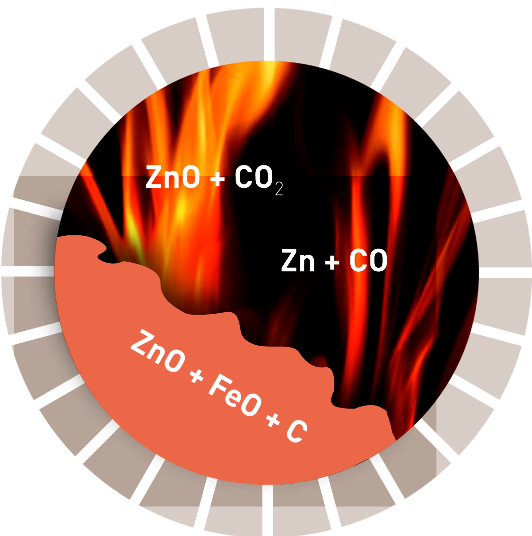


(a/b) Zn containing feed
(c) Waelz rotary kiln (picture)
(d) Burner
(e to i) Slag processing
(k to n) Oxide processing
(o) Electrofilter
(p) Waelz-oxide transport
(r to s) Blower/Stack

Figure 83 shows the main reactions that take place in the slowly rotating Waelz kiln, which can be over 100m long. The reduced Zn, due to its high vapour pressure, is volatilized as Zn-gas and then burned, forming ZnO powder that is collected in a filter as shown in Figure 82. The burning zinc liberates heat that is a major part of the heat balance of the kiln. Similarly, other metals such as Pb, Cd and Ag (if present in other residues also fed into the furnace) are volatilized as well and collected in the flue dust.

Figure 83:

The main reactions in a Waelz kiln (International Zinc Association, 2001–2002).



Reactions in the gas phase

$Zn + ½ O_2 \rightarrow ZnO$
$CO + ½ O_2 \rightarrow CO_2$
$ZnO + CO + O_2 \rightarrow ZnO + CO_2$

Escaping CO gas and Zn vapour

Reactions in the charge (Reducing)

$ZnO + CO \rightarrow Zn + CO_2$ $FeO + C \rightarrow Fe + CO$
$CO_2 + C \rightarrow 2CO$ $CO_2 + C \rightarrow 2CO$
$ZnO + CO \rightarrow Zn + CO_2$ $FeO + CO \rightarrow Fe + CO_2$

Table 26:

Typical analyses of the raw materials and products of a Waelz kiln (Meurer, 2010).

	EAF dust	Slag	Waelz oxide	Leached Waelz oxide
Zn	18–35	0.2–2.0	55–58	60–68
Pb	2–7	0.5–2	7–10	9–11
Cd	0.03–0.1	<0.01	0.1–0.2	0.1–0.3
F	0.2–0.5	0.1–0.2	0.4–0.7	0.08–0.15
C	1–5	3–8	0.5–1	1–1.5
FeO	20–38	30–50	3–5	4–7
$Fe_{(metallic)}$/Fe		80–90		
Basicity		basic 1.5–4.0	acid 0.2–0.5	

Table 27 gives some additional zinc residues and materials that can be processed to produce metals. High-grade materials can be remelted directly to produce brass and bronze products.

While the above represents the processing of most EAF dust and other zinc-containing materials, other processes such as the Meretech also are available. This process recovers for example 99 % pure zinc powder that can be remelted for galvanization.

Table 27: Composition of major zinc drosses and ashes (James, 2000).

	% Zn	% Pb	% Fe	% Cl	% Al
Galvanizing dross	92 – 94	1.0 – 1.6	1 – 3	–	–
HD galvanizing ash	60 – 75	0.5 – 2.0	0.2 – 0.8	2 – 5	–
Cont. galvanizing ash	65 – 75	0.1 – 0.5	0.2 – 0.8	0.5 – 2	0.1 – 0.5
Die-casting dross	90 – 94	0.1 – 0.2	low	–	1 – 7
Sal skimmings	45 – 70	0.5 – 2.0	0.2 – 0.8	15 – 20	–
Brass fume	40 – 65	0.5 – 7.0	1 – 2	2 – 7	–
Die-casting ash	55 – 60	0.1 – 0.2	low	low	3 – 10
Ball mill ash	55 – 65	0.1 – 1.0	0.2 – 0.8	2 – 5	–
Zinc dust/Overspray	92 – 95	1 – 2	0.1 – 0.5	–	–

8.6 Red-mud from alumina production

Similar to the zinc industry, which has to cope with jarosite, goethite and even a plant with haematite residue, the aluminium industry has to deal with its red-mud problem. Worldwide bauxite residue disposal areas contain an estimated 2.7 billion tonnes of residue (Figure 84), increasing by approximately 120 million tonnes each year (Klauber et al., 2011a, b). The world resources of gallium contained in bauxite are estimated in excess of 1 billion kg[a], or around 0.03 % on average.

a This equates to US $ 300 billion @ ca. US $ 300/kg (end of 2012), if recovered fully (but this obviously economically, technologically and thermodynamically not possible).

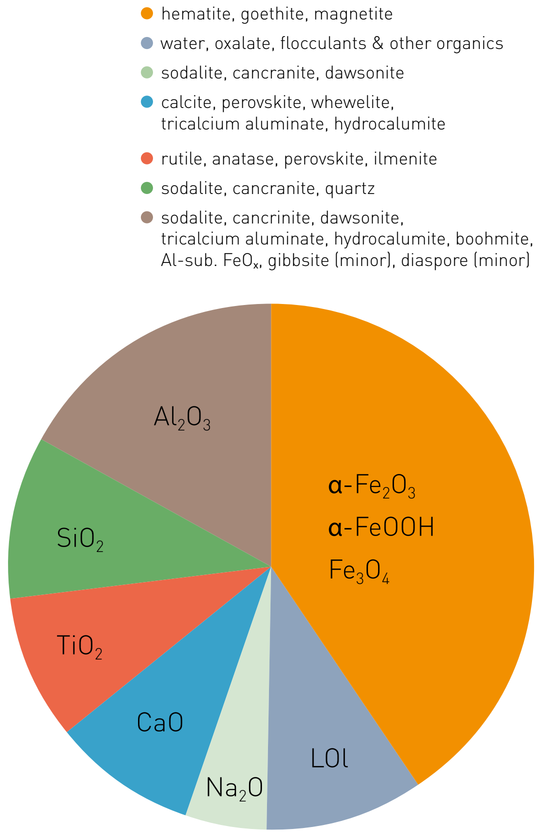


Figure 84:

Red mud production and inventory (Klauber et al., 2011a, b).

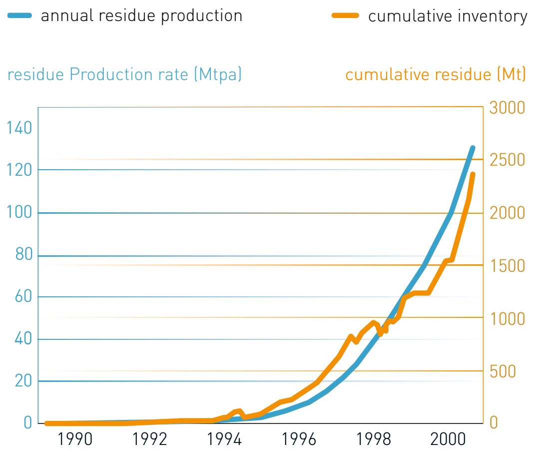
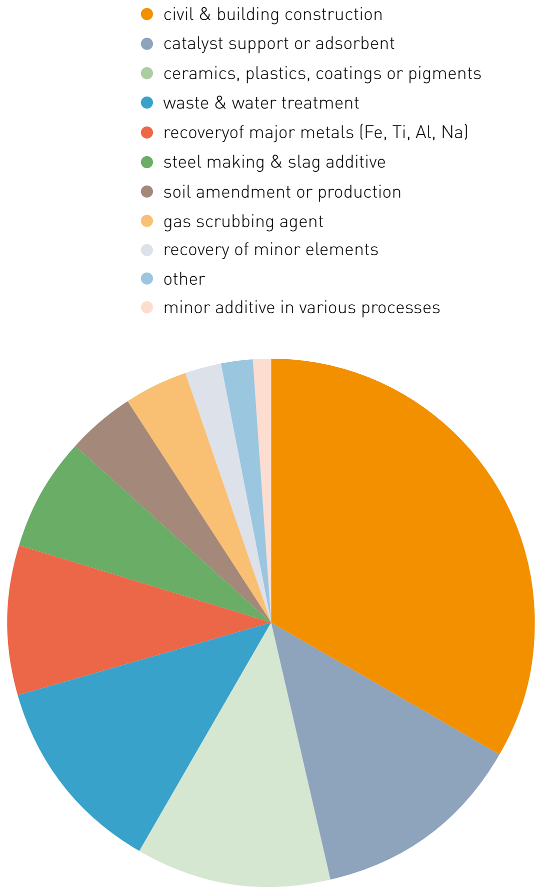


Figure 85:

Various patents for the processing of red mud (Klauber et al., 2011a; 2011b).



This residue affects its image and limits its processing possibilities as environmental licences are increasingly difficult to obtain, either for expanding existing red-mud ponds or for creating new ones. As long as landfill costs remain low and the aluminium industry does not collectively tackle the problem, processing of this material will remain a political issue and nothing will be done. The reasons for treating these materials will be: (i) If politics forces it; (ii) If landfill costs increase to a point where they financially hurt alumina-plant operators; or (iii) If plants are threatened with closure or if elements such as the contained gallium become worthwhile. Furthermore, another catastrophic and much published failure of ponds may further tarnish the industry; and could catalyse a global action to clean up the image of the aluminium industry.

Several attempts were made in the past to recycle and process red mud as shown in Figure 85. Many of the investigations aimed at extracting the iron, titanium or aluminium, but several attempts were also made to recover scarce/critical/valuable elements, such as rare earths (Luidold and Antrekowitsch, 2011). For example, the lowermost parts of some bauxite deposits of the third horizon of the Parnassos-Ghiona area in Greece showed an outstanding total lanthanide concentration of up to 1 % (Ochsenkühn-Petropulu et al., 1996). However, no information is available on the general content of elements in smaller quantities in red mud and, even today, the dumping of red mud is cheaper than its processing. Due to the currently very high prices of rare earth elements, the combined recovery of iron, titanium and REEs might drive an economic process. Basically, the technology exists for the recycling of metals from residues, but efforts must be made for a better cross-linking between the individual processes. For example, the exclusive recovery of tungsten from Tu-containing residues may not be economic, like the extraction of titanium from red mud or the exclusive recycling of indium from flat screens.

In addition, red mud can contain up to 10 % by weight TiO_2 as well as chromium, vanadium and zirconium, each over 1000 ppm, as well as traces of scandium, yttrium, gallium and other rare earth elements. Recently, research was done to use strongly alkaline red mud as an adsorbent for acid wastewaters to minimize their heavy-metal content. This can lead to higher chromium contents of the material, if it is used for neutralizing acidic-chromium-containing effluents from electroplating shops. Reprocessing of such charged red mud is thus potentially economic due to its solving problems with contaminated effluents, after which it can be used as an inert additive for cement, concrete or other building materials, thus saving large landfill volumes.

Red mud can for example be melted in a TSL Furnace (Figure 60) to produce a benign slag or pig iron, as well as fuming off the Ga, which might favourably change the economics. But even then, the low landfill costs are a redoubtable adversary of applying such technically feasible and environmentall desirable processes.

8.7 Residues from oil shale processing

Depending on the carbon content of the residues from oil shale, these could be very well smelted in a TSL furnace. Crucial is the energy balance, however. Power generation by the high-pressure steam from offgas could usefully offset the smelting costs that will produce a benign slag and possibly also pig-iron.

8.8 Sludges from water processing

Figure 60 shows the link between product recycling and water processing. Some interesting elements such as phosphorus can be recovered from water-treatment sludge. Especially in view of the severe problems that phosphorus (eutrophication – kg-PO_4 equivalent) can cause to nature, it is imperative that these sludges, animal materials, etc., are recycled for recovering the phosphorus. About 2 g P/person/day is emitted through sewage, which amounts to around 328,500 tpa. This in itself is a significant resource!

8.9 Slag cleaning

Slag cleaning is general practice and various technologies such as TSL and electric furnaces can be used for this. However, this is once again totally dependent on the economics surrounding the slag to be treated. Smelting technology, such as for recovering cobalt and copper from granulated slag with subsequent processing of the copper-cobalt matte, is general practice and hence a good example of dealing with pyro- and hydro-metallurgy at the same time for optimizing Resource Efficiency. Figure 21 shows that slags can also be cleaned with TSL technology, the advantage being that it can also recover indium, silver, germanium, etc., rendering the slag benign for use as building material as has been done for many years by Korea Zinc (South Korea). In addition, interesting new developments recover heat from slag (Figure 86).

8.10 Shredder fluff (floc/residue) treatment

This fraction, shown in Figure 87 as well as in Table 28, is an extremely dangerous recycling issue due to its complexity. TSL technology is well suited to handle this, using it as a secondary or refuse-derived fuel for lowering the TSL carbon footprint. However, such residues have a large compositional range that is a function of the shredder-feed type, of how the plant is run, what are the products, etc. It succinctly shows how diverse the EoL goods are that are fed into the plant, as well as the different operation modes of plants producing this diverse range of materials called automotive shredder residue (ASR).

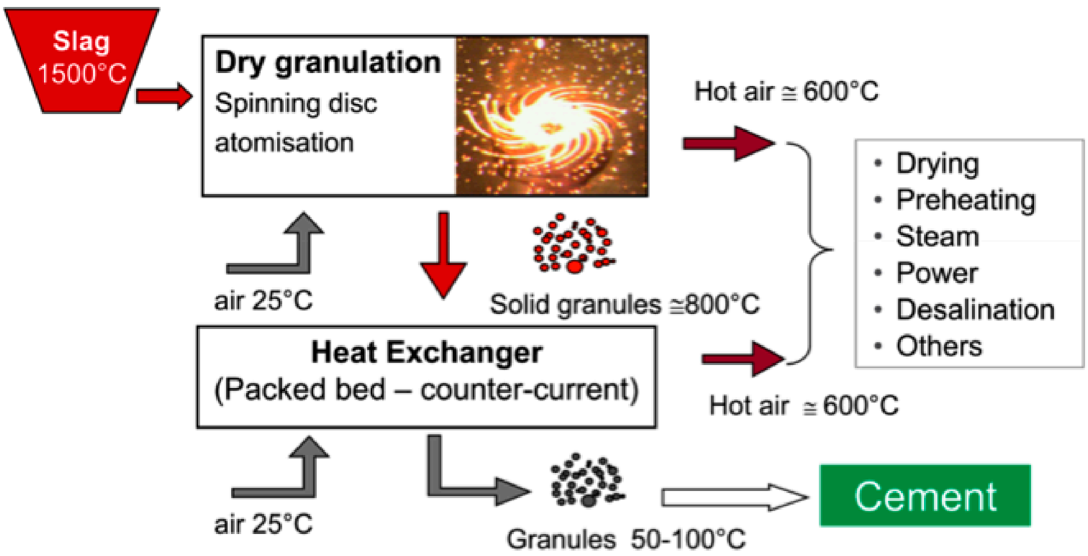


Figure 86:

Dry granulation of slag with heat recovery shown here for blast-furnace slags (Jahanshahi et al., 2011).

Figure 87:

Simplified view of a recycling plant (including extensive PST processing) where 1153 cars were recycled, showing a generalized composition of a fluff after extensive treatment (Reuter et al., 2005; Reuter and van Schaik, 2012a&b).

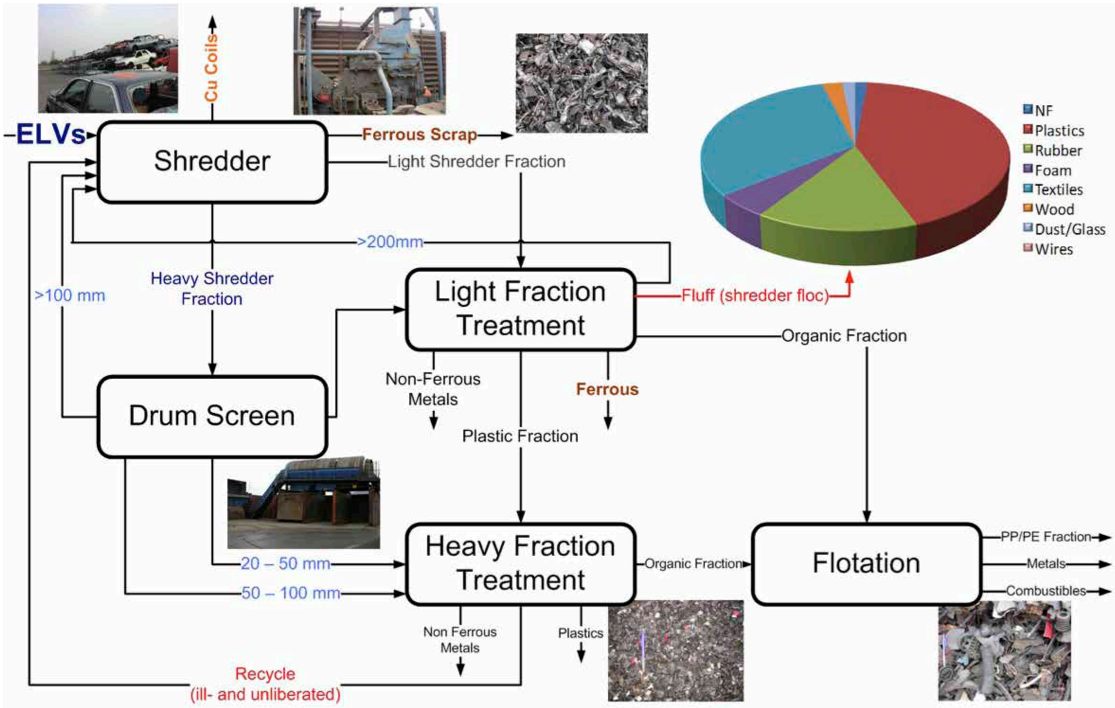


Table 28:

Composition of ASR light and heavy fluff for different operators (Numbers in brackets refer to references in Vermeulen et al. 2011).

Light fluff[a]	[26]	[27]	[30]	[47]	[158]	[159]	[165]
Metals	1 – 1.7	21	8.8	2.5	3.7	0.3	
Wire	2.9 – 3		4.7	1	2.2		0.5
Rubber	3.8 – 4	3.1	2.6	3	8.8	10.3	4.1
Textile	27.5 – 29.5		36.1	32.5	26.2	8.3	7.9
PUR foam	6.6. – 20.6		35.3	8			3.8
Plastic	16.1 – 24.1	31.8	11.7	9	46.1	11.0	8.7
Wood	0.03 – 0.4			1	2.7	0.6	
Paper	0.8 – 1.0				0.8		
Soil/sand	6.4 – 21.6				4.3		
Glass	0	2.3		43 (minerals)			
Others	2.7 – 6.2		0.8		5.2	69.5 (< 10 mm)	75 (fines)

a) Composition, as w% of ASR, according to the origin: light fluff.

Table 28_b:

Heavy fluff [a]	**[26] (stainless steel + heavy)**	**[27]**	**[47]**	**[159]**	**[165]**
Metals	0.2 – 1.4	1.6	5	0.7	
Wire	7.0 – 12.7		3		0.7
Rubber	14.1 – 17.3	9.3	55	43.7	44.8
Textile	7.7 – 11.6		3	10.5	10.5
PUR foam	0.9 – 2.8				3.3
Plastic	23.8 – 30.9	8	19	32.6	29
Wood	0.06 – 0.7		7	4.7	5.6
Paper	1 – 2.5				
Soil/sand	7.6 – 12.3		8 (minerals)		
Glass	8.3 – 11.0	9.4			
Others	4.6 – 14.0			7.8	6.1 (fines)

a) Composition, as w% of ASR, according to the origin: heavy fluff.

Table 29 gives a typical breakdown of costs around an ELV shredder, albeit for ca. 2006 data. It gives a feel for what affects the profitability of such a physical recycling facility.

Table 29:

A typical cost breakdown of an ELV dismantler (Ferrão and Amaral, 2006).

	Shredder
Working time (h/year)	2317
Total shredded scrap (t/year)	69,500
ELV (%)	44 %
Light industrial scrap and appliances (%)	56 %
Building costs (€/year)	113,446
Equipment costs – shredder mill, non ferrous separator, cranes, other (€/year)	374,299
Labor – workers, maintenance technicians and manager (€/year)	
Workers (7 in shredder A and 6 in shredder B)	110,880
Maintenance technicians (2 for both shredders)	39,600
Manager (1 for both shredders)	39,600
Maintenance, insurances and electricity (€/t)	7,7
SR landfill cost (€/t)	44,5
Cost of hulk acquisition (€/t)	46
Revenues from sale of shredded metallic scrap (€/t)	
Ferrous	120
Mix of non ferrous metals (Al, Cu, Zn)	250
Cost of transporting materials (€/t)	
Compacted hulks from dismantler to shredder	4,1
Ferrous metals for recycling	4,1
Mix of non ferrous metals for recycling	25
ASR to landfill	4,1
Shredder metallic scrap separation efficiencies	
Ferrous	0,96
Non ferrous metals (Al, Cu, Zn)	0,25

8.11 Incinerator bottom ash – aluminium recycling

In 2009, IAI and EAA presented a study by Pruvost (2011) about "The European Potential for the Collection and Recycling of Used Aluminium from Bottom Ashes" (European Aluminium Association, 2006).

8.11.1 Municipal solid waste contains around 1 % aluminium

Based on MSW sample analyses, CEWEP (Coalition of European Waste to Energy Plants) estimates an average metallic and non-metallic aluminium (Al) content in MSW sent to WtoE plants of 1 % or a bit more, which is therefore the maximum amount that can be transferred to bottom ash as metallic aluminium. It is estimated that between 50 to 75 % of this comes from aluminium packaging, though this number varies from country to country. This depends on the aluminium packaging mix (high per capita usage, large market share of aluminium cans) and the efficiency and/or structure of the local collection schemes. For example, in countries with dedicated can collection schemes (e.g. deposits) the share of aluminium packaging probably is lower, while non-packaging sources (e.g. kitchen utensils, doorknobs, etc.) become more dominant. MSW also includes aluminium from non-household sources, such as small- and medium-sized businesses, shops, restaurants, etc. Finally, aluminium appears as a chemical element in waste as part of chemical compounds in other materials, in dust, demolition debris, or street waste.

8.11.2 Waste treatment in WtoE plants will increase by 60 % or more within the next 15 years

For both practical as well as methodological reasons (a full mass balance creates too many uncertainties), the study focuses on the actual extraction of non-ferrous metals from bottom ashes, and the potential growth of this sector, assuming three key parameters:

- Non-ferrous metals extraction from all bottom ashes (which is not the case today!).
- A significant increase of WtoE during the next 10 – 15 years.
- An increasing use of improved sorting techniques and new processing methods.

Based on these assumptions, waste treatment in WtoE plants of the EU-27 should at least increase by 62 % (from 60 to 97 million tonnes) between 2006 and 2020, and even by 100 % in a more ambitious scenario, assuming that the remaining landfill of residual MSW will be fully replaced by recycling and WtoE in a ratio of 60 to 40.

8.11.3 Technological innovation will generate higher extraction yields

The main separation tool, the Eddy Current (EC) machine is increasingly (re-)designed so as to extract metals from specific bottom-ash grain sizes. This should result in higher aluminium extraction levels within the fine grainsize fraction (below 5 mm). New concepts of EC machines and of alternative sorting systems (sensor-ejectors) further stimulate the race for improved yields.

In addition, major adjustments in the flowsheets of processing plants are being applied on an industrial scale. This includes the removal by strong magnets of all ferrous material (in addition to iron and steel) ahead of the EC machine, segregation in two or three grain sizes, washing of bottom ash during classification and, last but not least, dry cooling of bottom ash instead of using a water box. This will lead to higher extraction levels and a higher quality of the non-ferrous metals extracted.

8.11.4 Potential increase of aluminium metal extraction of 80 kt (present) to 250 kt in 2020

Based on field research, interviews and statistical data, it is estimated that in 2006 about 130 kt of non-ferrous (NF) metals (gross weight) were extracted from bottom ashes in the EU-27 (+EFTA countries). The aluminium content of this NF metals fraction is relatively stable and ranges between 50 % and 75 %, 60 – 65 % being the most likely figure. Other NF metals, such as copper, zinc, brass and some stainless steel represent a small percentage, while stones, dust, slags, etc., could mount up to 25 %, depending on the treatment process. Therefore, the aluminium metal extracted in 2006 was estimated to be about 80 kt.

If all bottom ash had been processed with the basic technology available in 2006, the total tonnage of the NF metals fraction would have been around 175 kt. The combined result for 2020 of the three parameters of section 8.11.2 should be double or triple these figures:

- 280 kt of NF fraction within a modest of WtoE development scenario with standard technology, assuming that all bottom ash will be processed for NF metals extraction.
- 420 kt if we assume that the improved sorting equipments and optimized flowsheets will be in place in most processing plants and certainly all new ones, for an overall 50 % increase in extraction levels.
- 510 kt, within the ambitious forecast for WtoE with improved sorting.

This would lead to a potential aluminium-metal extraction of 170 to 300 kt, probably close to 250 kt.

Extraction of aluminium (and other NF metals) can be highly profitable. With price ranges from 300 €/t to 1000 €/t or more, the value of NF metals fraction per tonne of bottom ash is significantly higher than the ferrous metal value (whose prices strongly varied in recent times, from a high at 278 €/t to a low of 8 €/t).

It is difficult to indicate a profitability for the EC machine alone as its efficiency depends on the preliminary treatment of the bottom ash, the ferrous-metal extraction, the grain-sizes treated or not treated, etc., as well as on the whole set-up of the bottom-ash treatment plant. However, most operators mention a payback period of maximum two years and some refer to a “break-even price” of 400 – 500 €/t for the NF metals fraction.

Box 21:

AEB Amsterdam

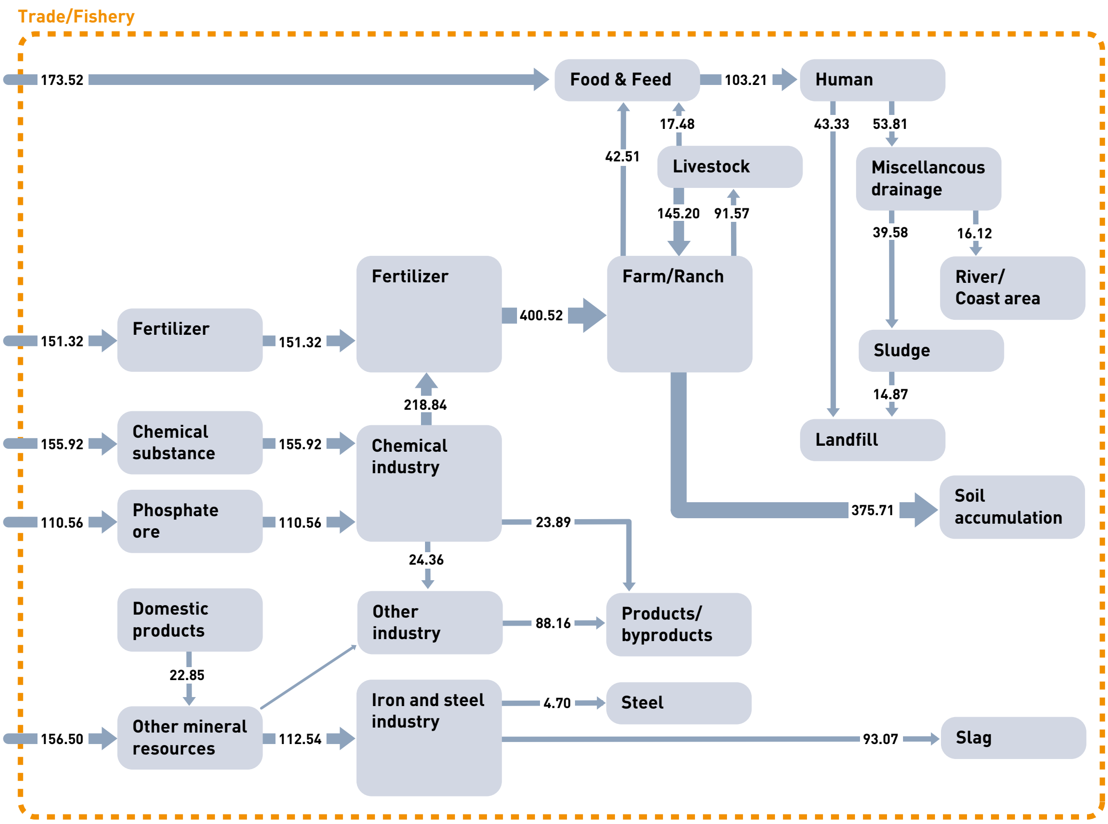
Waste-to-Energy plants (Stehlik, 2009; Münster and Lund, 2010) do not incinerate everything. Citing from AEB Amsterdam (AEB Amsterdam, 2012) 1000 kg of waste yields approximately:

- 850 kWh electricity
- 5 kg aluminium, stainless steel, zinc, lead, copper, silver and gold
- 25 kg iron
- 120 kg clean sand and silt (from the pilot plant)
- 100 kg pottery, glass and granulate
- 7 kg salt, 5 kg gypsum and 5 kg non-reusable material from flue gas

8.12 Recovery of recycled phosphorus

Phosphorus (P) management poses significant sustainability challenges (Abelson, 1999; Christen, 2007). P is supplied to arable land in both mineral and organic forms for food and biomass production, but is taken up by animals and plants with limited degrees of efficiency. At the global level, non-agricultural use of P represents less than 10 % of total P demand (Food and Agriculture Organization, 2011). It is important to note that a substantial dissipation of P occurs in metal production as well. In the steel making process, P occurring in iron ore is removed from the melted metal as dephosphorization slag. In Japan, for instance, the amount of P ending up in dephosphorization slag is equal to the total phosphate ore import (Figure 88).

Figure 88: Economy-wide flow of phosphorus in Japan for the year 2000 (kt-P) (Matsubae-Yokoyama et al., 2009&2010).



The main components of dephosphorization slag are CaO, FeO, SiO_2, and P_2O_5. Figure 88, obtained by an energy-dispersion-type electron-probe micro-analyzer (EPMA), shows the structure and phosphorus distribution among the phases precipitated in a sample of dephosphorization slag (Yokoyama et al., 2007). The white parts in the upper right-hand picture show high phosphorus concentrations, but no FeO. Depending on the total slag composition, phosphorus in slag can be segregated as solid solutions of calcium phosphate and dicalcium silicate (Futatsuka et al., 2004). This phosphorus-enriched crystal phase generally contains about 3 to 10 mass percent P, depending on operating conditions. The black parts in Figure 89 consist mainly of FeO-CaO-SiO_2, almost without phosphorus. Because these two phases have different magnetic properties, they can be separated by a strong magnetic field (Yokoyama et al., 2007). The proposed P-recovery technology from steel-making slag would result in significant recovery of this valuable resource (Figure 22). Furthermore, by returning the iron-rich residues to the sintering, hot-metal desiliconization, and hot-metal dephosphorization processes, the input of raw materials such as CaO and the genera-

tion of slag can also be reduced (Kubo et al. 2010; Matsubae-Yokoyama et al., 2009&2010).

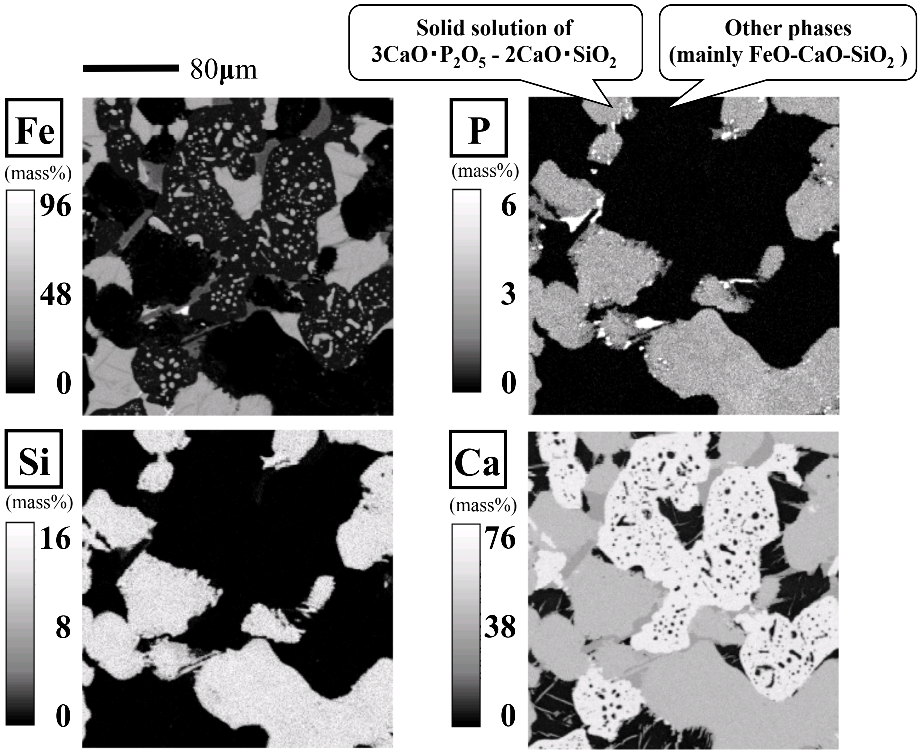


Figure 89:

EPMA image of dephosphorization slag (FetO = 19 %, CaO/SiO_2 = 4.4 %, P_2O_5=2.8 %) (Matsubae-Yokoyama et al., 2009&2010).

Box 22:

Iron recovery from Basic Oxygen Furnace (BOF) steel slags

These slags are a by-product of the steel industry. They represent large amounts (about 400,000 t/year only in France), and are difficult to recycle, mainly because of the slag's propensity for hydration and carbonation (linked to free lime levels of up to 20 %) and the presence of phosphorus. These slags consist of mineral phases containing iron and calcium (FeO, nCaO•nFeO•nFe_2O_3), as well as silica, calcium (nSiO_2•nCaO, CaO) and phosphorus (Gautier et al., 2009). The "zero waste" idea of the ORLA project (ORLA, 2011) is to recover these phases by milling and sorting, producing recycled raw materials suitable for reuse in steel manufacture and for use as a raw material or additive in the cement industry. The technical drawbacks for setting up such solutions include the small size of the mineral crystallites, the highly interlinked phases to be sorted (Figure 90), the presence of phosphorus that is relatively undesirable for both industrial sectors, and the grindability that has to be evaluated.

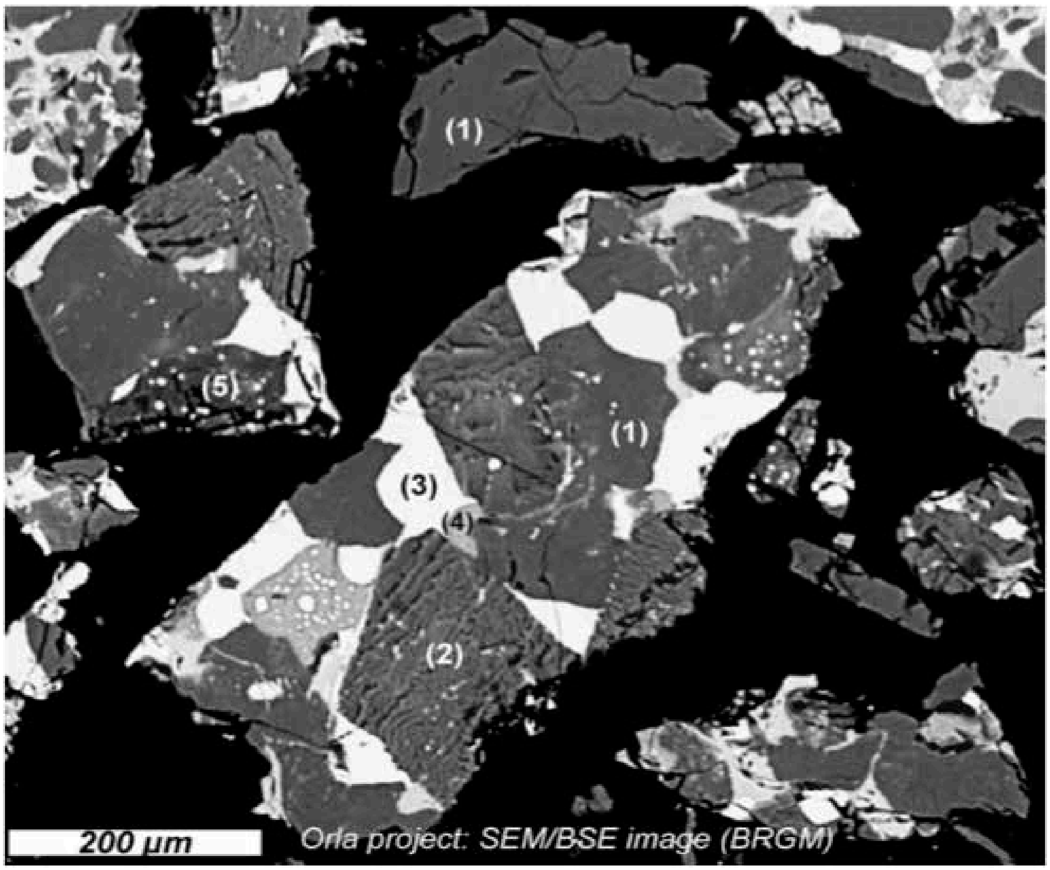


Figure 90: Recrystallized slags with minerals: (1) Primary dicalcium silicate (C2S), (2) Mixture of C2S and CaO, (3) Iron(II) oxide – wüstite, (4) Calcium ferrite, (5) Free lime and droplets of metal iron (Imbricated calcium, silica and iron carriers in BOF steel slag).

The search for dedicated processes with a favourable material and energy eco-balance, considering chemistry and mineralogy, the crystallinity of the constituent phases along with their reactivity, their cooling behaviour, and the speciation of key elements (Fe, P), has been the challenge of the project. Moreover, very demanding international economic and environmental issues include: increased recovery of Fe metal, reduced CO_2 emissions, improved management of stockpiled slags, less pressure on natural resources. It was shown (Bodénan et al., 2011) that:

Box 22: _c

- The pre-treatment of slag by staged crushing and magnetic separation is a necessary step for obtaining a better separation of a metallic-iron-rich product that can be recycled directly in the steel converter (5 to 20 % of slags).
- Successfully grinding the steel slag to < 50 µm is not sufficient for complete liberation of the iron- and calcium-bearing minerals due to the small size of crystallites. The only method, at this particle size, of providing a product sufficiently enriched in iron for recycling into steel works is wet magnetic separation, but the quantities are too small to be of industrial interest (< 5 % of slags).
- Recycling in the cement industry is of interest, since cement-slag-additive formulations have given a compressive strength equivalent to that of control cement as well as respecting the dimensional variations (about 50 %).
- Eco-balance calculations confirm that combined recycling of the slag reduces CO_2 emissions by several hundred thousand tonnes a year; assuming that this reduction would in particular be justified for the cement industry.

8.13 Recycling of hard-metal scrap

In the field of refractory metals, several processes exist for the recycling of tungsten and for the reclamation of molybdenum, vanadium, niobium and tantalum from recycling sources. Major sources for tungsten reclamation are residues and scraps from hard-metal production as well as worn hard-metal pieces. The methods for recovering tungsten from such waste can be divided into three groups, which will be discussed below.

8.13.1 Direct hard-metal recovery methods

The powders from disaggregated hard metals contain tungsten carbide, cobalt and any other material present in the original scrap, because the waste is processed without chemical conversion of the carbide or metal phase. Therefore, these technologies are only applicable for high-grade scraps with sufficiently low impurity contents. Examples for such processes are the zinc process, the coldstream process, bloating-and-crushing, as well as direct crushing (Figure 91).

8.13.2 Semi-direct hard-metal recovery methods

The carbide particles of the feedstock remain chemically unconverted, but the metallic binder is removed by chemical or electrochemical dissolution. A further possibility is represented by the menstruum process (Venkateswaran et al., 1996), which can treat hard-metal scrap as well as heavy metal tungsten scrap and ferrotungsten.

8.13.3 Indirect hard-metal recovery methods

This group of processes includes hydrometallurgy, where the tungsten content of the material is converted to ammonium paratungstate, and the pyrometallurgy. In principle, most tungsten containing scrap can be processed by hydrometallurgical techniques, but these are expensive, consume much energy and produce chemical waste. The applicability of pyrometallurgy, however, strongly depends on the quality of the scrap. Table 30 summarizes the products that can be recycled as well as the preferable scrap types.

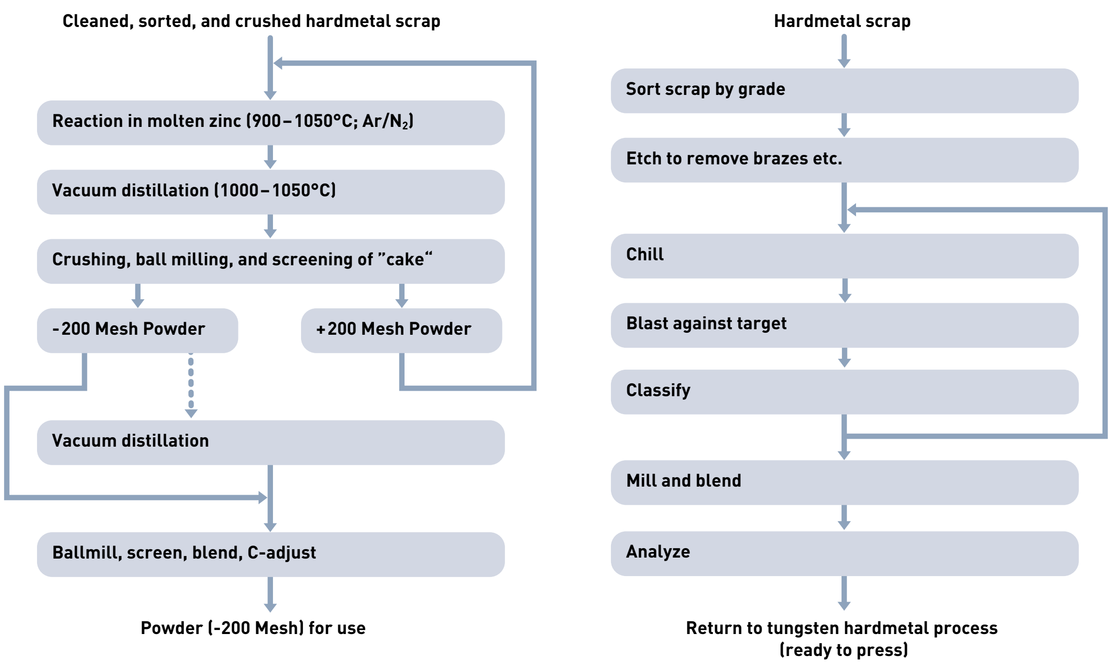


Figure 91: Flowsheets for the zinc process (left) and the coldstream process (right) (Lassner and Schubert, 1999).

Table 30:

Tungsten scrap in pyrometallurgy (Lassner and Schubert, 1999).

Product	Most preferable scrap type
Superalloys	1
Stellites	1, 3, 6, 9
Cast eutectic carbide	1, 6
Menstruum WC	4, 6, 9, 11, 12
Tool steel	1, 2, 4, 7, 11, 12
Ferrotungsten	1, 2, 4, 6, 7, 11, 12
Melting base	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12

No.	Scrap type	% W	Group
1	High-purity W	≥ 99	**Hard scrap** (solid pieces)
2	Oxide dispersed W alloys (ThO_2, ZrO_2, CeO_2, La_2O_3)	96 – 98	
3	Hard metal pieces (also containing Co, Ta)	60 – 97	
4	Heavy metal W alloys	92 – 94	
5	Tungsten – copper	60 – 90	
6	Pure tungsten powder	98 – ≥ 99	**Soft Scarp** (fine particles, powder, dust, timings, sludges)
7	W grinding sludge	30 – 60	
8	W cutting sludge	70 – 80	
9	Hard metal powder	60 – 95	
10	Hard metal grinding sludge	15 – 60	
11	Heavy metal powder	92 – 97	
12	Heavy metal turnings	92 – 97	
13	W – Cu powder and green compacts	50 – 90	
14	Floor sweepings (different sources)	40 – 60	

8.13.4 Hard-metal recycling for catalysts

Recycling also plays an important role in the production of molybdenum and vanadium as individual metals or as the corresponding ferroalloys. A possible feedstock for this purpose are catalysts from the petroleum industry for hydro-treatment (HDT), which among others eliminate N, S and O and even metals (Ni, V, etc.) from the treated hydrocarbons. The spent catalysts contain in general about 2–10 % molybdenum, 0–12 % vanadium, 0.5–4 % cobalt, 0.5–10 % nickel, up to 10 % sulphur and 10 % carbon, and are therefore an interesting recycling resource for molybdenum and other metals. An alternative for the recycling of these catalysts is pyrometallurgi-

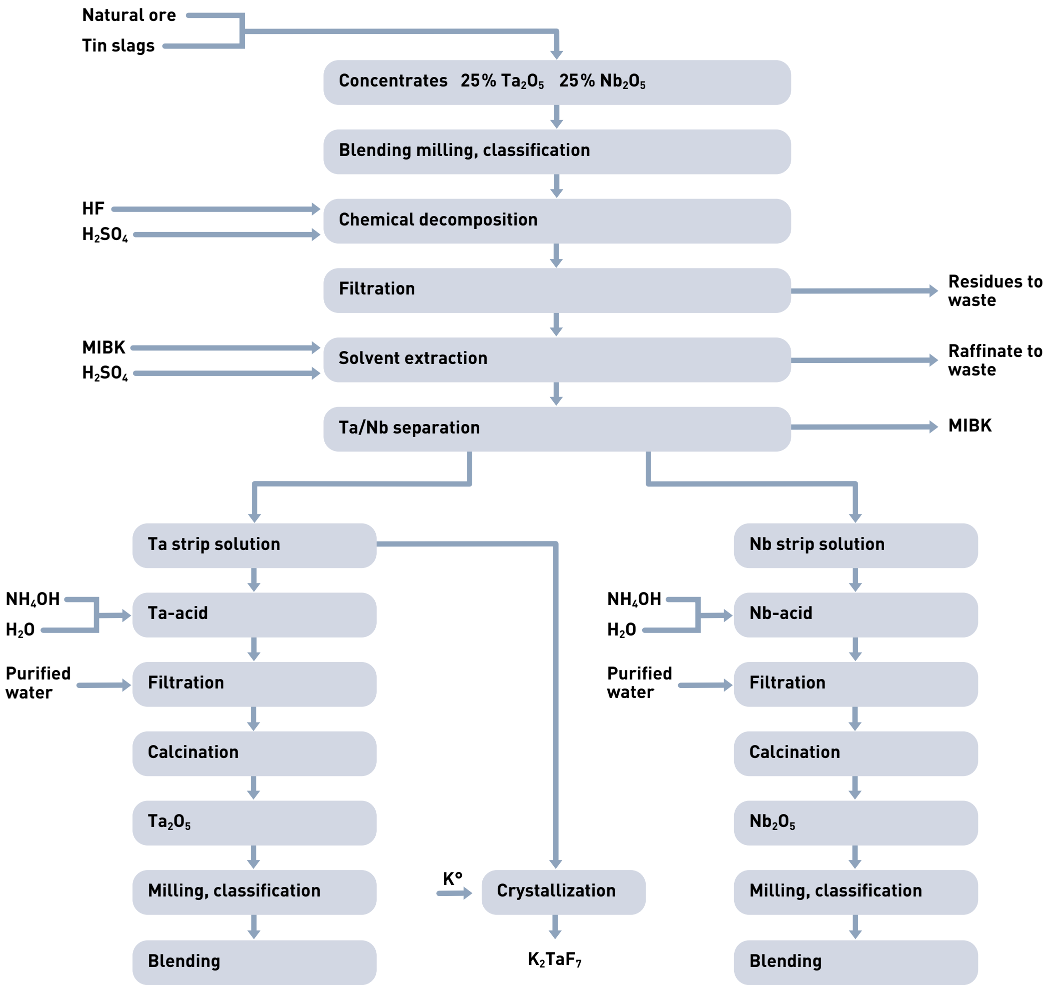
cal treatment for the recovery of ferroalloys. Otherwise, many hydrometallurgical processes are proposed for separating the individual value metals and extracting them in a pure state.

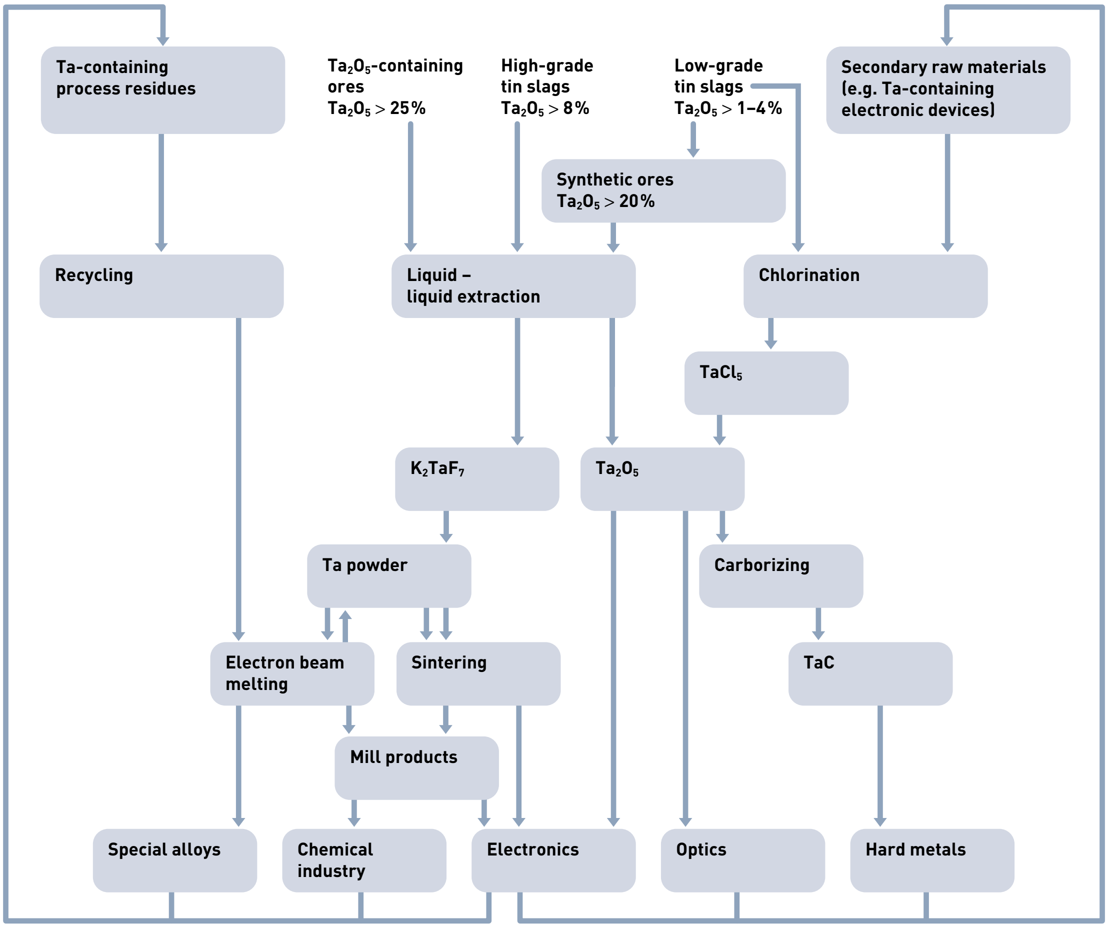
All these procedures follow the same concept. First, the spent catalysts are roasted to remove carbon, sulphur and volatile species or are alternatively pre-processed with acetone. The remaining material is then leached to dissolve the value metals. This uses different solvents with pH-values ranging from acid to alkaline, depending on the roasting conditions. For instance, roasting with soda converts molybdenum and vanadium into water-soluble compounds. Finally, the metals are separated mostly by solvent extraction, but selective precipitation and ion exchange can also be used as well as absorption/desorption for purification of the solution (Luidold, 2009).

There is significant less activity for the recycling of niobium and tantalum. Today, the recycling metallurgy of these metals, their reclamation from tin slag and process residues is well-established (Figure 92).

Figure 92:

Flowsheets for the reclamation of niobium and tantalum from different sources (Habashi, 1997).





8.14 Titanium recycling

The special value of titanium helps closing its material cycle. The source of scrap is highly diverse, originating from high-tech aerospace applications and hip-and-joint replacements. High temperature oxygen free melting is required (Krüger et al., 2005) and, depending on the melting route, it can either form part of a consumable electrode—if it is well sorted to produce a high-quality product—or it can be directly added to the melt in small pieces. Untreated titanium scrap of known composition can be added as alloying element to various metals, or can be used for producing master alloys such as ferrotitanium.

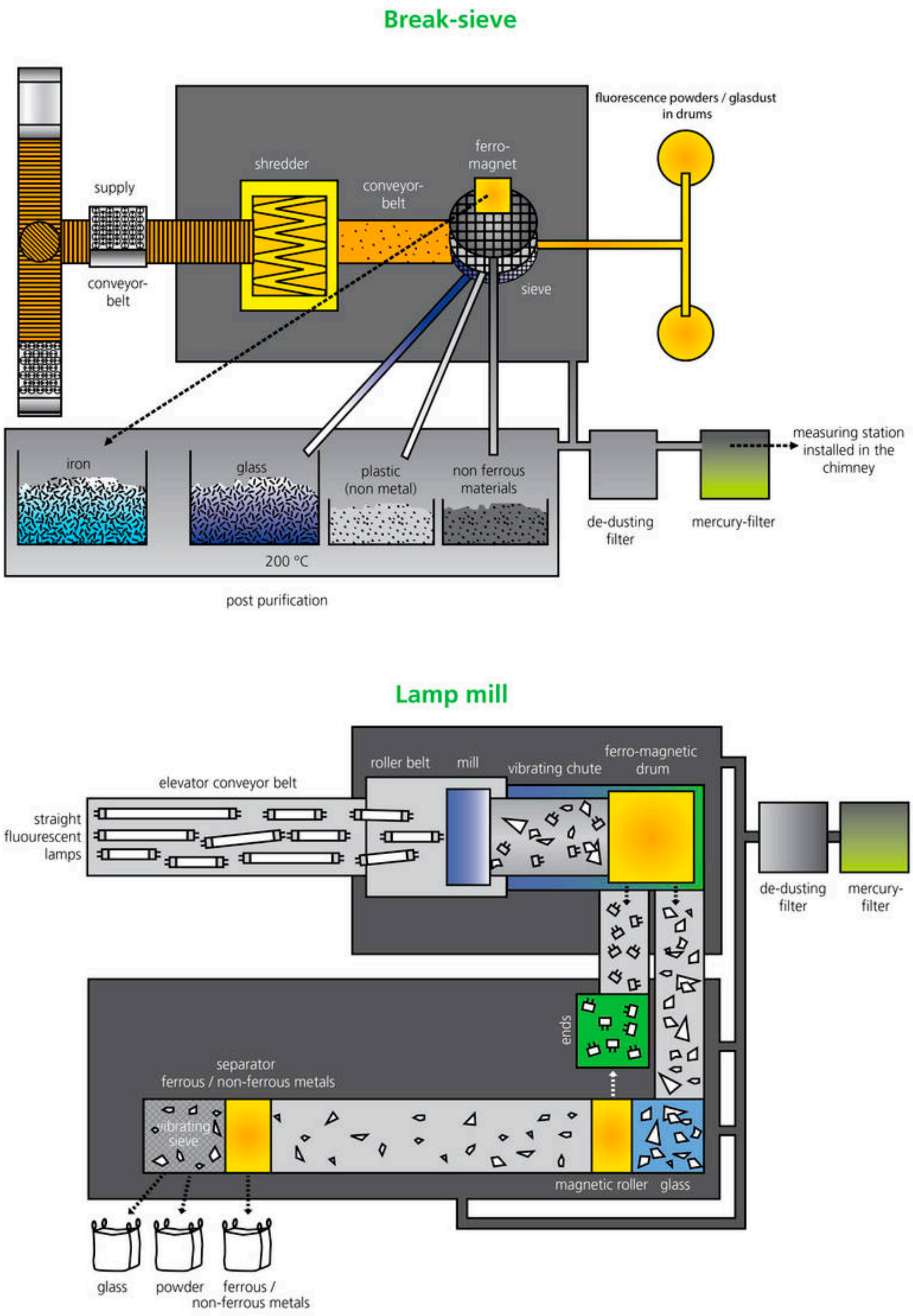
8.15 Technology for the recycling of lamps

The decontamination of fluorescent lamps can be done by three different methods: thermal processes, chemical processes involving leaching with aqueous solutions, or stabilization (Durao et al., 2008). The last method, stabilization, does not recover REEs from the treated material. In the thermal processes, which are more efficient than the chemical ones, the material is heated to a sufficiently high temperature to evaporate mercury. However, earlier studies showed that most of the mercury in spent lamps remains in the phosphor-powder matrix, because mercury exists in the phosphor-powder residue of spent fluorescent lamps as Hg^0, Hg^+ and Hg^{2+}. Especially the very strong interaction of Hg^{2+} with the glass present in the phosphor powders, makes mercury decontamination of

the powder more difficult, so that the thermal removal of this toxic metal requires high temperatures. Figure 93 provides a brief overview of the technology of the recycling of lamps. Note the attention to mercury removal.

Figure 93:

A schematic overview of the cutting and physical sorting of lamps (European Lamp Companies Federation, 2012).

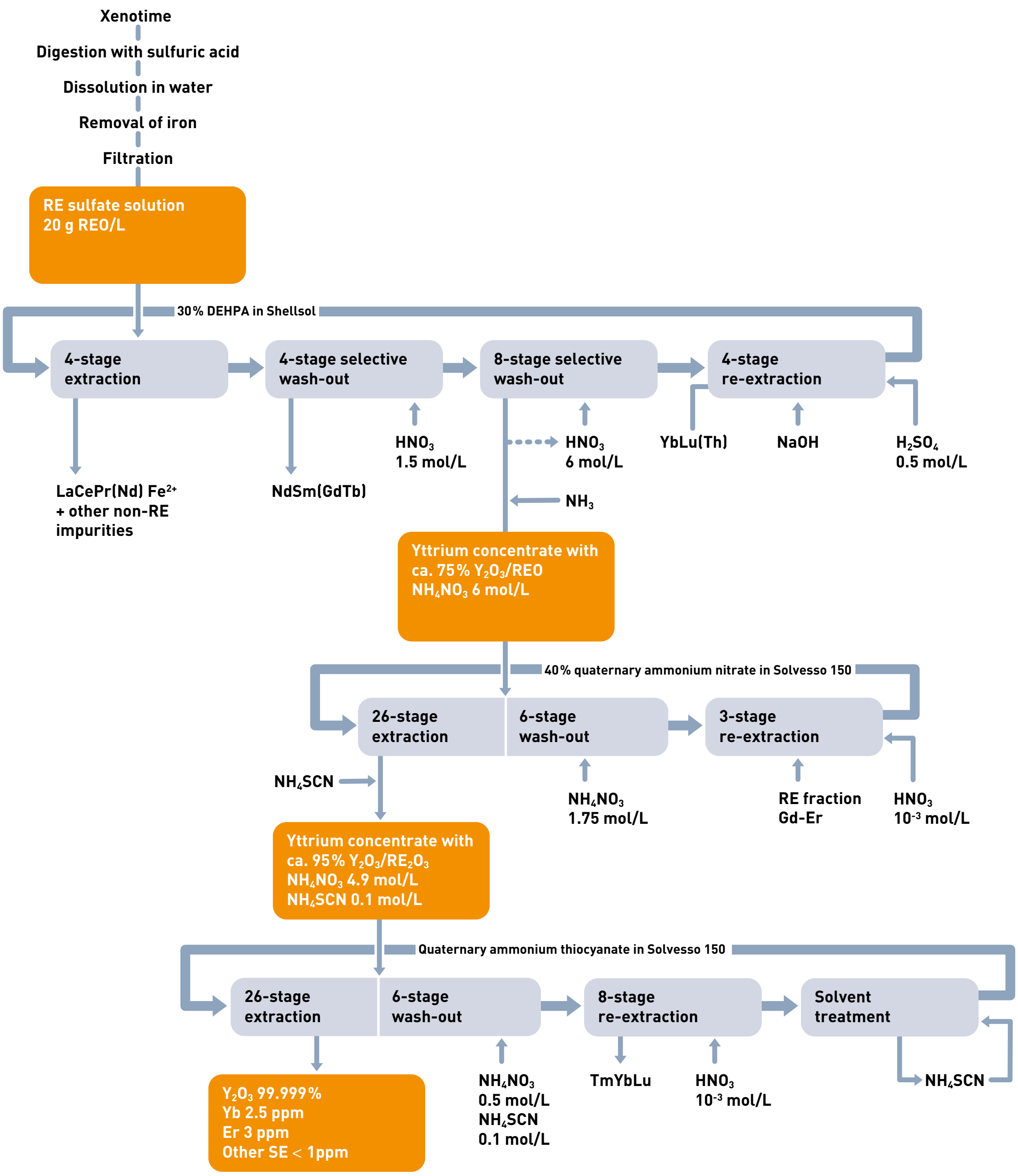


Similar combinations of technology should be used for any other Hg-containing materials, such as dental amalgam, mercury containing soils, etc.

Recycling is not only about physical separation as shown by Figure 93, but also requires sophisticated hydrometallurgy for recovering the valuable metals and compounds. Due to the low volume of the REO-recyclates, it is economically more viable to process them in existing plants. Figure 94 gives an idea of the complex hydrometallurgy required for processing the xenotime ore, especially the large number of solvent-extraction-unit operations required for extracting the yttrium oxide (McGill, 2010).

Figure 94:

Production of yttrium oxide from xenotime (McGill, 2010).



8.16 Photovoltaic cell recycling

Thin-film photovoltaic cells contain various elements such as Cd, Te, Sn, In and Ga, and their recycling is an excellent example of application of the Recycling Metal Wheel, requiring primary metallurgical-industry expertise and infrastructure for recovering these metals from the recyclates (Vasilis and Fthenakis, 2000). The physical separation steps are the same as discussed elsewhere in this document.

Figure 98 shows a scheme for recycling manufacturing scrap of thin-film photovoltaic cells. This can be used for well-sorted EoL scrap as well, but in reality the latter will always be contaminated with other materials and metals. Nevertheless, with a metallurgical infrastructure in place and ensuring that the valuable metals and their compounds are concentrated in suitable phases, the Metal Wheel shows that the recycling system can be "closed". It requires, however, a vision and policy to maintain the metallurgical infrastructure to this end; otherwise, the sustainability-enabling metals used in photovoltaic cells will be lost, with a total reliance on mining for further supplies.

8.17 Wind power generation

According to the International Iron and Steel Institute (2008b), Horns Rev wind farm, for instance, contains around 28,000 tonnes of steel, around 79 % of all materials used. Therefore, the recycling of this steel should pose no problem (if well collected) and represents a very high value. In this application, steel is a truly sustainability-enabling metal through its application as well as its recycling! If also well collected, the valuable metals in the turbines, such as copper and Rare Earth containing magnets, can also be recycled. Tam and Tam (2006) provide further background on construction-waste recycling.

Figure 95: A scheme for recycling manufacturing scrap, but EoL scrap can be mixed with other types thus complicating matters. (First Solar, Inc., 2012).

9. Appendix B: Details on Metals found in WEEE

This Appendix provides compositional and other data for various WEEE goods.

9.1 Metal contents of some EEE categories

Table 31 gives an overview of the metal contents of various EEE categories and their demand.

Table 31: World reserves, demand for EEE, mine production and the amount by weight (g) of metals in different WEEE categories (Ongondo et al., 2011).

Symbol	Silver Ag	Gold Au	Bismuth Bi	Cobalt Co	Copper Cu	Palladium Pd	Antimony Sb	Tin Sn
World mine production (t/a)	20000	2500	5600	58000	15000000	230	130000	275000
Demand for EEE (t/a)	6000	300	900	11000	4500000	33	65000	90000
Demand as % of production	30	12	16	19	30	14	50	33
World reserves (kt)	400	47	320	6600	540000	-	2100	5600
WEEE categories and sub-catagories as per EU Directive. Amount in EEE by weight (g).								
1A, 10	0.008	0.0019	-	-	1736	0.001	0.045	25.5
1B	-	-	-	-	958	-	-	-
1C	0.0023	0.00068		0.23	956	0.0014	0.029	-
2, 5A, 8	0.00033	0.0001	-	0.18	484	0.0002	0.0041	-
3A	0.48	0.079	0.048	0.27	159	0.03	0.19	-
4A	0.12	0.016	0.06	0.14	423	0.0029	0.24	-
6	0.001	0.00028	-	1.29	1075	0.00058	0.012	-
7	0.072	0.008	-	0.29	25.58	0.00059	-	-
3B	0.21	0.013	0.95	0.18	723	0.0048	3.02	0.81
4B	2.65	0.17	0.66	0.21	971	0.067	5.75	13
3C	0.52	0.2	-	-	310	0.041	0.16	0.53
4C	0.45	0.11	-	-	824	0.034	0.71	18.3
5B	0.00027	0.000025	-	-	2.76	0.000015	0.00074	0.11

1A: large domestic appliances excluding cooling and freezing equipment and ''smaller'' LDA items (e.g., cookers, washing machines); **1B:** cooling and freezing appliances (e.g., refrigerators, air conditioning units); **1C:** ''Smaller items within the large domestic appliances (e.g., microwaves); **2:** Small domestic appliances (e.g., toasters, vacuum cleaners); **3A:** IT and Telecom excluding CRTs (e.g., computers, telephones); **3B:** CRT Monitors; **3C:** LCD Monitors; **4A:** Consumer electronics excluding CRTs (e.g., DVD players, audio amplifiers); **4B:** CRT TVs; 4C: flat panel TVs; **5A:** lighting equipment – luminaries; **5B:** lighting equipment – lamps; **6:** electrical and electronic tools (e.g., drills, lawn mowers); **7:** toys, leisure and sports equipment (e.g., game consoles); **8:** small domestic medical devices; **9:** monitoring and control instruments (e.g., smoke detectors, thermostats) – there was no data for this category; **10:** automatic dispensers.

9.2 Printed wire boards

PWBs contain several "critical" materials, the mix depending on the type of application. The following materials are generally present in varying concentrations: PGMs, PMs, Sb and Ta (Goosey and Kellner, 2002). REEs are used in various components (e.g. lanthanum and neodymium). A printed wire board (PWB) from a PC contains on average 7% Fe, 5% Al, 20% Cu, 1.5% Pb, 1% Ni, 3% Sn and 25% organic materials, as well as 250 ppm Au, 1000 ppm Ag and 100 ppm Pd. In addition, As, Sb, Ba, Br and Bi are present (European Commission DG Environment, 2006; UNEP, 2009).

Table 32 to Table 35 give the composition of various PWBs from several WEEE categories. Due to large variations in composition, it is clear from the tables why the recycling of the PWB fraction in a copper-based smelter can be challenging. However, due to the relatively high level of economically valuable elements, such recycling generally is viable.

Table 32: Percentage of printed wire board (PWB) and precious-metal contents in diverse electrical equipment (Chancerel et al., 2009; Chancerel and Rotter, 2009a; United Nations University, 2007; Wecycle, 2011; Witik et al., 2011).

Product	Content of mother-board in product [%]	Metal concentration in PWB (g/t PWB)				Mass of equip-ment [kg]
		Ag	Au	Pd	Pt	
Computer keyboard	2–2.1	700	70	30		
LCD monitor	4–7.8	1300	490	99		
Computer mouse	8–8.2	700	70	30		
DVD player	10–16.2	700	100	21		2.95–3.4
Hi-fi unit	8–10.6	674	31	10		4.15–5.05
Laptop	15–17.1	1000	250	110		
Speaker	2	674	31	10		
Mobile phone	22–22.1	3573–5540	368–980	285–287	7	
PC	8.9–13	600–1000	81–600	90 –110	40	
Printer/fax	6.6–8	350	47	9		
Radio set	20–20.5	520	68	8		5.13–6.2
Telephone	21.9–22	2244	50	241		
Video recorder	10–14	674	31	10		4.0–6.4
Audi & video		674	31			

Table 32: _b

Product	Content of motherboard in product [%]	Metal concentration in PWB (g/t PWB)				Mass of equipment [kg]
		Ag	Au	Pd	Pt	
Computer CRT Monitor		150	9	3		
Small IT and communication equipment		5700	1300	470		
TV set – CRT Monitor		280 – 1600	17 – 110	10 – 41		
TV set – LCD Monitor		250	60	19		
Coffee machine	0.3					
Drill machine	0.2					
Shaver	2.2					
Hair dryer	0.1					
Hand held videogame console	21.5					
Mixer/blender	0.7					
Plastic electrical toys	2.1					
Calculator	14.1					
Bread machine	2.8					
Vacuum cleaner	0.7					
Game computer	19.6					

Table 33:

The average composition of PWBs in fractions (total=1) of the various WEEE categories (United Nations University, 2007).

Component Materials	1A LHHA	1CL HHA-small	2 SHHA	3A1 IT ex CRT PC's	3A2 IT ex CRT print-ing devic-es	3A3 IT ex CRT Small IT	3B IT CRT	3C IT FDP*	4A1 CE ex CRT Large Audio	4A2 CE ex CRT VCRs DVD etc	4B CE CRT	4C CE FDP	5B Lamps	6 Tools	7,1 Toys Game cons. Power b.	7,2 Toys Game cons. Power b.
Fe	9,9E-02	2,1E-01	1,2E-01	1,3E-01	3,9E-01	8,0E-02	1,0E-01	5,2E-03	9,3E-02	5,3E-02	1,1E-02	1,2E-01	1,2E-01	4,1E-02	2,7E-02	8,3E-02
Cu	1,3E-01	1,3E-01	1,1E-01	1,8E-01	1,4E-01	1,0E-01	1,8E-01	4,0E-01	1,9E-01	1,6E-01	1,2E-01	2,2E-01	1,1E-01	1,6E-01	2,0E-01	2,0E-01
Ag	1,6E-04	4,8E-05	2,2E-04	1,0E-03	3,5E-04	5,7E-03	1,5E-04	1,3E-03	5,2E-04	7,0E-04	1,6E-03	2,5E-04	2,2E-04	1,1E-03	4,3E-04	3,0E-04
Au	3,8E-05	1,4E-05	2,0E-05	2,3E-04	4,7E-05	1,3E-03	9,2E-06	4,9E-04	6,8E-05	1,0E-04	1,1E-04	6,0E-05	2,0E-05	1,8E-05	1,6E-04	1,8E-05
Pd	2,0E-05	2,9E-05	1,2E-05	9,0E-05	9,0E-06	4,7E-04	3,4E-06	9,9E-05	8,0E-06	2,1E-05	4,1E-05	1,9E-05	1,2E-05	4,8E-05	1,8E-05	
Al (general)	7,7E-02	7,6E-02	8,6E-02	4,0E-02	4,4E-02	2,0E-02	4,6E-02	1,9E-02	1,3E-01	5,9E-02	6,3E-02	1,5E-01	8,6E-02	5,8E-02	6,1E-02	1,8E-01
As						2,7E-05										
Be						8,8E-05										
Bi						2,0E-04	6,9E-04			6,0E-04	4,0E-04					
Cd						1,4E-06										
Cr	1,0E-04	2,9E-04	2,1E-04	5,5E-04	7,5E-04	2,5E-02	6,9E-04	2,0E-04	0.0E-00	4,0E-04	2,1E-04	3,5E-04	2,1E-04	2,1E-04		
Ni	5,0E-04	9,0E-04	1,1E-03	9,0E-03	1,2E-03	3,5E-02	2,5E-03	9,0E-03	2,8E-03	2,8E-03	3,0E-03	1,8E-03	1,1E-03	1,1E-03	3,5E-03	1,0E-03
Pb	1,5E-02	1,0E-02	3,0E-02	3,3E-03	5,4E-03	1,4E-02	1,1E-02	5,7E-03	5,6E-03	1,6E-02	1,5E-02	6,8E-03	3,0E-02	3,0E-02	4,5E-03	5,8E-03
Sb	9,0E-04	6,0E-04	6,0E-04	4,5E-04	4,0E-04	3,1E-03	2,2E-03	4,0E-04	1,2E-03	1,3E-03	3,5E-03	4,0E-04	6,0E-04	6,0E-04		
Sn	2,4E-02	5,8E-03	2,7E-02	4,8E-03	6,9E-03	2,1E-02	5,7E-04	1,3E-03	4,5E-03	6,6E-03	7,9E-03	1,0E-02	2,7E-02	2,7E-02	3,0E-03	3,2E-03
Zn	3,2E-02	6,8E-03	1,4E-02	1,6E-02	1,6E-02	1,4E-02	1,9E-02	2,5E-03	1,3E-02	1,7E-02	3,9E-03	1,3E-02	1,4E-02	1,4E-02		
Plastics (general)	4,4E-01	3,9E-01	4,6E-01	2,5E-01	2,3E-01	5,3E-01	3,9E-01	1,1E-01	1,6E-01	3,7E-01	2,7E-01	2,0E-01	4,6E-01	4,8E-01	2,8E-01	2,0E-01
Epoxy		1,7E-01	1,6E-01				4,6E-02		2,0E-01		3,9E-01		1,6E-01	1,5E-01		
Ceramics	1,4E-01			1,9E-01	6,9E-02		5,2E-02	4,4E-01	2,0E-01	6,4E-02	1,0E-01	1,8E-01			4,2E-01	3,3E-01
Glass LCD						1,0E-01										
Other (average)	4,4E-02	0.0E-00	0.0E-00	1,7E-01	9,9E-02		1,5E-01			2,3E-01		1,1E-01		3,0E-02		
Liquid Crystals						8,0E-03										
Br		3,2E-03	1,0E-04			3,8E-02	2,9E-03		1,2E-03	2,5E-03	1,2E-02		1,0E-04	1,2E-02		
Cl		3,9E-03	4,3E-03			5,0E-04				1,0E-02	2,3E-03		4,3E-03	2,7E-03		

Table 34:

Various elements in e-waste, and their application, typical concentration and emission (Williams et al., 2008).

[a](Morf et al., 2007).

[b]Assuming a global e-waste production of 20 million tonnes per year.

Contaminant	Relationship with E-waste	Typical E-waste concentration (mg/kg)[a]	Annual global emission in E-waste (tons)[b]
Polybrominated diphenyl ethers (PBDEs) polybrominated biphenyls (PBBs) tetra-bromobisphenol (TBBPA)	Flame retardants		
Polychlorinated biphenyls (PCB)	Condensors, transformers	14	280
Chlorofuorocarbon (CFC)	Cooling units, insulation foams		
Polycyclic aromatic hydrocarbons (PACs)	Product of combustion		
Polyhalogenated aromatic hydrocarbons (PHAHs)	Product of low-temperature combustion		
Polychloronated dibenzo-p-dioxins (PCDDs) polychlorinated dibezofurans (PCDFs)	Product of low-temperature combustion of PVCs and other plastics		
Americium (Am)	Smoke detectors		
Antimony (Sb)	Flame retardants	1700	34000
Arsenic (As)	Doping material for Si		
Barium (Ba)	Getters in cathode ray tubes (CRTs), in glass		
Beryllium (Be)	Silicon-controlled rectifiers		
Cadmium (Cd)	Batteries, toners, plastics	180	3600
Chromium (Cr)	Data tapes and floppy disks	9900	198000
Copper (Cu)	Wiring, conductors	41000	820000
Gallium (Ga)	Semiconductors		
Indium (In)	LCD Displays (ITO – Indium Tin Oxide)		
Lead (Pb)	Solder, batteries	2900	58000
Lithium (Li)	Batteries		
Mercury (Hg)	Fluorescent lamps, batteries, switches	0,68	13,6
Nickel (Ni)	Batteries	10300	206000
Selenium (Se)	Rectifiers		
Silver (Ag)	Wiring, switches		
Tin (Sn)	Solder, LCD screens (ITO)	2400	48000
Zinc (Zn)	Die castings	5100	102000
Rare Earth elements	CRT Screen, Lamps		

Table 35:

Average composition of a PC (European Commission DG Environment, 2006).

Name	Content (% of total weight)	Recycling Efficiency (current re-cyclability)	Weight of Material (lbs.)	Use/Location
Plastics	22,9907	20 %	13,8	Includes organics, oxides other than silica
Lead	6,2988	5 %	3,8	Metal joining, radiation shield/CRT, PWB
Aluminium	14,1723	80 %	8,5	Structural, conductivity housing, CRT, PWB, con-nectors
Germanium	0,0016	0 %	< 0.1	Semiconductor/PWB
Gallium	0,0013	0 %	< 0.1	Semiconductor/PWB
Iron	20,4712	80 %	12,3	Structural, magnetivity/ (steel) housing, CRT, PWB
Tin	1,0078	70 %	0,6	Metal joining/PWB, CRT
Copper	6,9287	90 %	4,2	Conductivity/CRT, PWB, connectors
Barium	0,0315	0 %	< 0.1	Vacuum tube/CRT
Nickel	0,8503	80 %	0,51	Structural, magnetivity/ (steel) housing, CRT, PWB
Zinc	2,2046	60 %	1,32	Battery, phosphor emitter/ PWB, CRT
Tantalum	0,0157	0 %	< 0.1	Capacitors/PWB, power supply
Indium	0,0016	60 %	< 0.1	Transistor, rectifiers/PWB
Vanadium	0,0002	0 %	< 0.1	Red phosphor emitter/CRT
Terbium	< 0	0 %	< 0	Green phosphor activator, dopart/CRT, PWB
Beryllium	0,0157	0 %	< 0.1	Thermal conductivity/PWB, connectors
Gold	0,0016	99 %	< 0.1	Connectivity, conductivity/ PWB, connectors
Europium	0,0002	0 %	< 0.1	Phosphor activator/PWB
Titanium	0,0157	0 %	< 0.1	Pigment, alloying agent/ (Aluminum) housing

Table 35_b:

Average composition of a PC (European Commission DG Environment, 2006).

Name	Content (% of total weight)	Recycling Efficiency (current re-cyclability)	Weight of Material (lbs.)	Use/Location
Ruthenium	0,0016	80 %	< 0.1	Resistive circuit/PWB
Cobalt	0,0157	85 %	< 0.1	Structural, magnetivity/(steel) housing, CRT, PWB
Palladium	0,0003	95 %	< 0.1	Connectivity, conductivity/PWB, connectors
Manganese	0,0315	0 %	< 0.1	Structural, magnetivity (steel) hoursing, CRT, PWB
Silver	0,0189	98 %	< 0.1	Conductivity/PWB, connec-tors
Antinomy	0,0094	0 %	< 0.1	Diodes/housing, PWB, CRT
Bismuth	0,0063	0 %	< 0.1	Wetting agent in thick film/PWB
Chromium	0,0063	0 %	< 0.1	Decorative, hardener/(steel) housing
Cadmium	0,0094	0 %	< 0.1	Battery, blue-green phos-phor emitter/housing/PWB, CRT
Selenium	0,0016	70 %	0,00096	Rectifiers/PWB
Niobium	0,0002	0 %	< 0.1	Welding alloy/housing
Yttrium	0,0002	0 %	< 0.1	Red phosphor emitter/CRT
Rhodium	< 0	50 %	< 0	Thick film conductor/PWB
Platinum	< 0	95 %	< 0.1	Thick film conductor/PWB
Mercury	0,0022	0 %	< 0.1	Batteries, switches/hous-ing, PWB
Arsenic	0,0013	0 %	< 0.1	Doping agents in transis-tors/PWB
Silica	24,8803	0 %	15	Glass, solid state devices/CRT, PWB

9.3 Materials in CRT TVs

Table 36 shows that CRT TVs contain various "critical" materials, including REEs and REOs in the phosphor powders, as well as PGMs and other precious metals in the PWBs. The getter/electron gun of a CRT TV uses tungsten. From the given data, an estimate can be made of the amount of "critical" elements.

Table 36: Composition of CRT TVs based on different literature sources.

Material [%]	(Matusewicz and Reuter, 2008)	(Dodbiba et al., 2006)	(DEFRA, 2007)	(United Nations University, 2007)	(Wecycle, 2011)	(Witik et al., 2011)
Iron/steel	17.8	12.0	15.1		4.5	
Copper	1.8	8.0			1.2	
Aluminium	7.0	2.0			0.2	
Other metal					0.1	
Glass	58.0	51.0			65.3	
Plastics	8.2	10.5	16.7		17.0	
Printed Wire Board (PWB)	5.0	3.0	9.7	6.2	6.1	
Fluorescent powder					0.0131 – 0.0136	
Wood				3.8	2.0	
Rubber					0.1	
Other	2.1	13.5	58.5		3.4	
Total	100.0	100.0	100.0		100.0	
	[kg]			**[kg]**	**[kg]**	**[kg]**
Mass				26.7	24.4 – 25.6	24.1

Rare earths are used in CRT TVs, primarily for the red-phosphor powder: YVO_4: Eu^{3+} (4.5 %), Y_2O_3: Eu^{3+} (3.5 %) and/or Y_2O_2S: Eu^{3+} (3.65 %) (Franz et al., 2010 and McGill, 2010). In the calculation, it is assumed that the green, blue and red phosphors are used in equal ratio.

Table 37 gives the average amounts of PGM, precious metals and REEs in CRT TVs. As CRT TVs are being replaced by flat panels, this source of "critical" metals will soon dry up; nevertheless, these figures are given here for information, as recycling organizations still have to deal with these products.

Table 37: Calculated "critical" materials in CRT TVs (Van Schaik, 2011).

Data per CRT TV (literature and calculated)	Min	Max	
Average mass CRT TV	24.1	26.7	[kg]
% PWB in CRT TV	3.0	9.7	[%]
Mass Ag in CRT (calculated)	0.20	4.14	[gram]
Mass Au in CRT TV (calculated)	0.01	0.28	[gram]
Mass Pd in CRT TV (calculated)	0.01	0.11	[gram]
Mass Co in CRT TV (calculated)	0.19	0.21	[gram]
Mass Sb in CRT TV (calculated)	5.20	5.75	[gram]
% fluorescent powder in CRT TV	0.0131	0.0136	[%]
Mass Yttrium in CRT TV (calculated)	0.37	0.50	[gram]
Mass Europium in CRT TV (calculated)	0.03	0.05	[gram]

9.4 Metals and materials in mobile phones

Figure 96 shows that a mobile phone contains more than 40 elements, including base metals such as copper (Cu) and tin (Sn), special/"critical" metals such as cobalt (Co), indium (In) and antimony (Sb), and precious and platinum-group metals including silver (Ag), gold (Au), palladium (Pd), tungsten, yttrium, etc. (UNEP, 2009) (see Table 38).

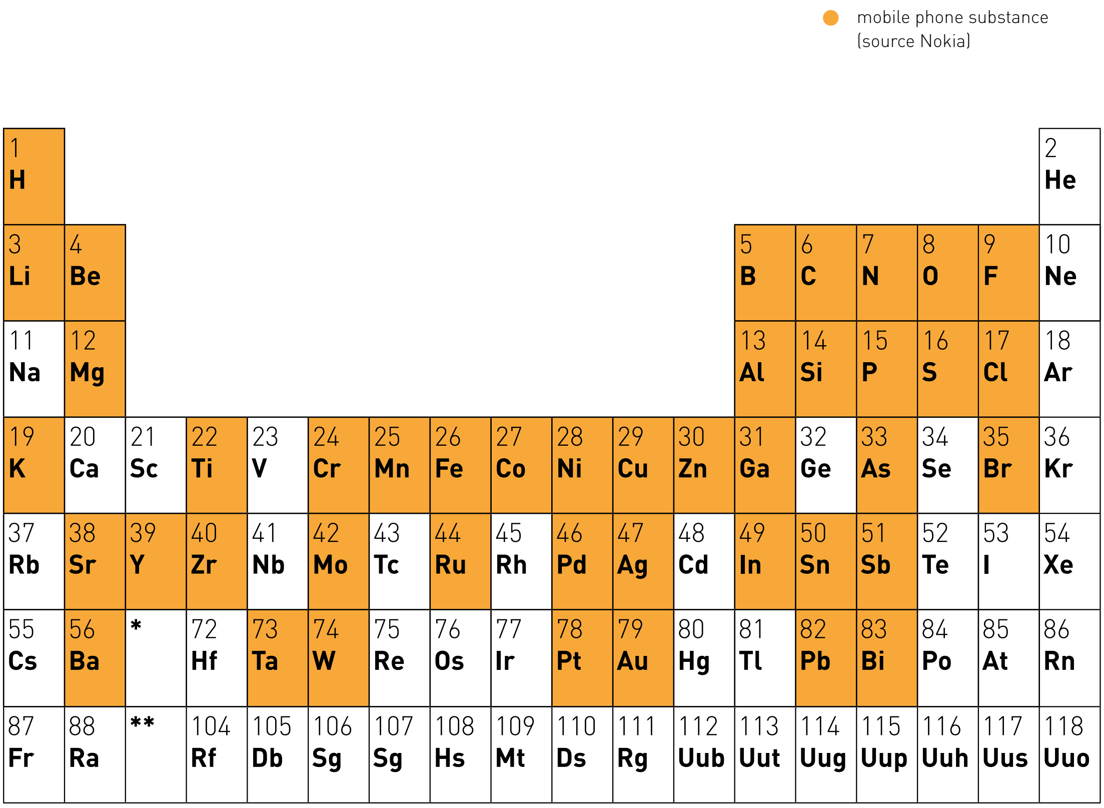


Figure 96:

Materials in a mobile phone (UNEP, 2009).

Table 38:

Composition of mobile phones from various sources.

Reference Materials	(UNEP, 2009) [%]	(UNEP, 2009) [%]	(UNEP, 2009; Umicore, 2011) [gram]	(UNEP, 2009) [%]	(UNEP, 2009) [%]
Al	2.300	2.914			
Cu	26.800	14.235	9		
Fe	2.400	8.039			
Glass	5.500	10.594			
Plastics	44.000	59.600			
Ag	0.080	0.244	0.250	0.079	0.122
Au	0.080	0.038	0.024	0.008	0.022
Pd	0.061	0.015	0.009	0.006	0.006
Pt/La	0.000	0.004		0.000	0.000
Sb	0.000	0.084			
Be	0.000	0.003			
Other	18.779	4.230			
Battery			20.000 (3.8 gram Co)		
Battery			20 (3.8 gram Co)		

9.5 Materials in washing machines and other large white goods

Large white goods, such as washing machines, fridges, ovens and, dishwashers, are composed of the following materials/metals (Table 39 and Table 40):

- Metals (steel, copper, aluminium, stainless steel and their alloys).
- Diverse plastics and organic materials, including their additives, fillers, stabilizers, as well as rubber, wood, textile, fibres, etc.
- Inert materials, such as glass and concrete (incl. ferrite-containing concrete in washing machines).
- Low value printed wire boards (PWB) and electronics containing precious and platinum-group metals.

Table 39:

Average composition of various white goods (Wecycle, 2011; Van Schaik, 2011).

Material [%]	Washing machine	Dryer	Dish washer	Oven
Iron/Steel	52.1	68.8	45.2	81.3
Copper	1.2	2.3	1.5	0.2
Aluminium	3.1	2.1	0.8	1.9
Stainless Steel	1.9	1.2	23.2	0.7
Brass	0.1	0.1	0.2	0.5
Plastics	6.8	15.9	12.6	0.7
Rubber	2.8	0.9	1.6	0.4
Wood	2.6	4.5	2.1	0.0
Other organic	0.1	–	5.3	0.0
Concrete	23.8	–	1.9	0.0
Other inert material	1.9	1.3	0.9	12.6
PWB	0.4	0.4	0.1	0.1
Cables (internal/external)	1.1	1.8	1.5	1.3
Other materials	2.2	0.8	3.2	0.3
Total	**100**	**100**	**100**	**100**

Table 40:

Variation in the composition of washing machines and large white goods from various literature sources.

Material [%]	Washing machine			Large white goods		
Reference	(Wecycle, 2011)	(Matusewicz and Reuter, 2008)	(Truttmann and Rechberger, 2006)	(Wecycle, 2011)	(DEFRA, 2007)	(United Nations University, 2007)
Iron/Steel	52.1	50.6	50.7	54.9	54.3	54.2
Copper	1.2	1.4	2.4	1.4	5.6	2.2
Aluminium	3.1	0.8	2.6	2.5		1.7
Stainless Steel	1.9	–		5.4		1.7
Brass	0.1	0.0		0.1		–
Plastics	6.8	40.5	8.9	9.3	12.4	12.4
Rubber	2.8	0.3	2.1	2.2	2.9	2.8
Wood	2.6	–	3.3	2.8	1.8	1.8
Other organic material	0.1	–	–	1.0	0.3	0.0
Concrete	23.8	–	28.8	14.8	7.5	20.2
Other inert material	1.9	–	1.3	1.9	0.7	0.7
PWB	0.4	0.4	–	0.3	0.1	0.001
Cables (internal/external)	1.1	2.0	–	1.3	1.8	1.8
Other materials	2.1	4.0	–	2.0	12.7	0.5
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

The composition of these white goods strongly varies from product to product, and as they become 'greener' their resource efficiency increases. The complexity and time-varying composition of the products entering a physical recycler makes recycling-efficiency estimates rather difficult, and there may be large variations in composition as shown by van Schaik and Reuter (2002), as well as by van Schaik and Reuter (2004a&b) for cars. The "critical" materials are mainly found on PWBs (United Nations University, 2007). According to these data, large white goods contain on average 20 ppm palladium (Pd), 160 ppm silver (Ag) and 38 ppm gold (Au). Usually, large white good recycling focuses on the recovery of bulk commodity materials according to WEEE recycling guidelines. For PWBs the following holds true:

- PWBs form a very small part of this recycling stream and are mostly lost.
- If recovered, physics limit the production of clean recyclates from PWBs, which makes subsequent processing in metallurgical plants difficult.

- PWBs will, because of the nature of mechanical separation plants, be spread throughout the recyclates of commodity materials (steel, aluminium, etc.). After that, they get lost during the metallurgical processes for these commodity metals, which do not cater for the thermodynamics that maximize recovery of "critical" elements as shown by Reuter et al. (2005) and van Schaik and Reuter (2010a).

9.6 Materials in lighting

Fluorescent lamps contain various materials and elements, which include a range of Rare Earth elements e. g. yttrium, lanthanum, cerium, europium, terbium and gadolinium (USGS, 2002; 2010a; 2010b; 2010c) in the phosphorescent and fluorescent powders. LEDs also contain an interesting suite of materials. Other "critical" resources, such as indium, gallium and tungsten (Hoek van den et al. 2010), are also present, while germanium is found in the fluorescent powder of high-pressure mercury lamps. In summary, lamps contain the following materials (Hoek van den et al. 2010; Franz et al., 2010; McGill, 2010):

- Metals (W including K, ThO_2, Re, Mo, Fe, Ni, Cr, Cu, Nb, Na, Hg, Zr, Al, Ba, Ni, Ta, Al and Zn).
- Glass and others, including SiO_2, Na_2O, K_2O, B_2O_3, Al_2O_3, MgO, CaO, BaO, PbO and SrO.
- Fluorescent powders contain, among others, $Ca_5(PO_4)_3(Cl,F)$, $BaMgAl_{10}O_{17}$, Y_2O_5, $LaPO_4$, $Y_3Al_5O_{12}$, YVO_5, etc., with metal ions (e. g. $Pb^{2+}/Mn^{2+}/Sb^{3+}$) of rare earths (e. g. $Eu^{2+}/Tb^{3+}/Ce^{3+}$) as activator; LEDs contain: AlGaOInP, InGaN, InGaN + (YAG:Ce) and $InGaN^{+}$phosphor.
- Special materials such as getters (W), amalgams, emitters, paint, cements, etc.

The average composition of REOs in phosphor powders of lamps is estimated from diverse literature sources (Rabah, 2004; United Nations University, 2007; Rabah 2008; European Lamp Companies Federation, 2009; Wecycle, 2011; Eurometaux, 2010; Welz et al., 2011; Schüler et al., 2011; Hoek van den et al. 2010) and summarized in Table 41.

Table 41: Summary of data and calculated amount of REOs per lamp (Van Schaik, 2011).

REO amounts calculated per lamp	
Average mass of lamp	0.07 – 0.2 kg
Percentage of fluorescent powders in lamps	0.3 – 2.9 %
Calculated average quantity of REOs/lamp	0.2 – 2.3 gram

Table 42 reflects the total mass of EoL in EU27 and the corresponding spread of REOs, while Table 43 compares this with the world production. From these tables it is clear that this is a relatively small amount.

Table 42: Calculated mass of REOs in EU27 (Van Schaik, 2011 based on data by Chemconserve, 2011; United Nations University, 2007).

Quantity of REOs in EoL lighting in Europe (2010) (Cat. 5 Lighting with fluorescent powders)		
EoL mass of lamps EU27 2010	44,489 (Chemconserve, 2011) – 77,000 (United Nations University, 2007)	[tonne]
Total REOs EU27 2010 (calculated)[a]	67 – 1,250	[kg]

a Calculated on the basis of average mass REO/collected kg lighting Cat. 5; further assumed that the End-of-Life population in the EU is similar to that in the Netherlands (real values can therefore differ due to errors in these assumptions).

Table 43:

Production, demand and use of REOs in 2010 (Van Schaik, 2011 based on data by United Nations University, 2007; European Lamp Companies Federation, 2009; Hoek van den et al. 2010).

Production, demand and application of REOs in 2010	EU27	World	
Items (# lamps)	776,000,000 (United Nations University, 2007) – 988,000,000 (European Lamp Companies Federation, 2009)	6,512,000,000 (Hoek van den et al. 2010)	#
Average kg REO in production lamps 2010 (calculated)	934,170 – 1,189,381	7,839,324	[kg]
REO production 2010		114,330,000 (Lynas Corporation, 2011)	[kg]
REO demand 2010		127,500,000	[kg]
Application of REOs in fluorescent powders (% demand)		6 %	[%]
Kg REO applied in fluorescent powders		7,650,000	[kg]

10. Appendix C: Details on Battery Recycling

Batteries convert chemical energy to electrical energy for powering a wide variety of cordless electrical products. The high variety of applications, from flashlights to vehicles, demands different battery chemistries and materials to be able to meet a wide range of power, energy, size, weight, safety and cost requirements. The 2010 global battery market size was reported at $ 60 billion with a breakdown of 70 % secondary batteries (rechargeable) and 30 % primary batteries (non-rechargeable), as seen in Figure 97. The dominant primary battery types are alkaline and zinc, while lead/acid dominate secondary batteries. Other secondary batteries include portable batteries – dominated by Li-ion and NiMH, while HEV batteries (mostly NiMH) compose a small but growing share of the market at 3 %.

Inside a metal or plastic case, a battery consists of a positively charged cathode and a negatively charged anode, which are kept from touching by an inert separator membrane that allows ions to pass (Figure 98). The electrolyte is a liquid, gel or powder that conducts ions from anode to cathode producing an electric current. The metal fraction of batteries is dominant, but varies greatly both in amount and in elements, with metals potentially contained in the anode, cathode, electrolyte and case/can, and being both valuable (Co, REE, etc.) and hazardous (Pb, Cd, etc.). Material compositions by weight of some batteries are shown in Table 44. The reaction equations occurring in each battery type is given by Table 45.

Figure 97:

Worldwide battery market in 2010 HEV is mostly Ni/MH, while large rechargeable includes Ni/Cd and Ni/MH, created with data from May (2011).

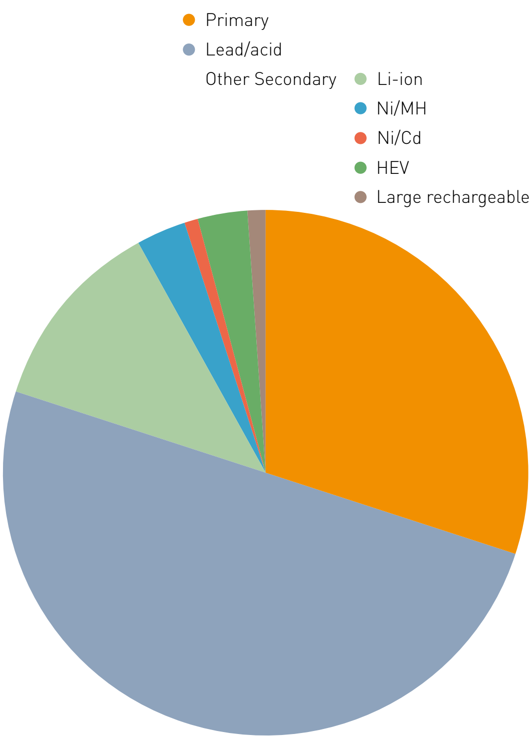


Figure 98:

General composition of a battery (Umicore).

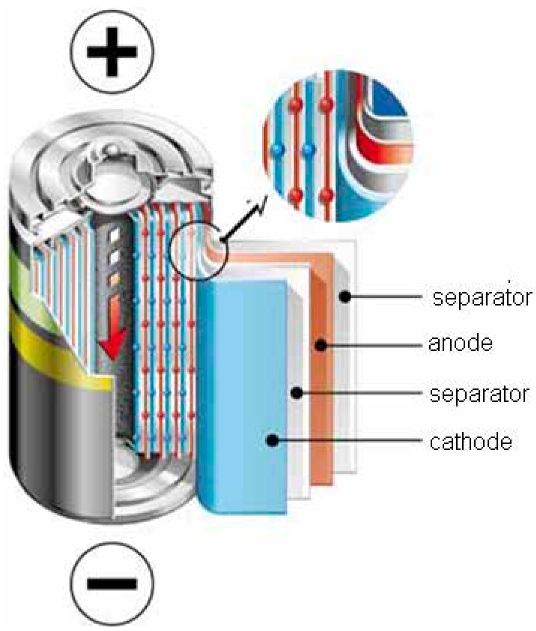


Table 44:

Material compositions of some battery types by weight[a].

a Various data can also be found in: Bernardes et al., 2004; Briffaerts et al., 2009; Sayilgan et al., 2009; Rombach et al., 2008; Umicore, 2010; 2011; Xu et al., 2008; Dewulf et al. 2010; Xua et al., 2008.

	Primary	**Secondary**						
	Zinc/ Alkaline	**Ni/Cd**	**Ni/MH**				**Li-ion**	**Li-polymer**
			Button	Cylindrical	Prismatic	Toyota Prius II		
Fe	5 – 30 %	40 – 45 %	31 – 47 %	22 – 25 %	6 – 9 %	36 %	24.5 %	1 %
Ni		18 – 22 %	29 – 39 %	36 – 42 %	38 – 40 %	23 %		2 %
Zn	15 – 30 %							
Mn	10 – 25 %							
Cd		16 – 18 %						
Co			2 – 3 %	3 – 4 %	2 – 3 %	4 %	27.5 % ($LiCoO_2$)	35 % ($LiCoO_2$)
Li								
REE			6 – 8 %	8 – 10 %	7 – 8 %	7 %		
Cu							14.5 %	16 %
Al								15 %
K			1 – 2 %	1 – 2 %	3 – 4 %			
Metals, unspecified						2 %		
Graphite/ Carbon			2 – 3 %	< 1 %	< 1 %		16 %	15 %
Plastics/ Polymer			1 – 2 %	3 – 4 %	16 – 19 %	18 %	14 %	3 %
H,O			8 – 10 %	15 – 17 %	16 – 18 %			

Table 45:

Battery-chemistry for different battery types.

Types & Materials in batteries	
Zinc-Carbon:	$Zn\ (s) + 2MnO_2(s) + 2NH_4 + (aq) \rightarrow Mn_2O_3(s) + Zn(NH_3)_2^{2+}(aq) + H_2O(l)$
Alkaline:	$Zn\ (s) + 2OH^-\ (aq) \rightarrow ZnO\ (s) + H_2O\ (l) + 2e^-$ $2MnO_2\ (s) + H_2O\ (l) + 2e^- \rightarrow Mn_2O_3\ (s) + 2OH^-\ (aq)$
Button:	$Zn(s) + Ag_2O(s) + KOH/NaOH \rightarrow ZnO + 2Ag$
Ni-MH:	$H_2O + M^* + e^- \leftrightharpoons OH^- + MH.$ $Ni(OH)_2 + OH- \leftrightharpoons NiO(OH) + H_2O + e^-$
Li-ion:	$LiCoO_2 \leftrightharpoons Li_{1-\chi}CoO_2 + \chi Li^+ + \chi e^-$ $\chi Li^+ + \chi e^- + 6C \leftrightharpoons Li_xC_6$
NiCd:	$2NiO(OH) + Cd + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2$

* $M=AB_5$ A=Rare Earth/B=Co, Ni, Mn etc.

10.1 Zn/alkaline batteries

These primary batteries use a zinc anode and manganese in the cathode. They can be pyrometallurgically processed with, for example, Valdi & Inmetco technologies. In these processes, ZnO and FeMn alloys are produced using the contained carbon as a reductant, while the slag can be used as a building material (see Bernardes et al., 2004, and Bertuol et al., 2006) for an overview of the recycling of batteries).

10.2 Rechargeable batteries

Rechargeable batteries are present in numerous EEE. Due to a significant use of "critical" materials in rechargeable batteries, their recycling is of importance. Figure 5 clearly shows that the use of these batteries increases exponentially. A brief overview of the composition of such batteries is given hereafter.

10.2.1 NiCd batteries

With a nickel anode and cadmium cathode, these batteries can be pyrometallurgically processed to recover Cd/CdO (distilled/flue dust) while producing a Fe/Ni alloy/product and a benign slag. Note, however, that this battery type is becoming obsolete, as its use has been banned in various countries.

10.2.2 Li-ion and NiMH

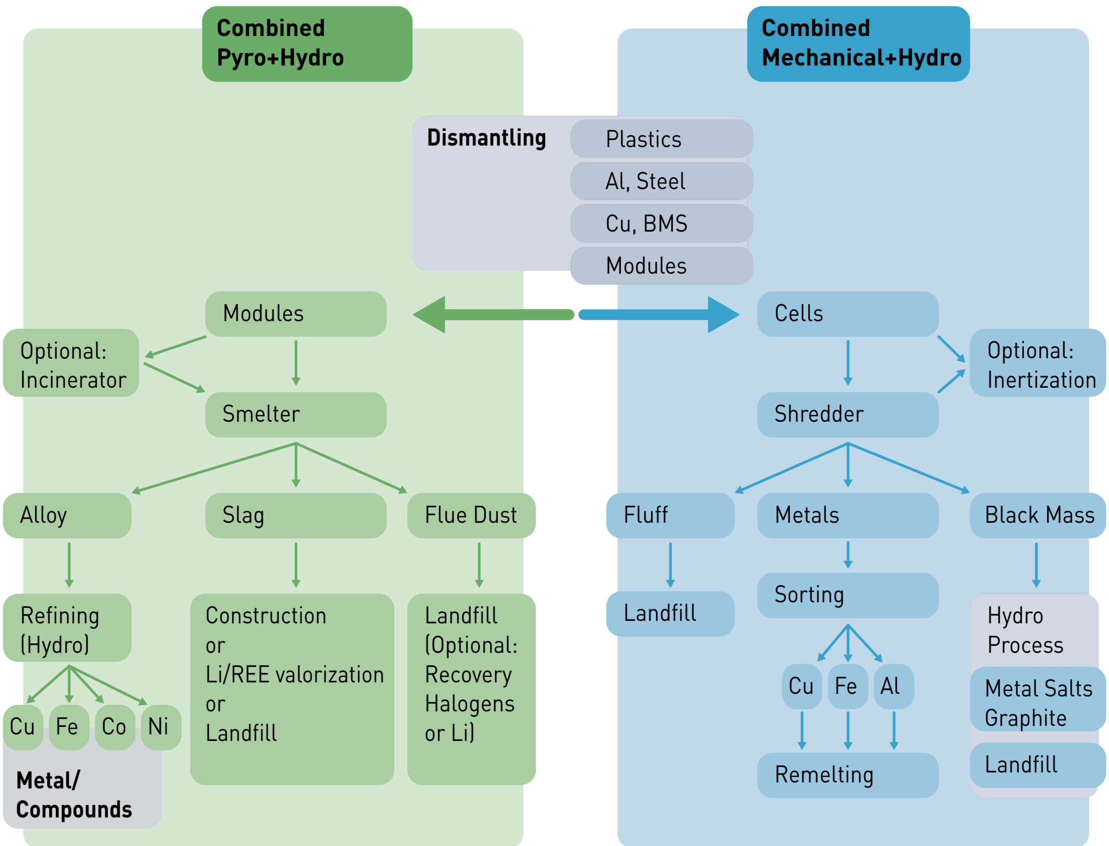
The recycling of these rechargeable battery types is in its infancy, despite their widespread use. Avicenne estimates that for these two rechargeable battery chemistries, 2,000 tonnes were collected in the EU out of a 30,000 t sales volume in 2008, i. e. a low collection rate of about 6.7 %, far below the overall average. With the dominant use of these batteries in consumer electronics, collection in developed countries is further hampered by both legal and illegal exports, and domestic hoarding. From 2011 on, a commercial breakthrough of hybrid electrical vehicles is expected as all major OEMs have announced the launch of at least one commercial model in 2012 or 2013. The growing demand for these rechargeable automotive batteries will spark a need for increased recycling, though in the short term EoL volumes will remain low due to the current low penetration of hybrid and electrical vehicles in the automotive market and the long lifetime of these batteries (> 10 years). Even so, there is still a need to develop a recycling infrastructure for this application as the European ELV-directive requires car producers to have a recycling scheme for new cars within six months after

a vehicle is put on the market, and increasing amounts of production scrap will have to be dealt with. Collection rates for portable batteries are also expected to improve in Europe because of the new WEEE directive, which sets a higher collection target on electrical appliances, as these will largely be collected with the batteries attached.

The recycling chain must begin with safe handling of both small and large Li-ion and NiMH batteries, as remaining charges represent a fire risk from short-circuiting, and, in the case of large batteries, an additional electrocution risk. The two main recycling routes available for Li-ion are a combined mechanical and hydrometallurgical process, and a combined pyro- and hydrometallurgical process (Figure 99). These options are compatible with NiMH compounds, in addition to pyrolysis. In the mechanical-hydrometallurgical process, batteries dismantled to cell size are fed into a shredder to produce three fractions: fluff (plastic and paper), metals (Cu, Al, Fe) and black mass (mostly anode graphite and cathode (Co-, Ni-, Al-, Mn-, Li-oxides) materials). Battery shredding can be dangerous due to risks of explosion, fire and the releasing of hazardous volatile organic compounds (VOCs). Toxco (Canada) applies a cryogenic process to freeze the VOCs, though this is energy-intensive (Toxco, 2003), while Recupyl (France) uses inert gases (CO_2 and Ar) to flush the shredder and prevent fire (IP, 2007). The fractions are then sent to different processes: fluff to landfill, metals to sorting and remelting, and for black mass the graphite is removed by incineration while hydrometallurgy is used to extract the metals as salts.

Figure 99:

Schematic overview of Li-ion battery recycling processes.



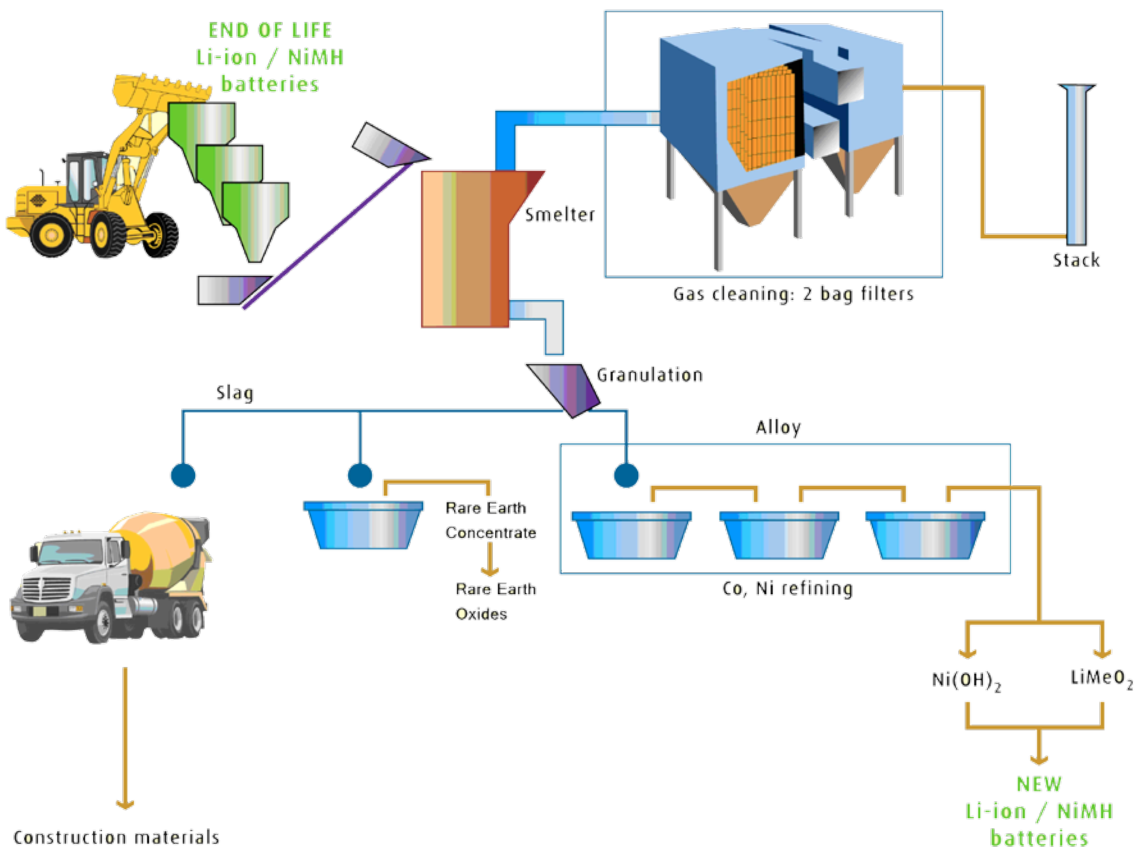
The pyro-hydrometallurgical route is the only process applied on an industrial scale today. In the Umicore Battery Recycling plant in Belgium, this process feeds battery modules directly into an ultra high temperature (UHT) smelter without any pre-treatment (except for the dismantling of large battery cases). Battery production scrap and slag forming agents are added to create three output fractions (Figure 100):

- Metal alloy – Co, Ni, Cu, Fe
- Slag fraction – Al, Li, Mn, REE
- Gas emissions – flue dust (only fraction landfilled)

The batteries themselves fuel the smelter as their combustible compounds heat the smelter to a high enough temperature that, in combination with a scrubbing system, ensure no VOCs or dioxins are emitted. The alloy is further refined in a hydrometallurgical process to produce a variety of Co- and Ni-containing materials for use in new batteries and other applications. Recently, a process was developed to extract a REE concentrate from the slag for further refining by Rhodia (France) to recover these critical elements. The rest of the slag is used in construction material, including Li, whose recovery is currently uneconomic. This process was awarded the BAT for portable and industrial battery recycling by the European Environmental Press, and exceeds the 50 % recycling efficiency standard imposed by the EU Batteries Directive.

Figure 100:

Process flowsheet for Umicore Battery Recycling (2010).



The multiple chemical compounds in Li-ion batteries highlight the need for robustness in the recycling system. Most portable Li-ion batteries use lithium cobalt oxide (LCO) compounds for the cathode, but the share of manganese oxide (LMO) and iron phosphate (LFP) compounds is increasing, particularly in cordless power tools. Anode materials are evolving as well, with C, Si, Sn and Ti compounds expected in the future. Currently, battery labels mention only "Li-ion" and not a specific chemistry. Unless sophisticated labelling and sorting methods are instituted for Li-ion, recyclers will have to cope with this diversity in materials, which will pose a major challenge. Starting the recovery process with a pyrometallurgical step has an advantage in this regard, as it allows more valuable metals to be easily separated into an alloy from those that are less valuable, which are slagged.

10.3 Drivers

Battery recycling is driven by metal value and legislation. The metal value of used rechargeable batteries is significant, driven mainly by Co and Ni, which in 2010 had average prices of $45 and $21 per kg (Metal Bulletin, 2010), respectively. The nickel in one tonne of NiMH batteries represents a value of about $6,000. Even greater value can be extracted from recycled batteries if the battery materials are recovered as compounds instead of breaking them down to elemental state. The continuous evolution of battery compounds, use of manufacturer-specific formulations, and extremely high quality requirements make this approach very difficult, though, unless one-to-one relationships between manufacturers and recyclers are developed. Though critical today for geopolitical reasons, Li and REE will require increased battery collection volumes to leverage scale effects and make their recovery economic. It is important to note from a recycling perspective that REEs are not the same in different applications. Combining REE waste streams to leverage scale effects would not be wise as it would greatly complicate the subsequent refining process.

Legislation encourages battery recycling mainly because of environmental and health risks from hazardous battery materials and concerns over the scarcity of raw materials. The scarcity issue revolves mainly around Co, Li and REE, each of which presents its own challenges. Co is seen as the main metal with scarcity concerns, but at least there is an economic incentive for its recycling, and it can be substituted by Ni and Mn, both of which are less scarce. Li, on the other hand, has no foreseeable substitute and presents geopolitical concerns with 80 % of its world resources based in Chile, Bolivia and Argentina. Though resources are significant, current production is relatively small-scale and increasing it in the short term will be challenging, as it relies on the evaporation of brines by sunlight.

Finally, in the case of REEs there are many competing applications as these unique metals are used in the miniaturization of many technologies. In addition, production today is highly concentrated in China. One response to this is from Toyota Tsusho, which announced its intention to cooperate with Indian Rare Earth Ltd. in 2010 to build a REE recovery plant for processing by-products from uranium and thorium mining in India, reducing Toyota's reliance on Chinese REEs (Toyota Tsusho Corporation, 2010).

The environmental benefits from appropriate battery recycling go beyond the prevention of hazardous material emissions to reducing primary metal production, though the magnitude of this benefit varies depending on the metals contained and processes used. The recycling of batteries that only contain abundant metals (Fe, Mn, etc.) could actually be more damaging than making the batteries from primary metal. In these cases, a critical evaluation from a life cycle perspective is essential for determining if other disposal methods are more favourable than recycling. In areas where battery landfilling is forbidden, such as the EU, downcycling these

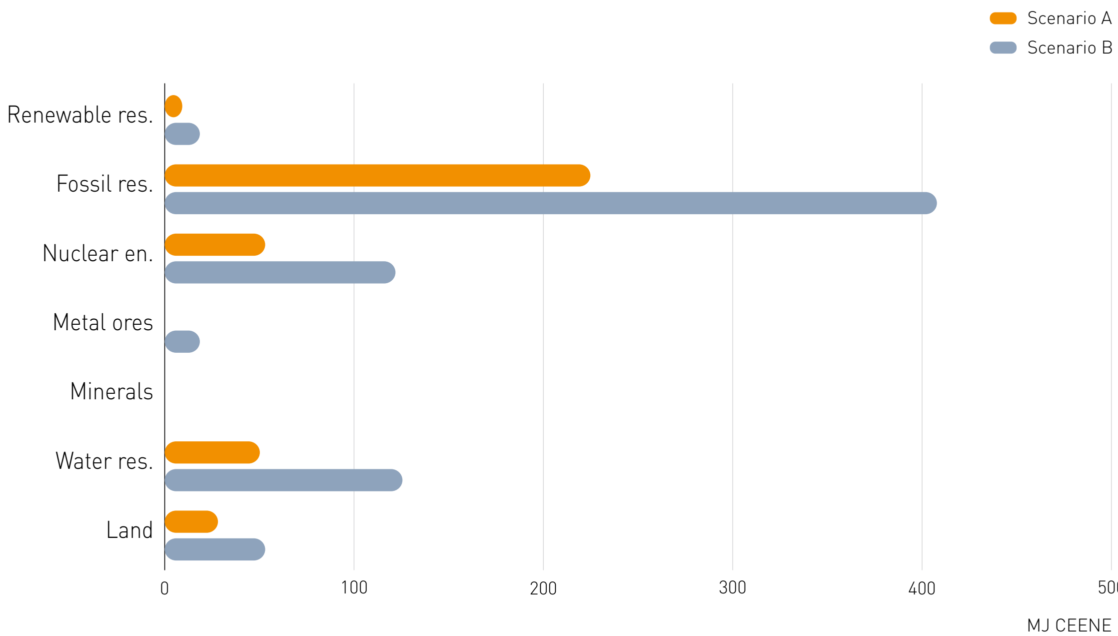
materials to construction slag may be preferable. In general, though, LCA has shown the positive impact of recycling batteries with appropriate technology, including CO_2 reduction benefits from using recycled Co and Ni rather than primary resources. Resource use, quantified as cumulative exergy extracted from the natural environment (CEENE), was shown to be 51 % lower for recycled cathode Co and Ni for a Li-ion battery, than primary material. The exergy savings arise mainly in fossil resources, nuclear energy and water resources (Figure 101). In response to an LCA study, which concluded that an HEV with a NiMH battery has greater acidification potential than a conventional vehicle, it was shown that HEV acidification potential can be largely neutralized if the batteries are efficiently collected and recycled. This is a result of the large benefit from replacing virgin nickel with recycled Ni.

tery recycling. The BD targets a 25 % collection rate by 2012 and a 45 % collection rate by 2016. The 2012 target has not yet been reached in all member states. Other relevant EU legislation includes the WEEE and ELV directives, which encourage battery recycling by targeting the main applications of rechargeable batteries, EEE products and vehicles, by setting collection and recycling targets as well. As the batteries remain in these products at the end-of-life, they are easily removed from the product as long as the product is collected.

In the US and Canada, battery recycling is based on domestic recycling competency. As no environmentally-friendly recycling of Li-ion batteries is available, only low or voluntary targets have been set on the State and Provincial levels. Regulation may become more severe if appropriate technology be-

Figure 101:

Dependency on natural resource categories for recycled (A) and primary material (B) to fill the Co and Ni requirement of a Li-ion cathode (Dewulf and van Langenhove, 2005).



In response to these concerns, the EU has instituted the most advanced battery recycling legislation in the world through the European Batteries Directive (BD). This has clear collection and recycling targets, though as these are for all batteries combined, the already high recycling rates of primary batteries allow some countries to meet the target without significantly increasing secondary bat-

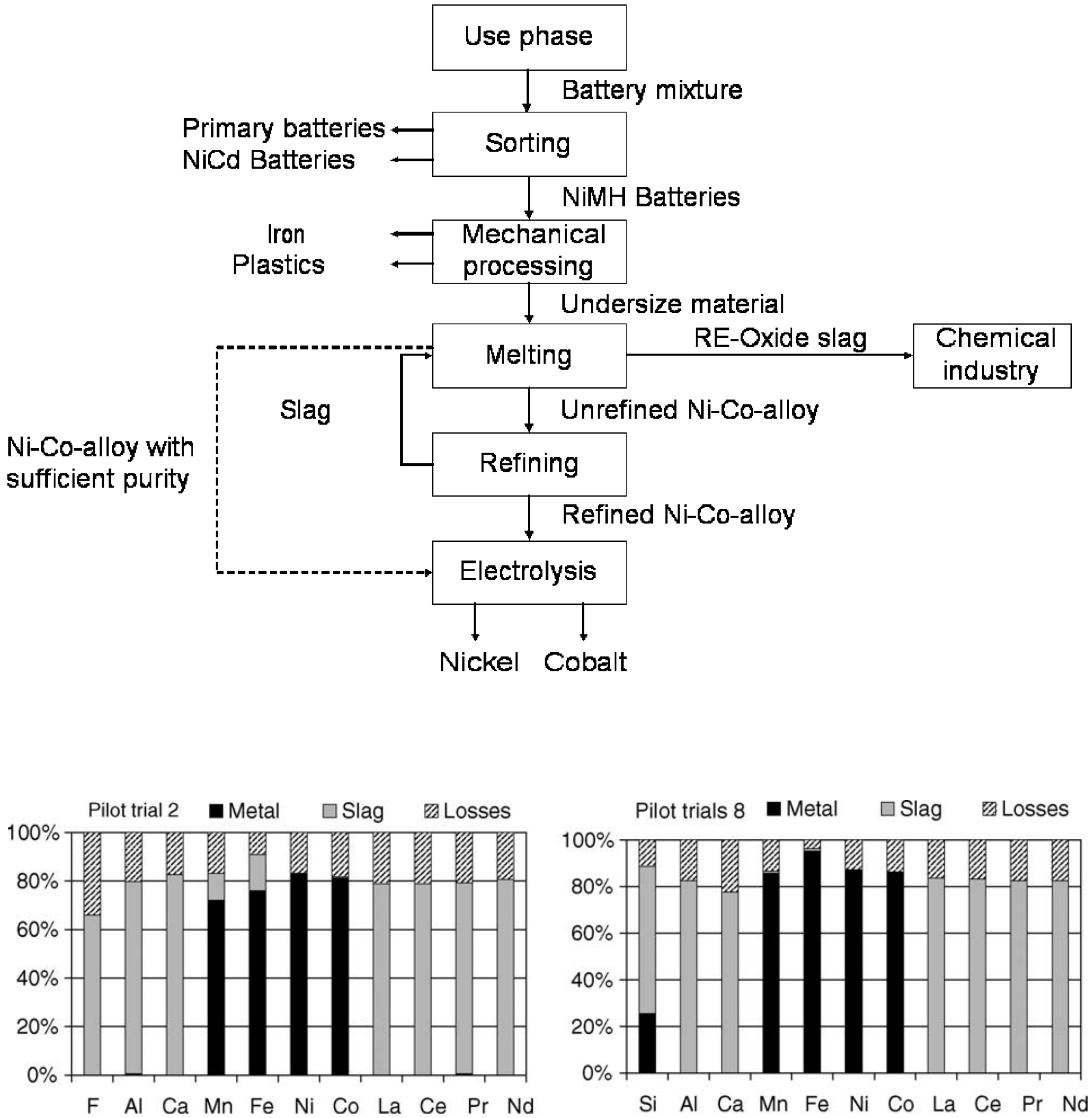
comes available. In addition, Japan regulates the recycling of portable rechargeable batteries and several South American countries have begun regulations on battery recycling. In light of the quickly growing global market for rechargeable batteries, it seems reasonable to expect recycling efforts to be encouraged and even regulated by law worldwide.

10.4 Additional data from academic research into battery recycling

Figure 102 reviews the recycling of NiMH batteries. Umicore and Rhodia recently developed a process for recovering REEs from NiMH batteries (Umicore, 2011; Bertuol et al., 2006; Pietrelli et al., 2002).

Figure 102:

Processing of NiMH batteries (Müller and Friedrich, 2006; Pietrelli et al., 2002).

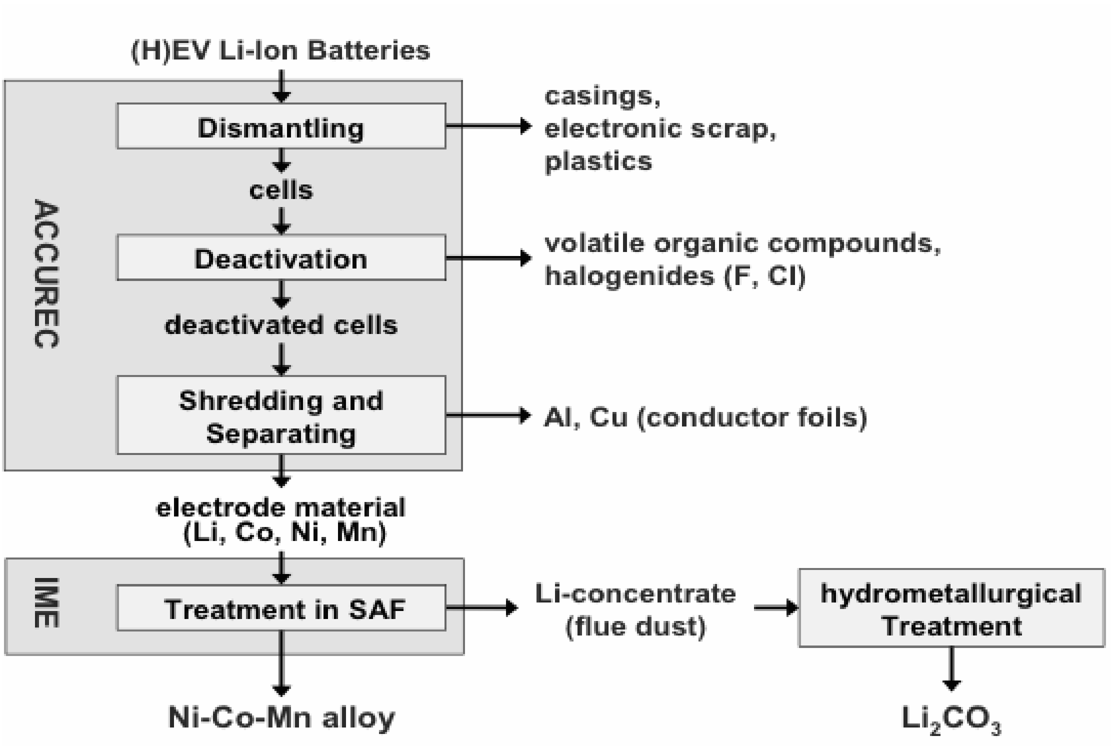


The IME-ACCUREC (RWTH Aachen) recycling concept is illustrated in Figure 103: Li-Ion batteries are disassembled into casings, waste of electronic and electrical equipment (WEEE), plastics and battery cells. Casings, plastics and WEEE are processed in existing recycling infrastructure. The battery cells are deactivated at 500 °C to evaporate organics, to ensure save handling and to remove halogenides such as fluorides and chlorides safely. Afterwards, the battery cells are shredded and separated into a Cu/Al-foil and a fine fraction. The foil fraction is integrated into the existing recycling infrastructure. The fine fraction contains the valuable electrode materials Co, Ni, Mn, and Li of a Li-Ion cell (electrode material, EM). The EM is pyrometallurgically processed to gain the valuable metals in an alloy and to concentrate the lithium in the generated flue dust. Afterwards, the flue dust is treated hydrometallurgically for generating a high quality Li-compound such as Li_2CO_3.

The pyrometallurgical treatment of the batteries is done in a submerged (electric) arc furnace (SAF). SAFs are ideal for battery recycling because of their high flexibility concerning input materials and process parameters, their high productivity for relatively small plant sizes, and their low offgas emissions. The process can be adapted to different input materials simply by choosing an adequate slag composition. Basically, the slag phase controls the process. Depending on the slag's composition, a metal accumulates in the alloy, in the slag phase or in the flue dust. To operate such a process, the slag characteristics basicity, solubility of metals, density, melting point and viscosity at process temperature have to be controlled.

Figure 103:

Flowsheet of the IME-ACCUREC recycling concept.



10.5 Lead batteries

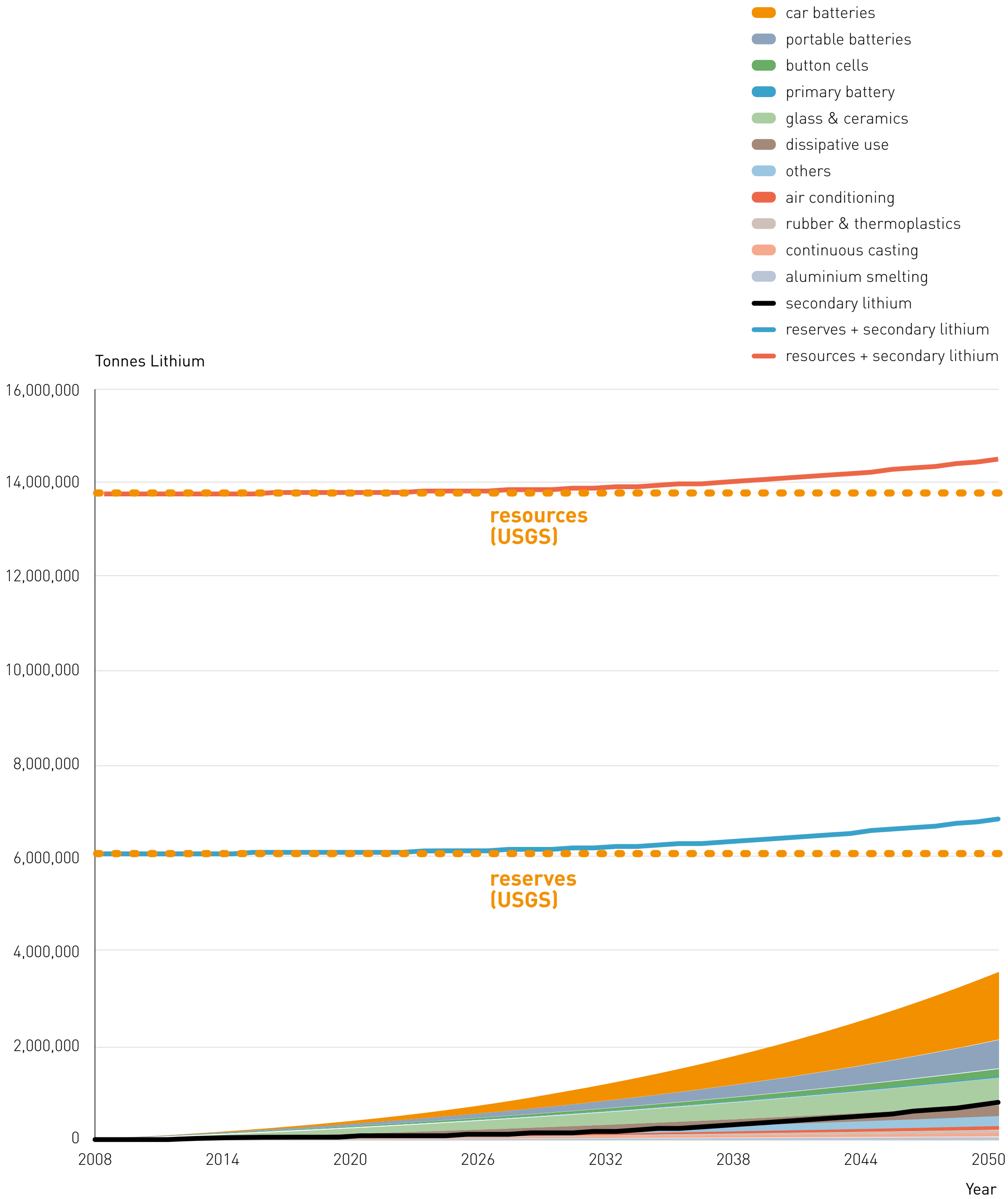
Used predominately for conventional car batteries, such batteries have lead electrodes and a sulphuric acid electrolyte solution. Collection rates are typically high (>90 % in many developed countries, though significantly lower globally) due to lead´s characterization as a hazardous substance and the existence of well-established recycling systems. Processing begins by breaking the batteries open, crushing and mechanically separating them into case materials, metal grids and poles, lead pastes (oxides and sulphate), and the acid, which is collected and reused or disposed. Pastes are then treated to remove sulphur before entering the furnace with the grid metal. Lead metal low in antimony is produced along with antimony metal containing lead from the grid metal. Smelting can occur in rotary furnaces as well as TSL technology (Figure 47), for example, which can produce around 130,000 tpa of recycled lead from a variety of feeds. Finally, the lead is refined to produce soft lead or, most commonly, new battery alloys. If other lead scrap is added during smelting, extra refining may be needed to produce a suitable metal quality.

10.6 Batteries in electric vehicles

The possible increase in the use of electric vehicles poses the question if there are enough resources for these new products. Lithium is an important element in this regard due to the required battery technology. A recent study by Fraunhofer ISI (EU, 2010) shows that if newly registered cars would globally consist of 50 % electric vehicles, only about 20 per cent of the currently known global lithium resources would have been used by 2050 (Figure 104). This scenario considers the use of recycled materials and lithium demand for other applications. Even if market penetration would reach 85 %, the resource would not be depleted by 2050, but the current resources that can be recovered by present technology will have been exhausted. Thus, developing recycling is important in addition to the development of technologies allowing the highest possible recovery of lithium form its natural deposits. Various projects recently started in the EU to address the recycling of lithium-containing batteries for the automotive sector.

Figure 104:

The demand for Lithium for 50 % market penetration of electric vehicles (EU, 2010; Schüler et al., 2011).



10.7 Quantifying materials in EoL batteries

Figure 105 summarizes the use of Ni, REs, Co and Li in batteries in diverse applications in the EU, measured relative to the total production of these metals. It is clear that nickel, REEs, cobalt and lithium are important metals for the future.

The following data are reported for small white and brown goods (Van Schaik, 2011; Wecycle, 2011): 0.0654 % NiCd (dry), 0.0336 % alkaline, 0.0118 % NiMH, 0.0056 % Li-ion en 0.123 % lead batteries (dry) (% of total), which is 26,456 tonnes in 2010 for the Netherlands. This translates to roughly 250 kg REEs/year for collected NiMH batteries in the Netherlands. This is an indicative though rather low number. Figure 105 projects the use of REEs and other metals used in batteries to 2020 from 2010, showing a large increase if vehicle applications increase. Noteworthy is the still rather low REE usage, Ni and Co being dominant. These would be well suited for recycling on the back of the Carrier Metals of Figure 15.

Figure 105: The use of Ni, REs, Co and Li in batteries in the EU and the use of the metals relative to total production (HEV: Hybrid Electric Vehicle; EV: Full Electric Vehicle) (Eurometaux, 2010) – (also EU Critical Metals).

11. Appendix D: Mobile Phone Collection

The efforts of mobile phone company Nokia (Nokia, 2012) to recycle mobile phones provide an example of what can be achieved with collection schemes (Elker 2012).

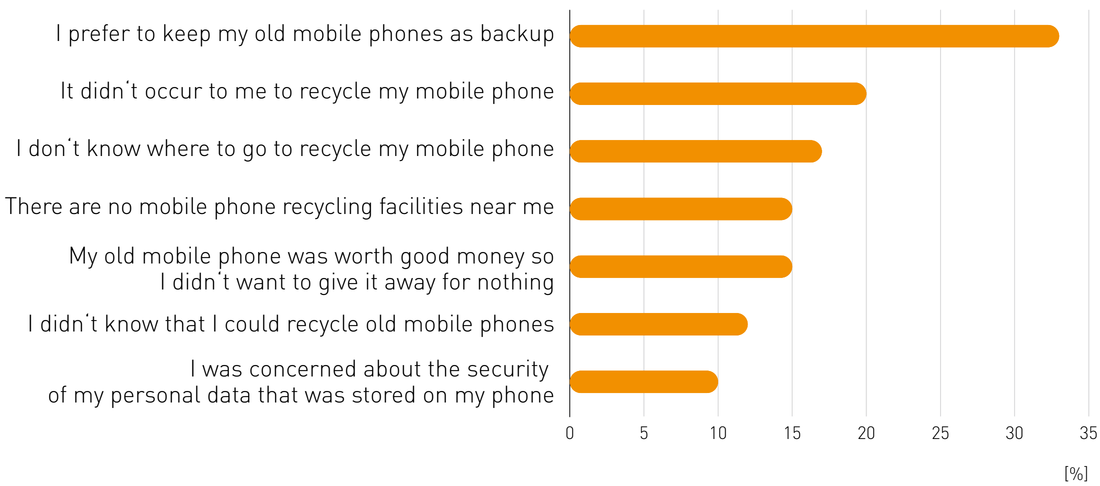
11.1 Mobile phone collection for recycling

Mobile-phone recycling programmes started in the late 1990s in Europe. Today, Nokia offers recycling programmes for mobile phones in almost 100 countries. At the company's own premises, very efficient waste sorting can lead to true closed-loop material circles. When discussing take-back of obsolete phones from consumers, the challenge is different, because of the difficulty in awareness raising of post-consumer waste and the building up of eco efficient collection infrastructures. Financial incentives can be used for initiating recycling behaviour, but their impact decreases when recycling becomes a daily habit. One of the main teachings of past take-back projects has been the use of the right language for communicating the benefits of recycling and finding the right partners, and, most importantly, creating long-term commitment to programmes. Consumers who recycled their old mobile phones increased from 3 % to 9 % between 2007 and 2011. There are differences between developed and developing markets in the access to recycling points and information, but the importance of the topic is becoming globally understood.

A 2011 study commissioned by Nokia found a disparity between the awareness of materials and items that can be recycled and actual recycling behaviour in the studied markets. Finland, Germany and Spain were the biggest recyclers in terms of the range of items that people usually recycle. Of the 11 countries in the study, the United Arab Emirates, Nigeria and Indonesia recycled the smallest range of items. Overall, developed countries were more aware of the range of different materials and items that can be recycled than developing nations, and also tended to recycle more. The barriers to recycling in developing countries were less awareness of what can be recycled and fewer recycling channels; see also Figure 18.

The main barrier for phone recycling is that people like to keep the phones as spare or back-up. Figure 106 shows seven reasons for not recycling a mobile phone.

Figure 106: Reasons for not recycling a mobile phone (Damanhuri, 2012).



Commonly used methods for collecting mobile phones, batteries and accessories are special collection bins for phones, mail-back envelopes and general e-waste collection locations. However, such bins need to be emptied often and finding an effective logistics solution that is economically viable is difficult in rural environments. People also tend to put all kinds of rubbish in the recycling bins, but their advantage is that they are effective in communicating the recycling message.

For a consumer, one of the easiest ways to recycle is to use the mail, which is especially suitable for small items such as mobile phones. Using pre-paid postage envelopes one can drop off the phone in the nearest mailbox and it will be sent to recycling. An example of a recycling envelope is shown in Figure 107. Results from envelope programmes have shown an average of 1.2 handsets per package. This cannot be classified as low environmental impact in terms of logistics, compared to programmes where hundreds or even thousands of handsets can be collected in a single drop-off location. However, mail back programmes offer consumers the easiest method possible. Communal waste collection points can also be used as take-back locations for a wider spectrum of waste, with special containers for mixed e-waste. This is a cost efficient way of collecting waste materials, and easy for people who can drop off different kinds of waste in one location.

11.2 Mobile phone take-back case studies

The first take-back pilot programme for mobile phones was run in Sweden and the UK by member companies of the ECTEL (European Telecommunications and Professional Electronics Industry association) group consisting of six mobile phone manufactures. Since then, there have been many collection initiatives worldwide, aiming at raising the consumer awareness. For Nokia the target is to raise consumer awareness of the recycling options. Campaigns always support the existing infrastructure, ensuring continuity in recycling behaviour.

11.2.1 Digital campaigns

The results of the consumer survey showing that awareness and phone hoarding are the main barriers to recycling has led to development of the Nokia "3 Steps to Recycle" programme. This digital programme gives simple answers on how and where to recycle. As noted above, one of the main reasons not to recycle is an emotional attachment to an old mobile that holds so many memories. To tackle this obstacle, Nokia started a recycling campaign on Twitter, called "I#Recycling". The campaign utilized old iconic Nokia phones such as Cityman, Nokia 3310, Nokia 8810, Nokia 5110 and Nokia 2760 and gave them different personalities. Phones were tweeting about recycling to make it fun and interesting, and gave practical hints on

Figure 107:

Recycling envelope for mobile phone.

where and how to recycle. During the three weeks of the campaign, it reached 170,000 people online in 44 countries and created 2800 Facebook "likes". The campaign was also translated into Chinese and run in Chinese social media channels.

11.2.2 The case Uganda

When Nokia planned the first mobile-phone recycling campaign in Uganda in 2010, many people were sceptical about the success of the campaign. Comments stated that "recycling may work in Western countries, but not in Africa", or "People expect money in return for their old phones, and if you don't give money you won't get any phones back." Even with such comments, there was a belief that with over 11 million mobile subscribers in Uganda, there was a great potential.

The first recycling campaign was arranged in the Uchumi supermarket in Kampala for two days. During those two days 459 old phones, 254 chargers and 239 batteries, in all almost one thousand items, were collected for recycling. Consumers in Uganda see every day the problems created by the illegal dumping of electronic waste in their country, and they are ready to take action. Among the success factors of the campaign were the radio ads that Nokia ran on several stations, encouraging people to recycle, and the distribution of small gifts and the organization of a raffle with a chance to win a new phone. In addition, permanent collection points have been set up at the Nokia repair centres, with recycling bins for people to drop off their unwanted phones and accessories.

11.2.3 Phone recycling in other countries

In Latin American countries, Nokia and other recycling programmes started in 2006 in Mexico, in cooperation with telecom operator Telefonica. Cooperation has expanded to Peru, Brazil, Chile, Columbia, Ecuador and Argentina. Latin American countries have already collected 375 tonnes of e-waste in these programmes, which are good examples of the long-term thinking needed when starting recycling programmes for consumers and how the working concept can be duplicated from one country to another.

Nokia Brazil started a recycling programme by partnering with Pão de Açúcar Group, the largest retailer in the country. With this, Nokia broadens considerably the number of recycling points, which, until then, had focused only on the Nokia service centres. For a limited period, a discount for a new phone is offered for those who recycle their old phone.

Nokia has also raised recycling awareness in cooperation with environmental NGO's in many countries. In Lebanon, it has been working in cooperation with the Association for Forests, Development and Conservation (AFDC) to conduct recycling events in universities. In the United Arab Emirates, there is collaboration with the Emirates Environmental Group (EEG) working with schools and corporations to raise the awareness level about recycling. Posters created by a well-known filmmaker in the UAE help to change children into "Recycling heroes". Nokia India also made two educational books for children in cooperation with TERI (The Energy and Resource Institute), to support awareness raising at schools. In Singapore, as part of Nokia's Environmental Conservation initiative—Recycle A Phone, Adopt A Tree—students from Temasek Polytechnic got a chance to participate in a field trip to WWF re-forestation site Rinjani Forest on Lombok Island, Indonesia, that Nokia is sponsoring. Wild Ocean is a nature film that in the USA has helped Nokia to spread the sustainability message for school groups. A Wild Ocean education campaign was launched utilizing Nokia-branded educator guides and activity posters available for schools.

12. Appendix E: Models and Simulation in Recycling

12.1 Multi-level models

Recycling modules in computer models often are relatively simple, as is still the general case for LCA analysis. Usually, they are based on rather simplistic models of systems and their design, often neglecting detailed physics (Brunner and Rechberger, 2004).

Recycling tools, models and derived guidelines have been developed and applied by Reuter (1999), van Schaik and Reuter (2004a&b, 2010a, 2011) to try and correct this problem, embracing a more Product-Centric view to recycling (Figure 108).

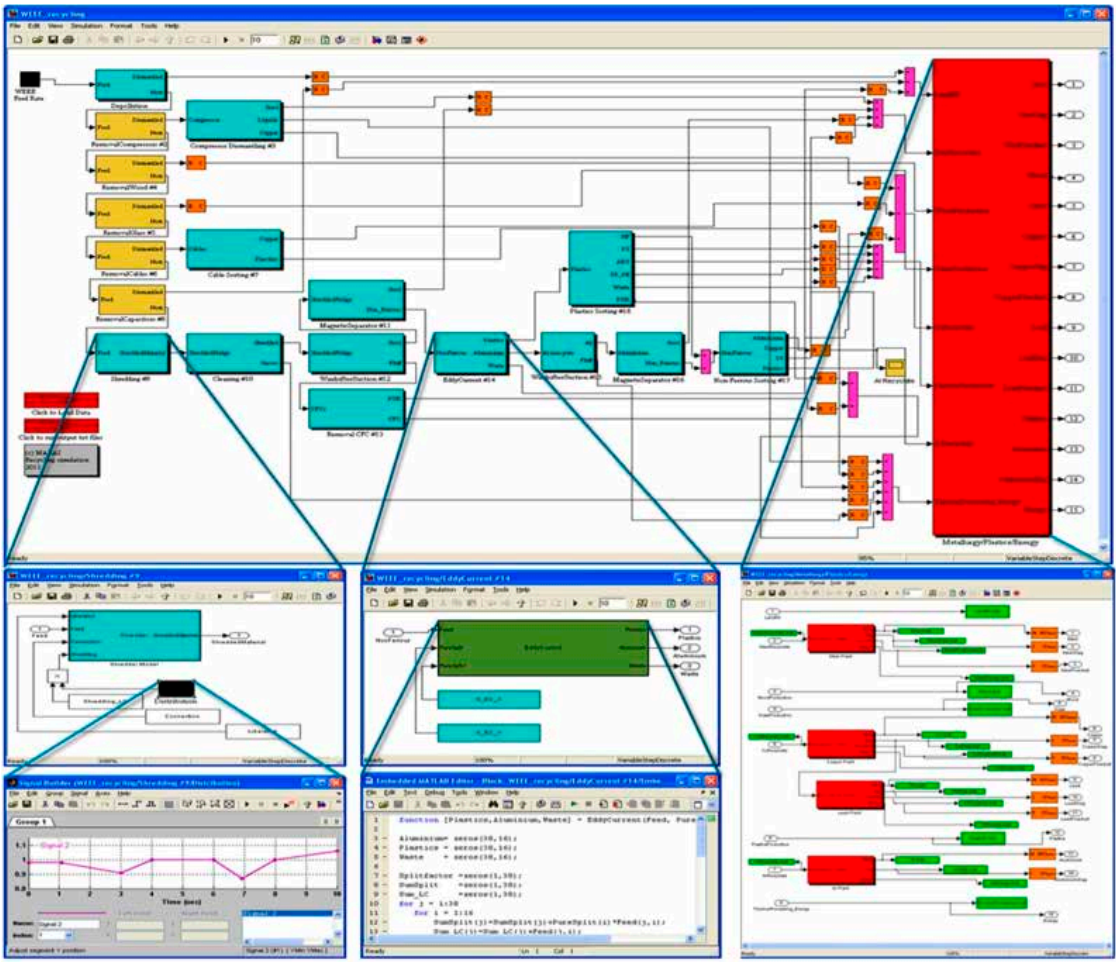


Figure 108: Product-Centric multi-level dynamic process simulation models that predict recyclate quality, grade, and recovery levels linked to product design (Reuter and van Schaik, 2012a&b; van Schaik and Reuter, 2012a&b).

Recent research based on extensive industrial and experimental data (van Schaik and Reuter, 2004a, 2007, 2010a; van Schaik et al., 2004; Reuter et al., 2005; Reuter and van Schaik, 2012a&b) has developed physics-based models that simulate the effect of design on the liberation behaviour and quality of recyclates from complex consumer products. Through this physics-based link between product design and resource efficiency through DfR, they developed dynamic recycling simulation models for cars and e-waste/WEEE. Comminution-breakage laws as a function of material connections and related to particulate characteristics of recyclate flows, are addressed and linked to sorting physics, chemistry and thermodynamics of high-temperature processing and resource recovery from recyclate streams. Since such recycling models are far too complex to be linked to CAD and LCA software, van Schaik and Reuter have developed and applied fuzzy recycling models (van Schaik and Reuter, 2007; Krinke et al., 2009) that capture the detail of the recycling optimization models in a semi-empirical way. These were linked to CAD and LCA software for the automotive industry in the SuperLight Car project (SuperLightCar, 2005-2009; Goede et al., 2008; Krinke et al., 2009; Reuter, 2011a; van Schaik and Reuter, 2007) and were used for calculating the recycling rates of this lightweight multi-material design.

Such models (Reuter et al., 2005; Reuter, 2011a) can predict the recycling performance of different EoL-systems and mixtures of products, recovery of (precious/scarce) materials, and loss of elements for different plant configurations (including dismantling), shredder settings, and future design and recycling trends. They capture the dynamics of product- and plant-input composition and mixture, and predict recycling performance as a function of time. Figure 109 shows the predicted recycling rate for an e-waste product over time, and Figure 110 illustrates the distributed properties of the recycling rate of individual materials in e-waste.

Figure 109:

Dynamic recycling-performance calculations of an e-waste product as a function of time, showing different recycling rates due to distributed properties, such as material liberation, complex interlinked materials in products due to functionality, quality distribution of recyclates, distribution of analyses, range of products and changing designs (van Schaik and Reuter, 2012).

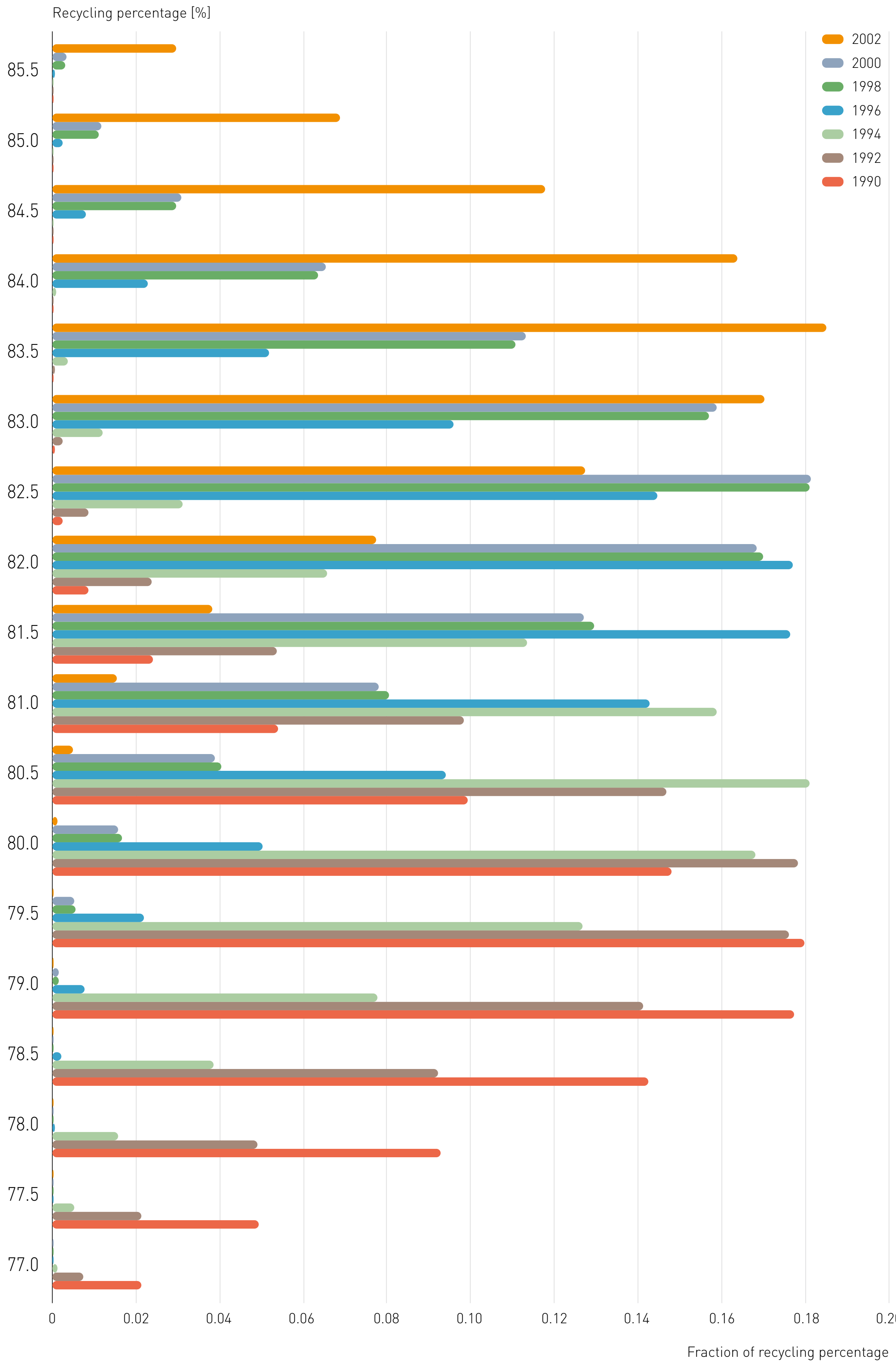
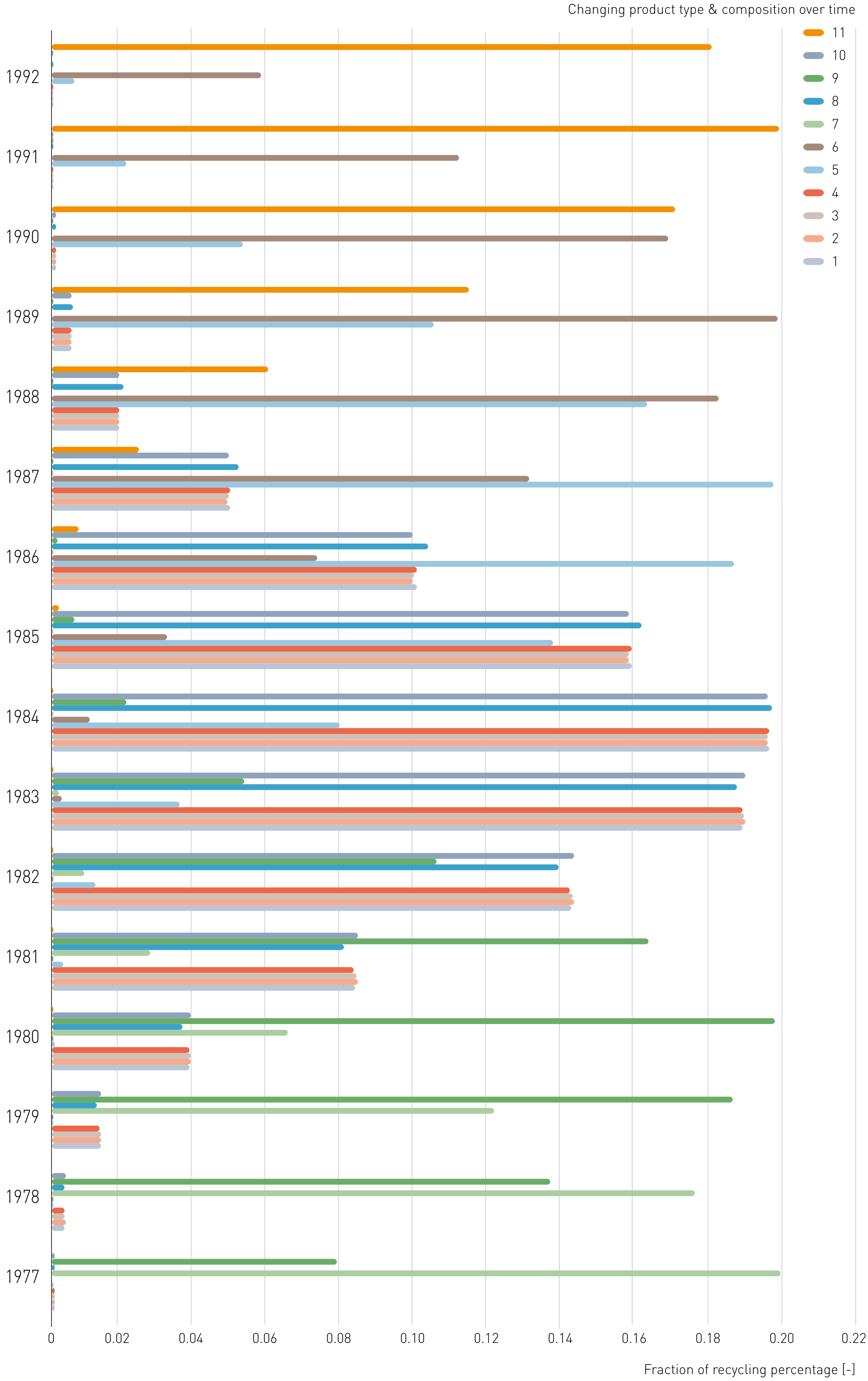


Figure 110:

Dynamic recycling rates per material (total recycling rates given in Figure 109) as a function varying product weights, composition and plant input over time (van Schaik and Reuter, 2012).



An extensive recycling flowsheet (for example for ELVs, see Figure 111) was defined in these models representing the entire recycling system based on a network of processes and material flows. This describes, defines and optimizes the combination of individual recycling processes for material flows originating from multi-material design (see Figure 59). This flowsheet is the basis for investigating different processing routes for a product. Multi-dimensional flowsheets provide a graphical and technological blueprint of recycling system models, to predict and calculate the possibilities and limits of recycling.

rate calculations. Figure 112 shows, as an example, the calculated mass flow (relative to input/output of plant) of selected recycle streams from e-waste recycling. These predictions include a bandwidth of the results as a function of changing processing conditions, input composition (based on changing mixture of plant input), changing product weight, composition, etc. Figure 113 shows the calculated distributed nature of quality, based on the example of a ferrous recycle. This illustrates that the quality and grade of recyclates are not only calculated from its ferrous content, but also include other materials and

Figure 111: Post-shredder technology plant for ELVs as operated by ARN (2013).

The predicted recyclate and recycling-product mass flows by these models, including the presence of contaminants and dispersion of critical and/or toxic materials during recycling, is the basis for the illustrated recycling contaminants in the recyclate streams, due to imperfect separation and liberation. This type of modelling is needed to drive changes and identify recycling possibilities and limits for future situations.

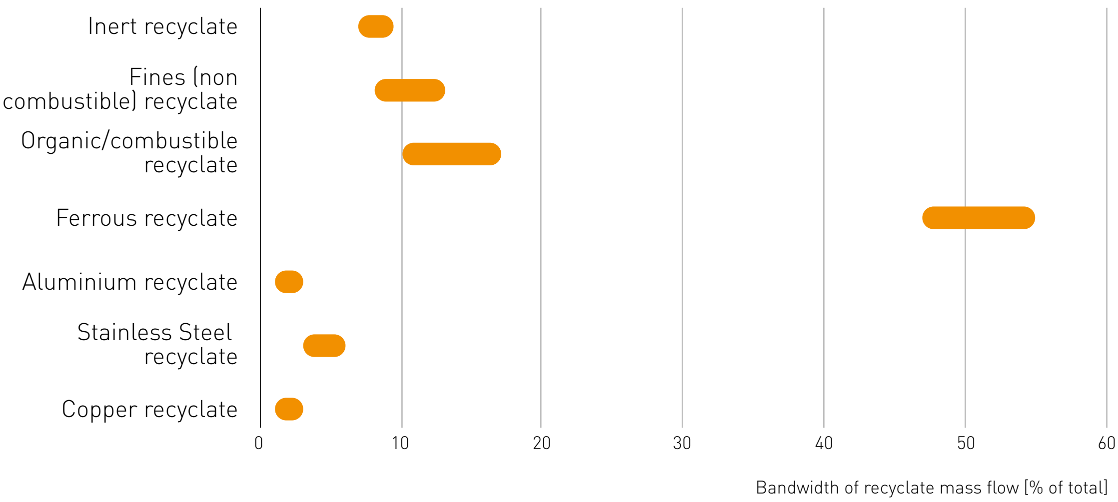
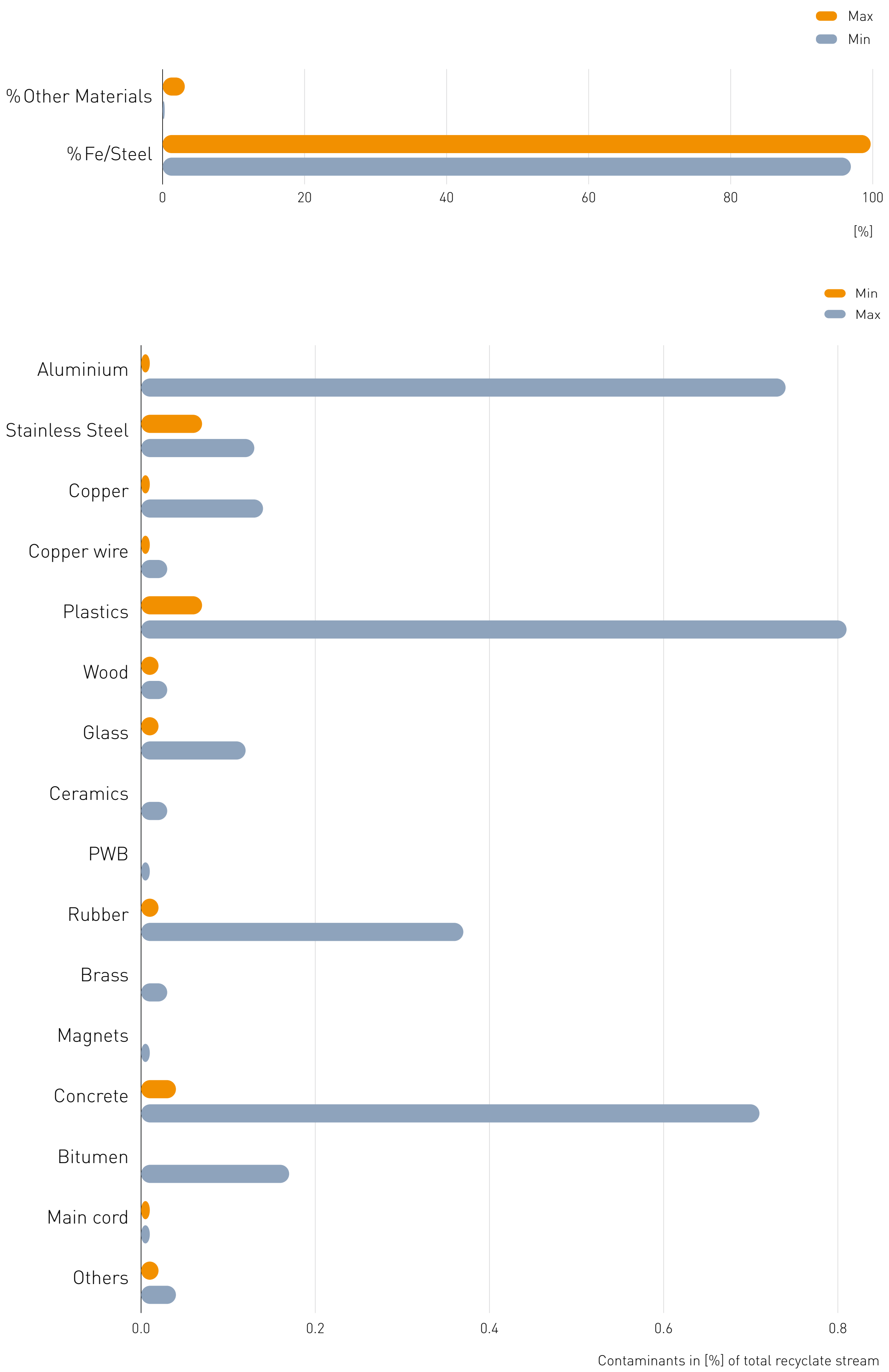


Figure 112: Bandwidth of various produced recyclate streams (van Schaik and Reuter, 2012).

Figure 113:

Quality of ferrous recyclate stream including the quantification and specification of the composition and contamination of the recycelate streams – it is obvious that the 3.1 % copper in the top figure is not good for steel quality (van Schaik and Reuter, 2012).



12.2 Uses of multi-level simulation tools

Engineering- and industry-friendly simulation models define and provide the essential metrics for measuring, controlling and improving recycling, determining recycling concepts, and enhancing product design, thus facilitating high recycling and energy recovery rates while advising policy. While similar models were discussed elsewhere in this document for WEEE recycling, the following example based on ELVs illustrates some of the modelling that has been done to date. The models developed for the EU funded SuperLightCar project managed by Volkswagen AG, provide detailed and physics-based calculations on recycling and recovery of ELVs, and have also been applied for determining optimal recycling concepts (combination and arrangement of processes) for a car body, including the following aspects:

- Product design and liberation.
- Separation physics of automated sorting.
- Chemistry and thermodynamics of metal production and recycling systems.
- Recyclate and recycling product quality (physical and chemical) as a function of product design choices and calorific values of the (intermediate) recycling streams.
- Losses and emissions.
- Optimization and selection of plant and flowsheet architecture with changing product design (Figure 59).

This enables the following industrial applications:

- Calculation and prediction of the dynamically changing recycling and recovery rates of ELVs and light-weight car-design concepts and of all individual materials in these products for different recycling scenarios and objectives (maximum total recycling/recovery, maximum recycling of metals, minimum production of waste, legislative constraints, etc.) as a function of the distributed ELV population over time (see Figure 10); this approach has also been applied to different types of e-waste products;
- Prediction of grade (quality/composition) of all (intermediate) recycling streams (steel, copper, plastic, etc.) and recycling products (metal, matte, speiss, slag, flue dust, off gas) (see Figure 114).

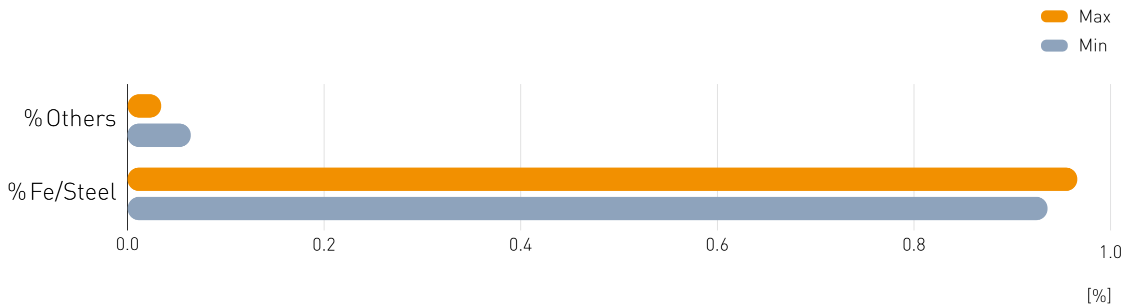


Figure 114:

Quality of (a) ferrous and (b) aluminium recyclate streams, including quantification and specification of the composition/contamination of recyclate streams (c) and (d) respectively for ferrous and aluminium fraction (presented as bandwidths as a function of changes in input, recycling routes, etc.) (Reuter et al., 2005; SuperLightCar, 2005–2009).

Figure 114_b:

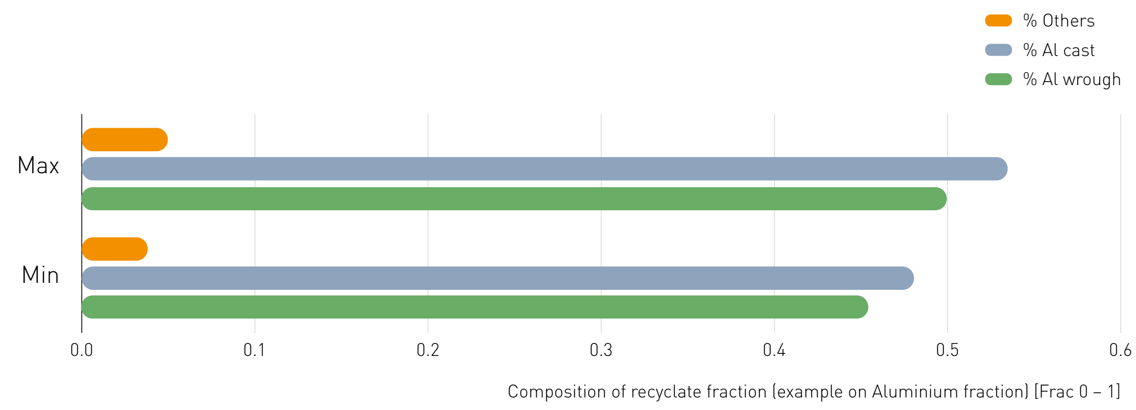


Figure 114_c:

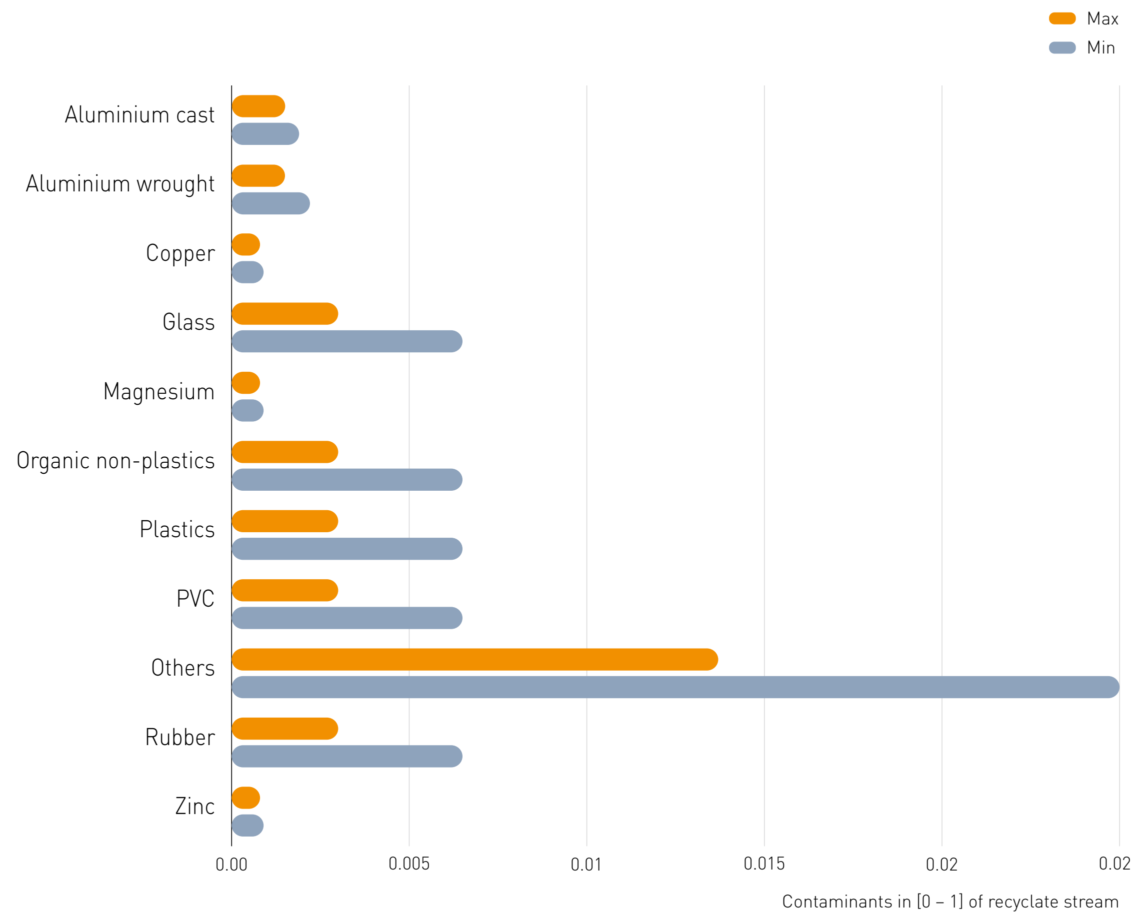
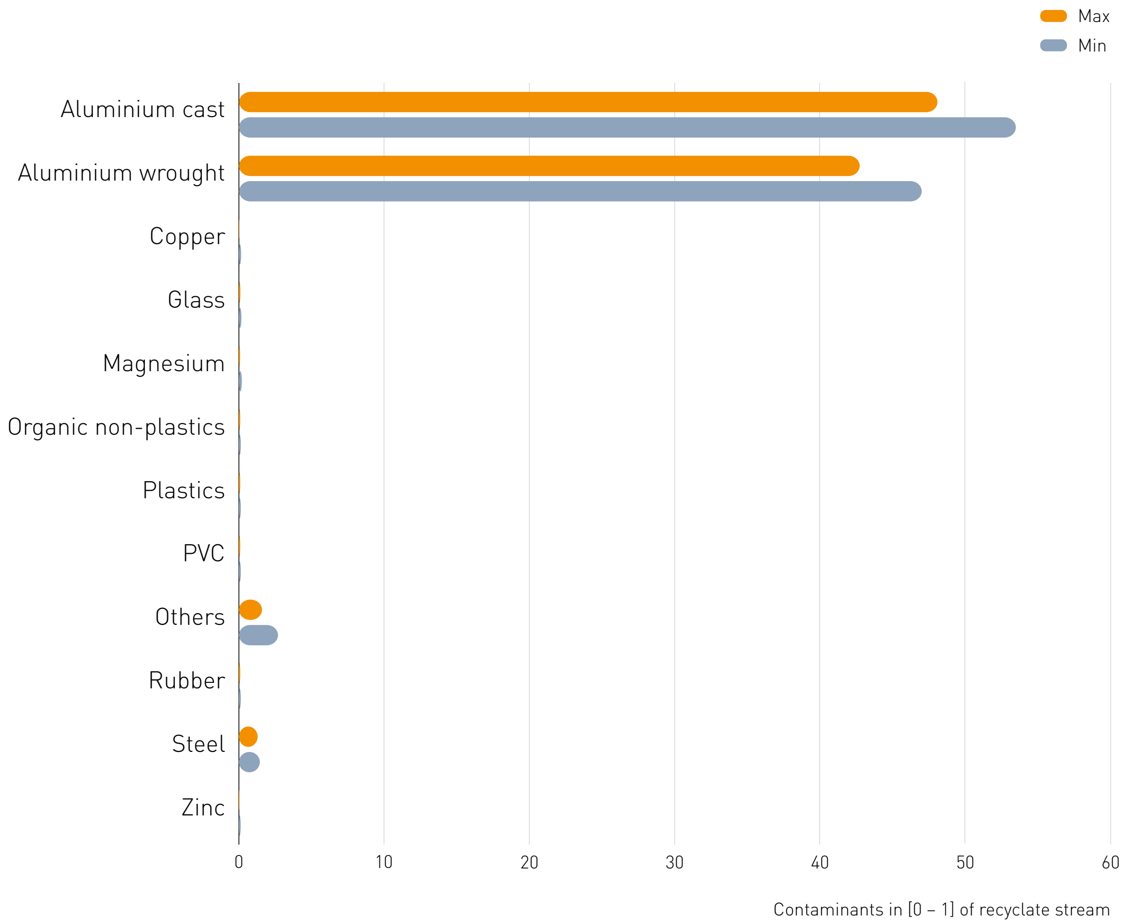


Figure 114_d:



- Prediction of the dispersion, occurrence and appearance (chemical phase) of possible toxic/harmful elements in recycling products.

- Prediction of the limits and possibilities of recycling technology in view of the EU ELV directive.

- Definition of the best recycling concept for multi-material designs such as the SLC concept (recycling plant/flowsheet configuration) for optimal recycling results and/or minimal material losses.

These tools can play a significant role in benchmarking recycling efficiency through quantifying process performance with state-of-the-art environmental-impact software. HSC Sim and GaBi show this connection, a basis for creating benchmark BAT LCI data, complementing the present more averaged data from the industry. It is now even possible to perform exergy analyses of metallurgical and recycling plants directly with simulators such as HSC Sim (Outotec). These exergy data in addition to LCA data provide a basis for running an LCA analysis, using for example GaBi that maps the detailed simulation model in HSC Sim. Hence, all metallurgical-process designs of whichever complexity, on numerous levels, and all based on thermodynamic and reactor technology principles, can be benchmarked. In addition, as all compounds of each stream are known, toxicological detail can be investigated to a detail not possible within a LCA tool.

12.3 Fuzzy set recycling (liberation) models and DfR

Simpler Mass Flow Analysis approaches define separation efficiency only for the different individual materials, which does not reflect industrial reality. In addition, they ignore that recycling streams are a complex combination of materials, which cannot be separated by physical separation and hence drastically affect the quality of the streams. This argument holds even more true for the critical and potentially toxic elements and their compounds that are often present in low concentrations.

Physical and chemical recyclate quality are related and affect each other during recycling. Recyclate quality must be expressed in terms of the chemical composition and based on the particulate properties expressed in terms of physical composition. This enables predicting the quantities and composition of the recycling products.

Box 23:

A theory for modelling recycling systems
Separation efficiency can be described as a function of particle composition in the recycling models as depicted in Figure 115 (Reuter et al., 2005; Reuter, 2011a; van Schaik and Reuter, 2004a; 2010a; 2007; 2010b). This means that separation efficiency calculations of multi-material (unliberated) particles are based on the pure elements in a process, describing the imperfection of separation to achieve recyclate quality and hence recycling performance (Figure 60). The separation efficiencies for multi-material particles are calculated for all physical separation processes and for all multi-material particles (material connection classes) according to a weighted average (see eqs. A and B):

$$R_{i,y}^{l} = \frac{\sum_k R_{i,y}^{k} \cdot F_i^{l,k}}{\sum_k F_i^{l,k}}$$

$$R_{i,x}^{l} = \frac{\sum_k R_{i,x}^{k} \cdot F_i^{l,k}}{\sum_k F_i^{l,k}}$$

where

$R_{i,y}^{l}, R_{i,x}^{l}$	recovery factor (separation efficiency) for particle composition (including liberation) class l for unit operation i to intermediate and recycle output streams y,x, etc.
$R_{i,y}^{k}, R_{i,x}^{k}$	recovery factor of pure material/element k for unit operation i to stream y, x, etc.
$F_i^{l,k}$	input stream composed of materials k in particle composition class l to unit operation i

in which (maintaining closed mass balances for all connected and liberated materials)

$$R_{i,y}^{k} + R_{i,x}^{k} + R_{i,z}^{k} = 1$$

and

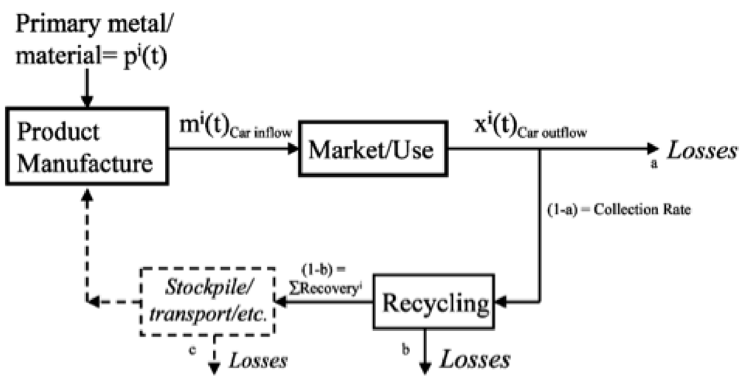
$$R_{i,y}^{l} + R_{i,x}^{l} + R_{i,z}^{l} = 1$$

Box 23_b:

This description and modelling of the efficiency of the physical recycling processes ensures that the actual composition (and thus quality) of each recyclate stream in every stage of the recycling system is captured as a function of design and shredding intensity. This is in turn determined by particle composition and separation physics, and the input to metallurgical treatment processes is predicted based on industrial reality. The imperfection in separation and liberation (as a function of design and dismantling/shredding intensity) directly determines the grade of recyclate streams and the recovery during physical sorting. This also implies that the relation between grade and recovery for complexly connected multi-material products such as WEEE/e-waste and cars as depicted by the grade/recovery curve for physical sorting does not comply with the standard shape as shown in Figure 116. This relationship changes as a function of particulate nature (degree of liberation and amounts of different materials present) of the particles.
The above equations can also be cast into distributions that reflect the distributed nature of data, i. e. complete bulk flow of products as well as the distribution of elements within products. The theory has its roots in classic minerals processing, and the mathematics for product recycling and the derivation of recycling rates was developed by van Schaik and Reuter (2004a&b). Recycling rates as defined on this basis include the standard deviation of analyses and flows, and therefore give an indication of the accuracy of all presented data.

Figure 115:

Dynamic recycling models that include also the convolution integral, and hence permitting the simulation as a function of standard deviation of all analyses and flows of the system for products and mixture of products (van Schaik and Reuter 2004a).



$$\frac{dy^i(t)}{dt} = m^i(t) - x^i(t)$$

where

$$m^i(t) = \int_{t_1=t}^{t+\Delta t}\int_{w_1}^{w_2}\int_{mp_1^i}^{mp_2^i} C(t_1)mp^i\, h^i(w, mp^i, t_1)g(t_1, w)\, d(mp^i)\, dw\, dt_1$$

$$x^i(t) = \int_{t_2=t}^{t+\Delta t}\int_{t_1=0}^{YP}\int_{w_1}^{w_2}\int_{mp_1^i}^{mp_2^i} C(t_1)mp^i\, h^i(w, mp^i, t_1)g(t_1, w)\, f(t_1, t_2) \times d(mp^i)\, dw\, dt_1\, dt_2$$

$$\text{where,} \sum_{i=\text{Al, steel, Cu, plastics, etc.}} \int_{mp_1^i}^{mp_2^i} mp^i\, h^i(w, mp^i, t_1)d(mp^i) = 100$$

In addition to this, analysis exergy (Szargut, 2005) has also been included for evaluating recycling systems, as shown by Amini et al., (2009), Ignatenko et al., 2007, and Meskers et al., (2008).

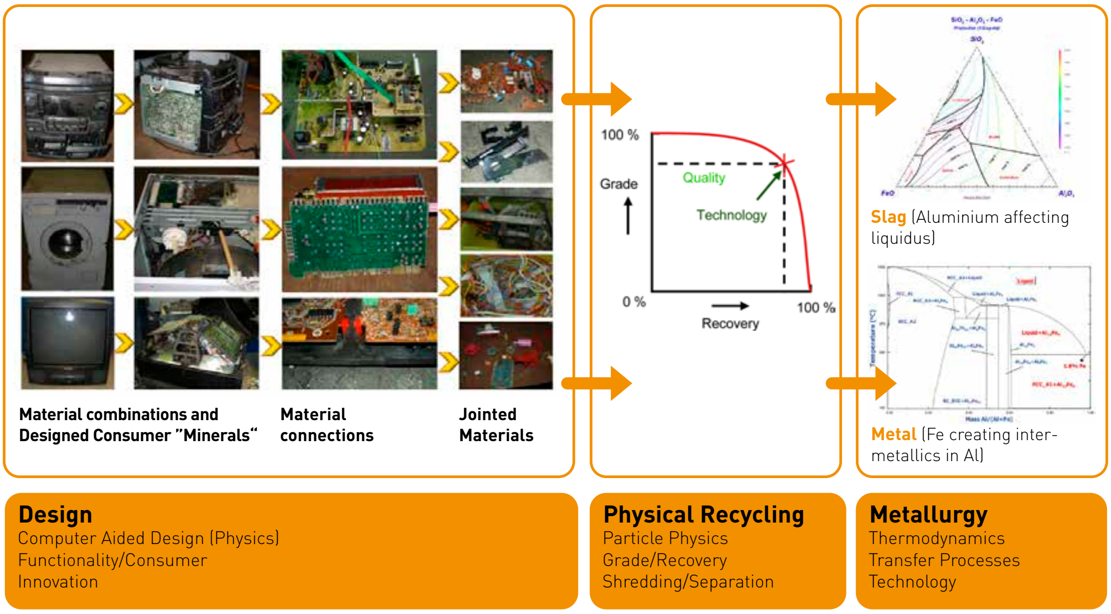


Figure 116: Design for Resource Efficiency Designer Mineral to Metal (The effect of Aluminium in WEEE on Slag and Metal Properties in Smelter). Metal recovery as a function of process technology, thermodynamics and transport processes, here showing the effect of liberated and un-liberated steel on the recycling quality of aluminium and slag (Reuter et al., 2005; Reuter, 2011a). Products with high aluminium content, which oxidizes during processing, have a disruptive effect on processing and hence on resource efficiency as the systems have to be diluted with virgin material to operate them well.

Since the complex recycling system models are far too complex to be linked to CAD and/or LCA software, fuzzy set recycling (liberation) models have been developed, which can hence be applied for DfR and provide real-time design-related recycling calculations (van Schaik and Reuter, 2007). For the complex recycling and liberation process, a fuzzy set modelling approach has been developed with Matlab's Fuzzy Logic Toolbox® (Matlab, 1984-2011), which is based on the knowledge provided by physics-based recycling models. This approach is well suited for creating a link to product design with CAD software. These fuzzy set models were integrated with both CAD and LCA tools within the SLC project to ensure that environmental models are provided with physics-based information on the EoL behaviour of products (Figure 117). Figure 118 illustrates the recycling-rate calculations performed by the fuzzy model for the SLC concept for aluminium as a function of design variations in the BIW concept (different steel and polymer contents).

In addition to LCA data, this physics-based approach provides recycling rates and exergy data based on achieved recyclate quality and therefore design. This information helps original equipment manufacturers (OEMs) in producing sustainable product designs, creating awareness of the costs and benefits of design, products and recycling systems for manufacturers, designers, legislators, recyclers, etc. They also show the (un)feasibility and environmental (in)efficiency of imposed recycling/recovery targets (van Schaik and Reuter (2002; 2004a; 2004b; 2007; 2010a; 2010b; van Schaik and Reuter, 2012; van Schaik, 2011).

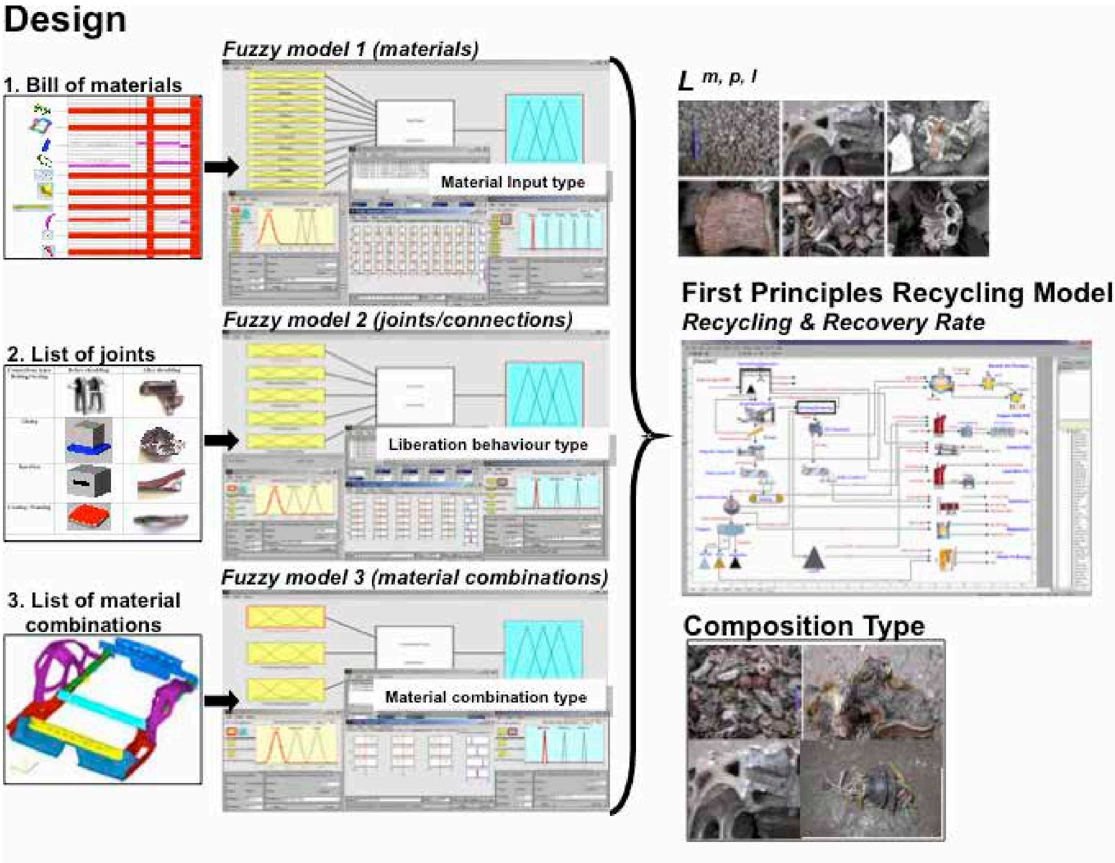


Figure 117:

Overview of the fuzzy rule liberation recycling model, predicting liberation behaviour and hence recycling/recovery rate as a function of design specifications (list of materials, joints and material combinations) (van Schaik and Reuter, 2007).

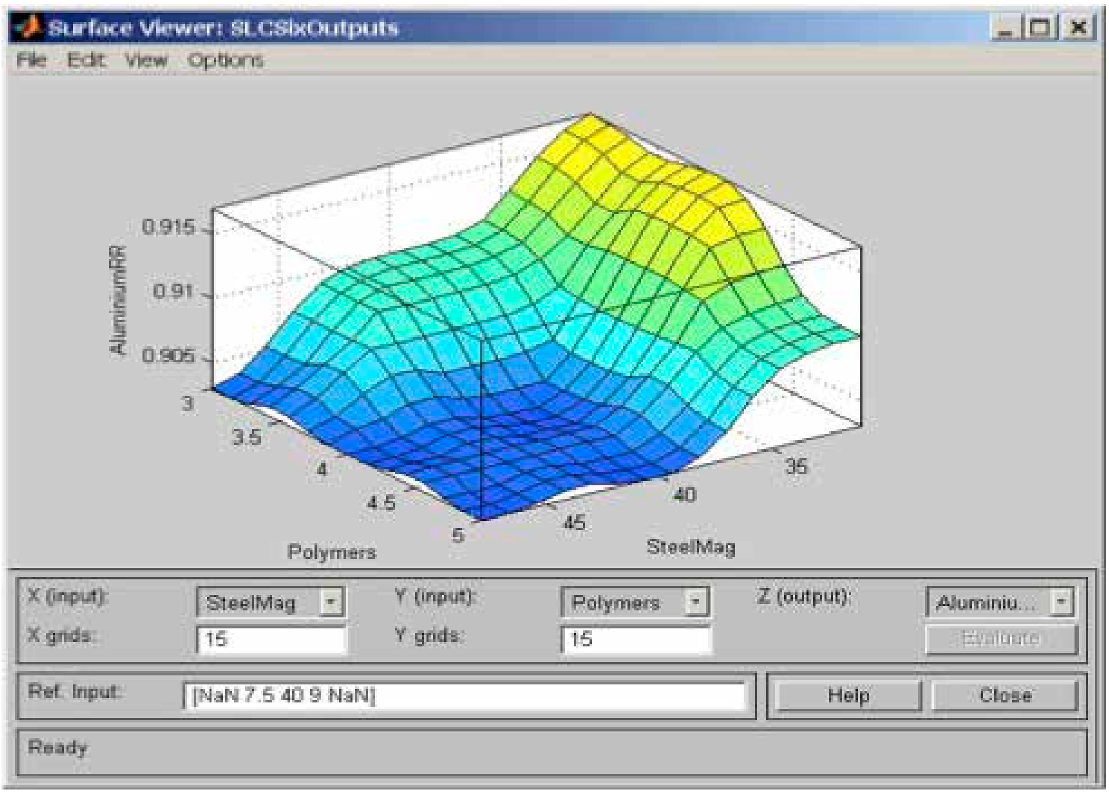


Figure 118:

Example of recycling-rate calculations for the SLC concept in the fuzzy recycling model (illustrated for Al) as a function of variations in design for steel and polymer content. There is no single recycling value as it is a complex function (van Schaik and Reuter, 2007). The figure shows why the simplistic one-dimensional recycling rate definitions used in the IRP's report 2a (UNEP 2011b) only apply to limited cases as they do not consider complexity.

The physical materials in the model are translated not only into its corresponding chemical elements, but also its phases. The physical quality or composition of (intermediate) recycling streams is directly related to the chemical composition of the metal fraction (alloying composition, contamination, oxides, etc.), the inorganic fraction, and the chemical composition and heat content of the organic fractions. This crucial information highlights the effect that design has on recycling efficiency and environmental performance of the system. Figure 117 shows the physics-based link that is created between the physical description (i. e. the material combinations created by the designer and by physical separation) and the chemical description of post-consumer goods bridging the gap between design, physical separation and chemical metal, and material recycling and energy recovery. The recycling flowsheet and recycling models for ELVs include several final-treatment options, including: (i) Steel converting; (ii) Aluminium recycling; (iii) Magnesium recycling; (iv) Metallic zinc recycling; (v) Copper production/recycling; (vi) Thermal processing (e. g. EBARA, Reshment, Thermoselect, CITRON (Ignatenko et al., 2007)); (vii) Incineration; (viii) Plastics processing; and (ix) Landfill. Since recyclate quality does not always meet the requirements for metal production, primary-production processes were included in the assessment of ELV recycling, to determine the amount of primary metals required for diluting or upgrading the produced metal alloys to sufficient quality/alloy composition. This directly affects resource depletion and energy consumption, and therefore is an important parameter for determining the environmental impact of the recycling system. Primary-metal producing processes such as (i) Electrolytic copper production, (ii) Electrolytic zinc production, (iii) Electrolytic magnesium production, (iv) Electrolytic aluminium production, (v) Si production, and (vi) Pig iron production, are considered in the ELV recycling models (see Figure 59).

The separation and recovery in these types of processes into different phases (metal, matte, speiss, slag, flue dust, off gas etc.) are modelled based on process thermodynamics and the chemical content and interaction between different elements/phases in the recyclates obtained from dismantling and/or physical separation. The simulation models for ELV recycling are therefore based on physics-based understanding as well as industrial (also tacit) knowledge of thermodynamics and associated process technology in an appropriate economic environment.

12.4 The importance of relevant data on product design and composition

Without a good understanding of the "mineralogy" of products and the representative data for this, as briefly presented in this section, no physics-based simulation models can be calibrated. Meaningful data must include at least the following for describing and innovating recycling systems on a physics basis:

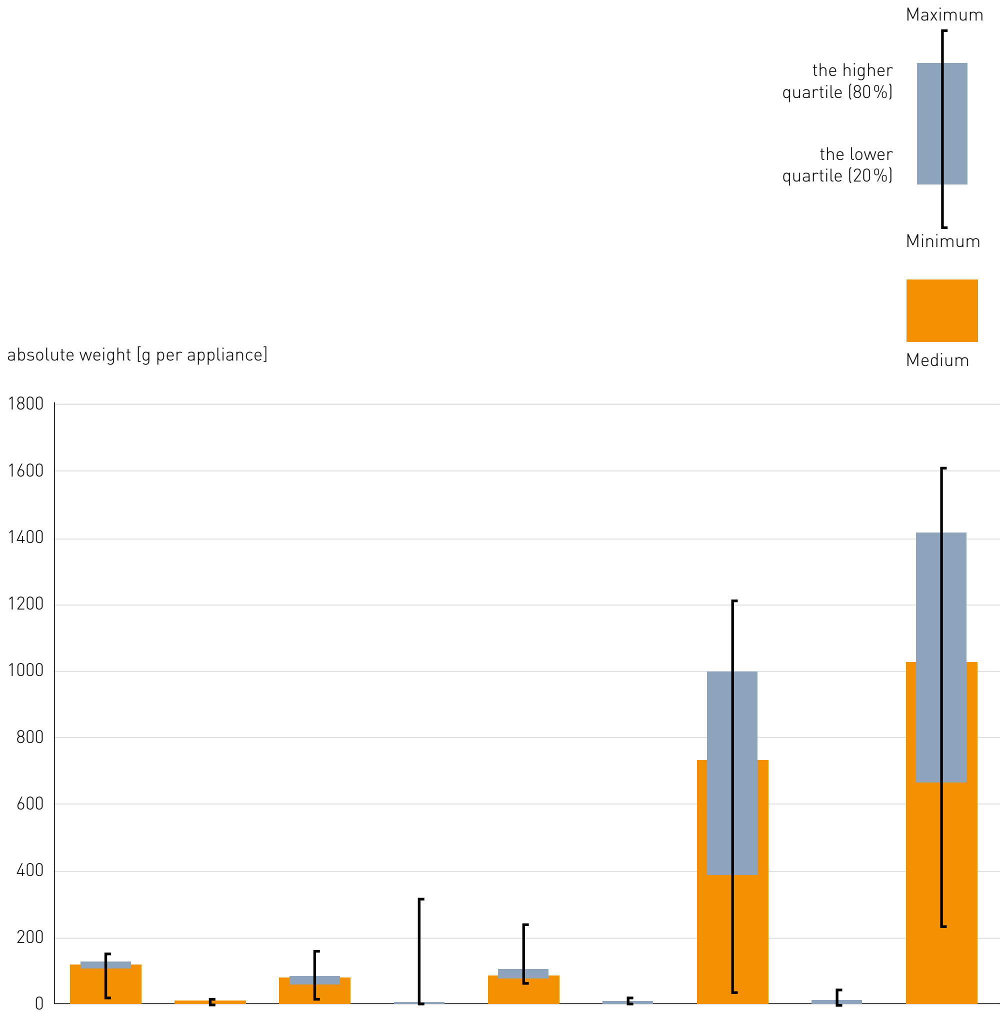
- The total metal-flow rates (usually as required by MFAs) including their average and standard deviation.
- The flow rates of different product types (average and standard deviation).
- The composition of product types in terms of sub-groups as shown in Figure 119, such as metals, alloys and compounds (average and standard deviation).
- The definition of connections/joints from which liberation behaviour can be estimated for the various functional groupings of the equipment.
- The definition of different particle categories.
- Mapping of different data sets in a compound/metal format that is useful for a pyro- or hydro-metallurgical process.

- The morphology of the recyclate as, for instance, aluminium turnings or swarf react differently than an ingot in a furnace when remelting/refining.

Figure 119 (Chancerel et al., 2009; Chancerel and Rotter, 2009a) provides useful data for recycling from which simulation models can be calibrated and used for predicting system performance. The results reflected by these data could be simulated by van Schaik and Reuter (2010a), showing that they have the data detail required for evaluating systems and system physics.

Figure 119:

The importance of good data (for a coffee machine) that are aligned and of value to modelling and simulation of processes, either with reconciled mass-balance data and/or simulation tools (Chancerel et al., 2009; Chancerel and Rotter, 2009a).



	Cable	E-motor	Ferrous Metal	Glass/Ceram-ics	Non-Ferrous Metal	Other	Plastic	Printed circuit board	Total mass
Median [g]	118.0	11.0	73.0	0.0	87.0	0.0	729.0	0.0	1022.0
Arithmetic mean [g]	114.1	10.9	74.2	48.4	100.3	2.3	634.5	3.0	987.7
Standard deviation [g]	46.0	6.1	47.6	125.7	64.0	6.3	427.1	18.2	501.9
Required sample size* n (α=90 %, e=20 %)	12	23	31	510	31	562	34	2731	20

Box 24:

How to build improved models for aluminium recycling – Multi-level simulation

The following discussion relates this use of models specifically to aluminium from complex products, referring to various technologies used for recycling aluminium, its different grades and the issues that can occur. Figure 120 gives an overview of different aluminium recyclates, each with different properties. Describing and optimizing recycling of these diverse aluminium grades and qualities can only be done with multi-level physics-based models.

Figure 120: Aluminium recyclates from EoL vehicles, showing the effect of product/component composition and material connections on the particulate nature and degree of (im)purity of recyclates (Reuter et al., 2005; Reuter and van Schaik, 2008).

It is important to consider a multi-level approach (Figure 108), the available options and the detail they reveal when using different methodologies and hence the results of each:

- **Material-flow approach (MFA):** purely mass oriented, provides some availability information, but does not show the relationship between all the metals in a consumer product, such as an aluminium laptop and the effect of all its other 50+ elements on the ultimate quality of the produced recyclate and alloys.

- **Material-quality consideration approach:** ultimately, this is an alloy and trace element analysis due to strict limitations on alloy classes, applications, etc.

- **Metallurgical limitations of scrap usage:** quality constraint on material uses in subsequent processes, as shown by the technologies shown in Figure 40.

Therefore, to improve the models for aluminium, the following aspects will have to be developed based on available data and theories, moving from a more Material (&Metal)-Centric viewpoint to a Product-Centric view:

- With changing demand and supply patterns of different materials and alloys, material purity will become much more important. The above-cited example of automotive castings will then lead to the question of which other car component or product area can absorb ELV scrap?

Box 24_b:

- Already today, customers require a high recycled content and it could well be that EU legislation will favour the recycled content for green labelling.
- Consequently, we must know how much scrap can be used in closed or open loop systems before the metallurgical limits are reached in terms of castability/formability/physical properties/surface appearance, as well as losses, residues created, etc.
- Dynamic models are required, due to the changing chemical composition of today's scrap and the ongoing development of material specifications (and properties) (Figure 28, Figure 29 and Figure 30).

To move from static MFA models to dynamic models the following limitations and challenges must be considered.

Material flow approach: The present situation is:

- At European level, different recycling efficiency indicators exist for product and material considerations (recycled content vs. end-of-life recycling).
- Metals must overcome the disadvantages of long-life products in MFA calculations caused by the material gap in growing markets.
- Presently, MFA considers material flow as mass flow only and not in a dynamic manner as shown by Figure 60 (van Schaik and Reuter, 2004a).
- The forecast of scrap availability is production oriented and growth determined.
- For recycling quotas and recycled content calculations, only theoretical scrap amounts are used, based on product shipments and static lifetimes.

The issues at present are:

- In MFA models, the "accessibility" of recycled EoL raw materials in terms of collection probability is still missing.
- MFA models already give a good description of the order of magnitude of recycling raw material for stakeholders, but now must aim at the understanding of stocks as dynamic consumer- and application-determined systems.
- Regional and temporal data (lifetime distribution, trade and per capita "consumption" of materials) are needed.
- With such a demand and supply model in place, an extension including CO_2 emissions is possible. Furthermore, scenarios for different targets and the contribution of recycling can be calculated (e. g. long-term scenarios evaluating the contribution of recycling in IEA 2050 targets).

Box 24_c:

Because aluminium applications are relatively simple, the MFA approach works. However, considering a complex tablet type application packaged in aluminium and containing 50+ elements, some of the above statements could be problematic as these elements, plastics, etc. may affect produced alloys and losses as shown in section 3.4.1.3.

Material quality consideration: The detailed recycling models discussed in this document, describing scrap and particle types, liberated or not and connected to various metals, brings us to **quality**, the key point that recycling models (van Schaik and Reuter, 2004a; 2004b; 2007; 2010a; 2010b; van Schaik and Reuter, 2012; van Schaik, 2011) must describe. If scrap flows are known in terms of collection, defined recycling loops and their amount, the next criterion is material quality. Consider:

- First an evaluation is needed of the condition in which the individual part/material/alloy/element is present (e.g. gallium in PV cells or 6063 aluminium profiles in ELV shredder fractions; see section 3.4.2).
- Secondly, the "metallurgical accessibility" at element or alloy level must define the need for thermal or mechanical upgrading or sorting processes and, if possible, for metal refining (see section 3.4.2).
- The achievable purity before the melting step determines the recyclability or scrap value for the target application, if no later refining is possible (see section 3.4.1.3).
- A long-term goal is to develop a "quality constraint material availability model", based on dynamic stock modelling with the understanding of alloy qualities and limited refining possibilities (see Figure 59 and Figure 60).
- The aim is to discover element accumulation trends in life cycles (alloying and trace elements; see section 5.4.5).
- With the quality extension of the pure demand and supply model application, specific scenarios can be calculated: e.g. will casting alloys in car applications remain available as a sink for high alloyed scrap if alternative drive concepts require fewer and smaller engines?

12.5 Details of life-cycle assessment

12.5.1 General aspects (UNEP, 2011c)

According to standards 14040 and 14044 of the International Organization for Standardization (ISO, 2006a, 2006b), four phases are distinguished within an LCA study (see Figure 121):

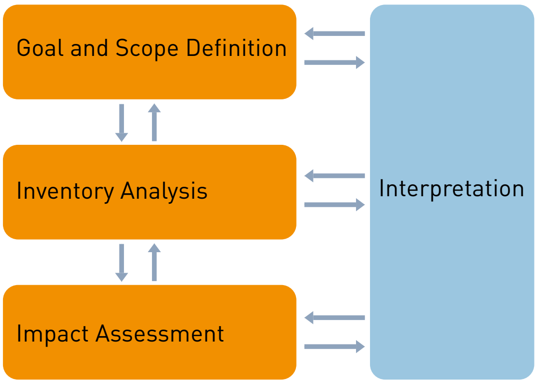


Figure 121:

The LCA framework according to the ISO 14040/14044 series (ISO, 2006a).

- Goal and scope definition: The scope, including system boundaries and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and breadth of LCA can differ considerably, depending upon the goal of a particular LCA (ISO 2006b).

- Life-cycle inventory analysis (LCI) is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied. It involves the collection of data necessary to meet the goals of the defined study (ISO 2006b).

- Life-cycle impact assessment (LCIA) is the third phase of the LCA. Its purpose is to provide additional data for assessing a system's inventory results, to better understand and evaluate the magnitude and significance of potential environmental impact related to the LCI data (ISO 2006a, 2006b).

- Interpretation is the final phase of the LCA. Here, the findings of either the inventory analysis or the impact assessment, or both, are evaluated in terms of the defined goal and scope, in order to reach conclusions and recommendations (ISO 2006b).

LCA is a relative and iterative approach, based on transparency and comprehensiveness. Relative, as an LCA is always structured around a functional unit that defines what is examined, all further activities then taking place are relative to this functional unit. Iterative, because, as shown in Figure 121, each step uses the results of the other steps. Which, by passing several times across the various steps, results in comprehensiveness. As almost all product life cycles include processes that occur worldwide, a high-quality global environmental inventory database is mandatory to ensure sound and credible results of LCA studies.

In relation to the topic of this report, i. e. the recycling of various metals, the goal and scope of the respective LCA studies is either the examination of the impact of producing a specific amount (e. g. 1 kg) of (recycled) metals, or the total impact of the various treatment options for a specific amount of waste input. When not only the production, but also a complete life cycle of a metal for a specific use context is considered, the goal and scope step ensures that all functionalities of the metal for this context are taken into account and adequately covered, by choosing a suitable functional unit and the system boundaries.

12.5.2 Life-cycle inventory (LCI)

As mentioned above, this is the second phase of LCA, resulting in an inventory of input/output data with regard to the system being studied. Input data are energy and material amounts consumed in the various process steps, from extraction of the metal-containing ore, through the various beneficiation and concentration steps, up to the final supply of one unit (e. g. one kg) of a metal to the global metal market. On the output side, the amount of emissions to air, water and soil, the amount of waste water and waste, is recorded as detailed as possible for the same process steps as the above mentioned input data.

In analogy to primary production, recycling production of metals from scrap (often a complex mixture of metallic compounds, such as e-waste), leads to the joint production of different metals. Hence, allocation issues play an important role (Stamp et al., 2011). Dubreuil et al. (2010) reported that representatives from ferrous and non-ferrous metal groups agreed on a "consensus-mapping presentation of a general allocation approach and the identification of harmonized metrics". The developed approach distinguishes between four different cases called "recycling map models", each of them representing a typical life cycle of a metal. A table in Dubreuil et al. (2010) gives some examples for each of the four types (see Table 46).

Table 46: Table with metal-recycling-loop examples (Dubreuil et al.,2010).

Type 1 Closed metal loop	**Type 2** Alloy loop	**Type 3** Transfer to another metal pool	**Type 4** Metallurgical re-separation
Steel scrap is recycled by a minimill where it is remelted and formed into semi-products.	Stainless steel alloys are retained in a distinct metal pool. Constituents include iron, chromium, nickel and other elements.	Nickel in low-alloy steel is recycled into the steel loop, where it is retained in dilute fractions in the steel pool.	Gold and platinum group metals are retained in copper-rich metallic fractions during electronic equipment recycling. At the copper smelter, these other metals are separated and refined.
Steel scrap is recycled by an integrated mill where the recycled metal is blended with primary metal coming from the blast furnace into the basic oxygen furnace.	Aluminum-magnesium alloy used for beverage cans is recycled as a distinct pool. The purity and properties of the alloy are managed and preserved.	Chromium coating on steel is recycled into the steel loop, where it is retained in dilute fractions in the steel pool.	Zinc used for galvanizing follows the steel onto which it is coated. During steel recycling, zinc is separated to Electric Arc Furnace dust, which is treated to remove cadmium. Zinc is then recovered in an Imperial Smelting Furnace.
Copper in applications where it is nearly pure is recycled back to semi-fabricators, where it is remelted and reformed into semi-products.	Brass is a copper-zinc alloy that is collected and recycled to retain alloy properties.	Due to inefficiencies in physical separation, copper particles are entrained with the steel recycling flow. Once melted, copper cannot be removed economically from the steel.	

So far, however, there are no generally accepted, accurate allocation factors available for an application of these four above described types and, as mentioned in Dubreuil et al. (2010), "important work needs to be done" to achieve this. Despite this shortcoming, several LCA and/or LCI studies on metals exist and are published, using their own, specific allocation factors.

12.5.3 Life-cycle impact assessment (LCIA)

In the Life Cycle Impact Assessment (LCIA) phase, the third step of the ISO framework, the emissions and resource data collected in the preceding LCI step are translated into indicators that represent environmental and health impacts as well as resource scarcity. This is based on factors that represent the impact per unit emission or resource consumption. These factors are generally calculated with models (EU, 2010), but over the past two to three decades a broad variety of such LCIA factors has been developed and published. An overview of this can be found e.g. in the 'Ecoinvent' database, which is not yet complete, as its developers want to publish a clear guidance on the use of LCIA factors and methods in combination with data from their database, but without actively developing LCIA methods (Hischier et al., 2010).

As part of the International Reference Life-Cycle Data System (ILCD) handbook – a series of technical documents providing detailed guidance on all steps required for a Life-Cycle Assessment (LCA) – the European Commission's Joint Research Centre (EC-JRC) started a public consultation on recommended methods for Life-Cycle Impact Assessment after a thorough analysis of the existing approaches in 2010 (European Commission, 2010a; 2010b; 2010c). The report with recommended LCIA factors was distributed in the LCA community and a workshop was held in Brussels in October 2010; a draft of this report is available on the Internet, but may not be cited.

In relation to the recycling of metals, important indicators are available among the huge amount of LCIA indicators in a variety of LCIA methods (for a recent overview see e.g. European Commission, 2010a) According to the above-mentioned draft report on recommended LCIA factors, the following modelling approaches are recommended for such single-impact assessment factors:

- **Resource Depletion:** For this topic, the draft report recommends using the 2004 update of the factors for the depletion of abiotic resources reported in the EDIP 97 LCIA method (Hauschild and Wenzel, 1998; Hauschild and Potting, 2005). This model considers fossil fuels and minerals, and introduces the "person-reserve", meaning the quantity of resource available to an average world citizen. For calculation of the characterization factors, the amount extracted is divided by the global production of the reference year (2004) and weighted according to the economically viable reserves of this material.

- **Global Warming Potential (GWP):** For this, it is recommended to use the "default" 100-year baseline model for greenhouse gases according to the IPCC report (IPCC, 2007). The IPCC factor is used in all LCIA methods that consider GWP, though not all methods use the latest version of the IPCC report. Among the three perspectives (20, 100 and 500 years), the 100-year baseline is commonly used; this is also the time horizon used for the Kyoto protocol or further policy work in the area of climate change.

- **Acidification Potential (AP):** For this, the EC draft report recommends the so-called "Accumulated Exceedance" by Seppälä and co-workers. This method not only considers the dispersion of an emission in the atmosphere, but also the sensitivity of the ecosystem receiving the (additional) deposition due to this emission (Seppälä et al., 2006), and calculates European country-dependent characterization factors. The atmospheric transport and deposition model to land areas and major lakes/rivers is determined with the EMEP model, a detailed model for long-range transport of air pollutants in Europe, combined with a European critical-load database for sulphur and nitrogen deposition in Europe. However, few LCA software tools have as yet integrated this approach for practical application.

- **Ecotoxicity Potential (ETP):** For ETP, the recent common international framework for toxicity categories (Rosenbaum et al., 2008) was used. This approach results from a consensus-building effort among related modellers and the underlying principles reflect the agreed recommendations from these experts. The model accounts for all-important parameters in the impact pathway as identified by a systematic model comparison within the consensus process. It addresses the freshwater part of the environment problem and includes the vital model elements in a scientifically up-to-date way. USEtox has also been set up to model a global default continent. USEtox distinguishes between interim and recommended characterization factors, qualitatively reflecting the level of expected reliability of the calculations. Ecotoxicological characterization factors for 'metals', 'dissociating substances' and 'amphiphilics' (detergents) are all classified as interim in USEtox (Rosenbaum et al. 2008).

In case of Cumulative Energy Demand (CER), the European Commission does not recommend any factor, but indirectly recommends dealing with these resources as with mineral/metal resources. In any case, the consumption of fossil fuels is also part of the above-described ARD factor for resource depletion. However, CER analysis has a rather long tradition; and the indicator was created, as reported e.g. in Hischier et al. (2010), in the early 1970s after the first oil-price crisis (Pimentel, 1973; Boustead and Hancock, 1979). At the same time, CED is widely used as a screening indicator for environmental impact (Hischier et al., 2010). Here, we use the definition of CED from the Ecoinvent database, based on the respective document from the German Industry Association (VDI). However, in contrast to the Ecoinvent database that shows the various factors of CED in a non-aggregated form; we have aggregated all these values into a single number, the "Total Cumulative Energy Demand". More details about this issue can be found in Hischier et al. (2010).

12.5.4 Life-cycle impact assessment of larger or complete systems

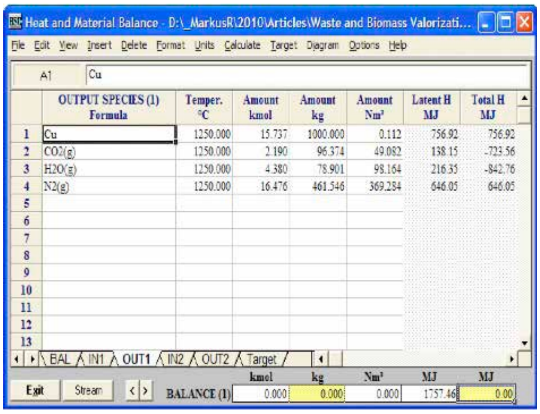
True resource efficiency can only be achieved if all the complex non-linear interactions are considered and optimized simultaneously. Of great importance is the linking of metals, materials, water and energy in such assessment, to truly improve society's resource efficiency. By linking all aspects into a bigger flowsheet and using BAT to create the baseline (Figure 6 – left) and then link it to an environmental assessment tool (Figure 6 – right) can help much in determining the true limits of resource efficiency.

13. Appendix F: Physics of Extractive Metallurgy

We briefly discuss some theoretical aspects of extractive metallurgy in this section, as this knowledge is required for defining legislation and maximizing resource efficiency on a physics basis. The Metal Wheel (Figure 15) succinctly captures the many steps of metallurgy that are defined by the thermodynamics briefly discussed hereafter.

13.1 Energy balance of recycling – Possible energy reductions

The remelting of pure scrap, e. g. copper coils, is only possible if it has been very well sorted. For this case, the theoretical amount of energy required to remelt pure (100 % Cu) coils into copper would be 756.9 MJ/t Cu at a remelting temperature of 1250 °C (Figure 122), a necessary processing step to render it suitable for further processing into high-grade products. However, if impurities enter with the scrap, such as shown on the bottom part of Figure 122, this minimum remelting energy rapidly increases. The maximum improvement that can be achieved by design, which has a direct impact on the achievable scrap quality, separation technology and metallurgy, would be (1493.8 – 756.9) MJ/t. In general, the closer the energy required for remelting any scrap is to the theoretical baseline, the better.



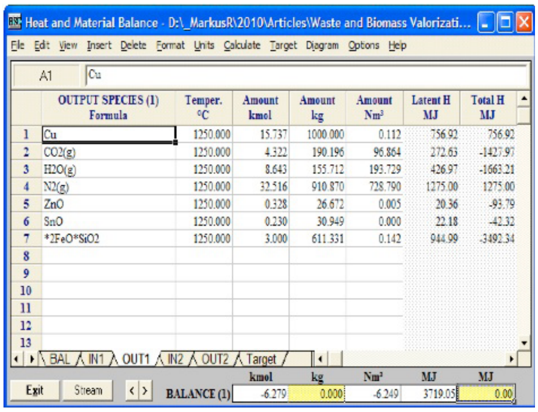


Figure 122:

A comparison of pure copper scrap melting 756.9 MJ/t Cu (top) and impure copper recyclate smelting 1493.8 MJ/t Cu, showing the effect of impurities in scrap feed (down) at 1250 °C as calculated by HSC for adiabatic conditions with methane as fuel (HSC Chemistry 7, 1974 – 2013).

It is clear from Figure 122 that, generally, the baseline will be the energy required for smelting a defined material, and that impurities will increase the energy required. However, exothermic reactions of the contained materials will offset this problem, lowering the carbon footprint of the system and improving efficiency, a major focus of "sustainability" though engineers call this just "better efficiency". What really improves the system is to minimize impurities in the feed, which is what a good system model must be able to predict as well as suggesting improvements. Optimizing the system is thus more equated to "sustainability". Also clear from this example is the CO_2 fraction used for remelting is only a small fraction of the value summarized in Figure 24.

13.2 The stability of oxides and other metal-containing minerals

Concerning the primary production of metals and their recovery from end-of-life applications, some principles of chemical thermodynamics must be understood. Figure 123 shows the abundance of chemical elements in earth's upper continental crust. Metals seldom occur in their native state in nature, though some precious metals, such as Au, Ag and Pt do, but only in limited amounts. Most common metals are found in a wide variety of stable minerals, including oxides, sulphides, fluorides and halides. Parts of these occur as ores, containing mineral concentrations near the surface of the earth that can be mined economically. The relative abundance of metals in the earth's crust ranges from very low (e. g. 0.001 – 0.01 ppm for Au, Os, Pt) to very high (Si 27.7 % by weight, Al 8.1 % by weight, Fe 5.0 % by weight).

Metal ores include mainly oxides, sulphides, carbonates and halides. As sulphides and carbonates are easily converted into oxides by roasting or calcination, metal extraction is mainly from oxides by chemical or electrolytic reduction.

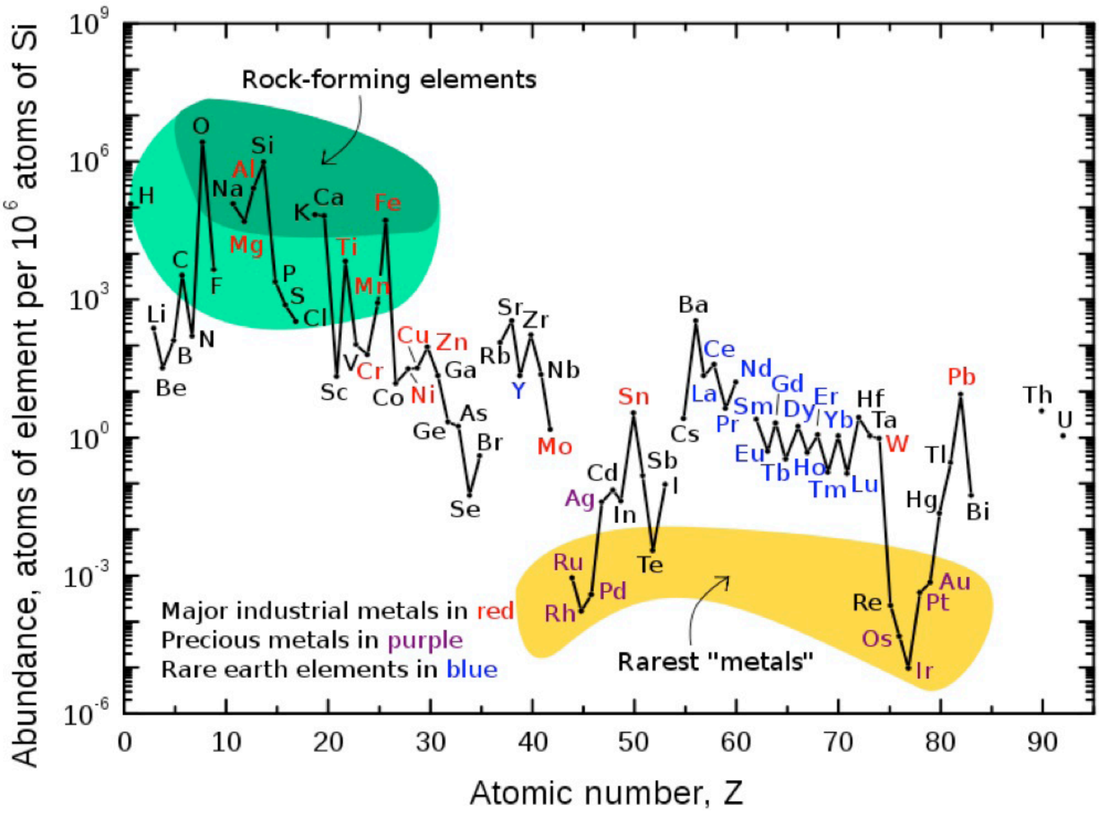


Figure 123:

The abundance (atom fraction) of the chemical elements in the earth's upper crust as a function of their atomic number. The rarest elements (yellow) are the densest. Major industrial metals are shown in red (USGS).

According to the principles of equilibrium thermodynamics, every material system tries to minimize its Gibbs free energy, G, on the way to its equilibrium state. The simple fact that most metals in nature are not pure, but are bound to oxygen, sulphur, chlorine, etc., reflects that their Gibbs free energy is lower than the corresponding Gibbs free energies of the unreacted elements. Consider for example the reaction:

$$Si + O_2 = SiO_2$$

The standard free energy of formation of SiO_2, $\Delta G^0 SiO_2$, is the difference between the standard Gibbs free energy of the reaction product (1 mole of pure SiO_2) and the standard Gibbs free energy of the reactants (1 mole of pure Si and 1 mole of pure O_2 at a pressure of 1 atm, Figure 124).

The Gibbs energy of an element or compound is expressed with respect to a standard state, often that of the pure element in its stable crystal structure at a given temperature (liquids and solids) and for gases the perfect gas at a given temperature. For any chemical reaction, hence also for the formation of oxides, sulphides, etc., the actual reaction free energy can be expressed, referring to the standard states, as:

$$\Delta G = \Delta G^0 + RT \ln Q$$

where the reaction quotient Q (e.g. SiO_2 formation) refers to the actual activities of reactants and products:

$$Q = \frac{a_{SiO_2}}{a_{Si} . a_{O_2}}$$

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	T	DeltaH	DeltaS	DeltaG	K	Log(K)
1	Si + O2(g) = SiO2					
2	T	deltaH	deltaS	deltaG	K	Log(K)
3	C	kJ	J/K	kJ		
4	0.000	-910.712	-182.002	-860.999	4.605E+164	164.663
5	100.000	-911.010	-182.985	-842.729	9.498E+117	117.978
6	200.000	-910.800	-182.506	-824.448	1.059E+091	91.025
7	300.000	-910.261	-181.481	-806.245	3.049E+073	73.484
8	400.000	-909.420	-180.135	-788.162	1.460E+061	61.164
9	500.000	-908.253	-178.524	-770.227	1.100E+052	52.042
10	600.000	-906.230	-176.079	-752.487	1.047E+045	45.020
11	700.000	-905.485	-175.271	-734.920	2.823E+039	39.451
12	800.000	-904.731	-174.534	-717.430	8.380E+034	34.923
13	900.000	-901.895	-171.936	-700.189	1.509E+031	31.179
14	1000.000	-901.059	-171.252	-683.030	1.061E+028	28.026
15	1100.000	-900.238	-170.631	-665.936	2.160E+025	25.334
16	1200.000	-899.437	-170.068	-648.902	1.025E+023	23.011
17	1300.000	-898.660	-169.557	-631.921	9.638E+020	20.984
18	1400.000	-897.909	-169.095	-614.989	1.589E+019	19.201
19	1500.000	-947.222	-198.374	-595.476	3.495E+017	17.543
20	1600.000	-946.292	-197.863	-575.664	1.133E+016	16.054
21	1700.000	-945.359	-197.378	-555.902	5.218E+014	14.717
22	1800.000	-934.158	-191.777	-536.577	3.316E+013	13.521
23	1900.000	-932.335	-190.917	-517.442	2.745E+012	12.438
24	2000.000	-930.534	-190.107	-498.392	2.841E+011	11.453
25						

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Figure 124: Various thermochemical data for the given reaction (HSC Chemistry 7, 1974 – 2013).

The activities of pure solids and liquids are the activities in the corresponding standard states and are equal to 1. The activity of gas at moderate pressures is equal to the actual pressure of the gas, therefore:

$$Q = \frac{1}{p_{O_2}}$$

A reacting system comes to equilibrium when its Gibbs free energy reaches its minimal value, when the driving force for the reaction is:

$$\left(\frac{\partial G}{\partial \lambda}\right) = \Delta G = 0$$

where λ is the so-called progress variable. From the above equation we conclude that at equilibrium:

$$\Delta G = \Delta G^0 + RT \ln Q_{eq} = 0$$

and hence:

$$\Delta G^0 = -RT \ln Q_{eq} = -RT \ln\left(\frac{1}{p_{O_2}}\right)_{eq} = RT \ln p_{O_{2,eq}}$$

In the case of SiO_2 formation, the standard reaction free energy predicts what will be the equilibrium pressure of oxygen as a function of temperature (which is $\log(pO_2) = -11.453$ at 2000 °C as can be seen from Figure 124). The more negative ΔG_T^0 becomes, or the more stable the oxide, the lower will be this equilibrium pressure of oxygen: the oxide hardly decomposes. A negative ΔG_T^0 for the formation of a compound indicates directly how much energy is at least required for decomposing the compound into its elements, hence to produce pure metal out of its mineral.
The Gibbs free energy is composed of two contributions: enthalpy (H) and entropy (S):

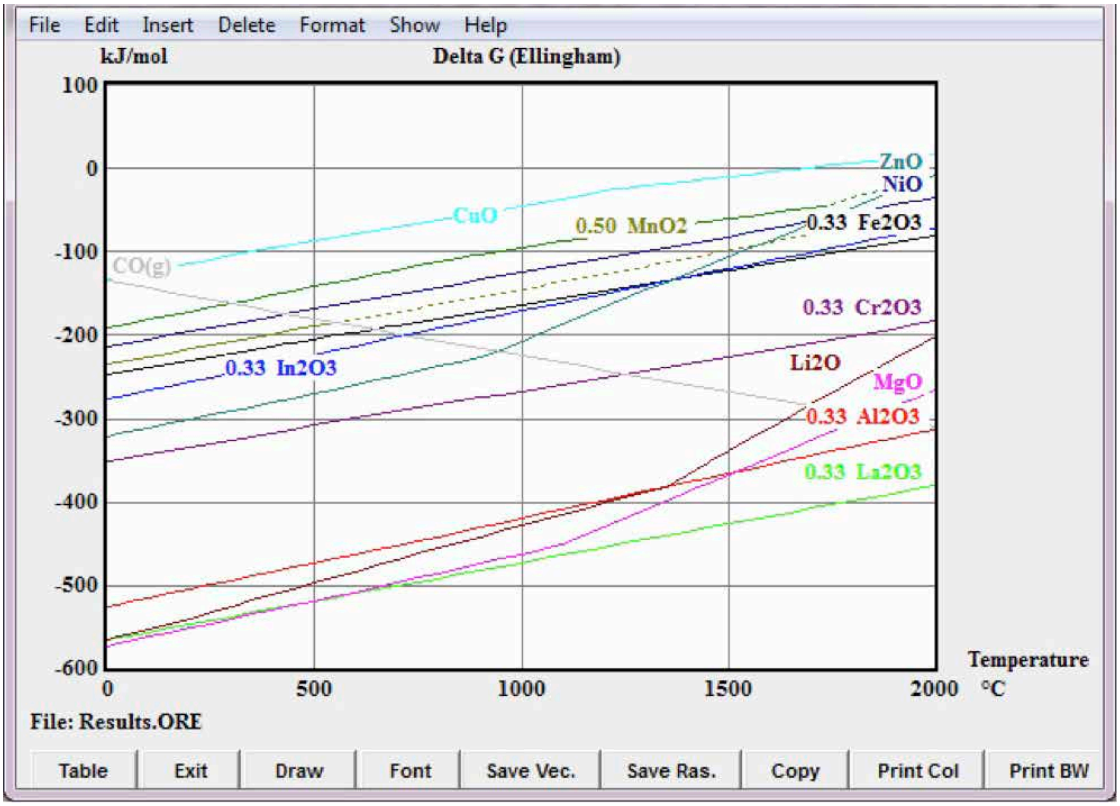
$$G = H - TS$$

thus, for the formation of the above-mentioned compounds (see Figure 124),

$$\Delta G_T^0 = \Delta H_T^0 - T\Delta S_T^0$$

Figure 125:

Various ΔG (Ellingham) functions of temperature for given oxides, showing that the REO La_2O_3 is most stable and CuO the least. Therefore it is easiest to create metal from CuO and most difficult from La_2O_3 (HSC Chemistry 7, 1974–2013).



Ellingham was the first to plot ΔG_T^0 as a function of temperature for oxidation and sulphidation reactions for a series of metals, relevant to the extraction of metals from their ores. Figure 125 shows an Ellingham diagram for oxides. In between temperatures at which phase transitions of reactants or products occur, the relation between ΔG_T^0 and T is approximately linear, the slope being equal to the average value of -ΔS_T^0. From Figure 125 it is clear that the slopes are almost the same for all oxides. This is because the entropy changes in all these cases are similar, being almost entirely due to the condensation of 1 mole of oxygen:

$$-\Delta S_{298}^0 = \left(\frac{2x}{y}\right) S_{298}^0[M] + S_{298}^0(O_2) - \left(\frac{2}{y}\right) S_{298}^0[M_xO_y]$$

Such a diagram shows the relative stability of the different oxides and the minimal amount of energy required to produce the metal. The more negative the ΔG_T^0 at a given temperature, the more stable is the corresponding oxide, and hence the more energy will be required for extracting the metal from it. A metal oxide can be reduced by any metal or element that itself forms a more stable oxide.

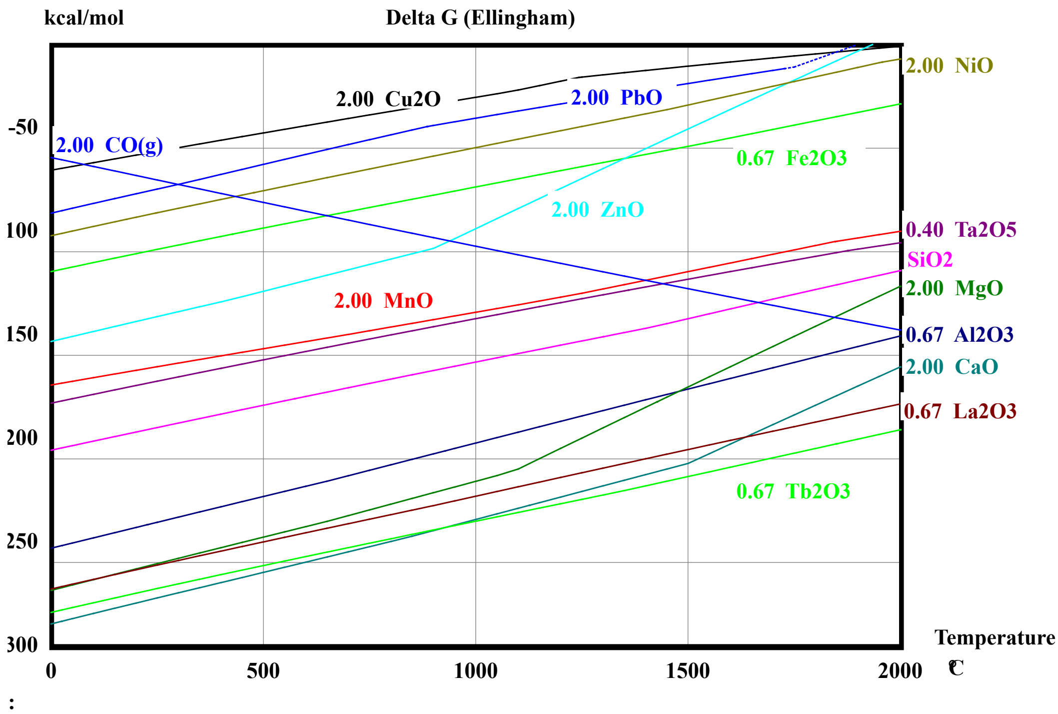


Figure 126: Standard free energy of formation of selected oxides, corresponding to the general reaction (2x/y) $M + O_2 = (2/y)$ MxOy kcal/mol (HSC Chemistry 7, 1974 – 2013).

13.3 The unique properties of carbon

The unique position of carbon in the Ellingham diagram for oxides is clear from the respective reactions:

$$2C + O_2 = 2CO$$

$$C + O_2 = CO_2$$

$$2CO + O_2 = 2CO_2$$

We see that in reaction 3 there is a net loss of one mole of gas (slope of ΔG_T^0 versus T curve similar as for most metal oxides). In reaction 2, the number of moles of gas remains the same (entropy change close to zero and hence a horizontal line in the Ellingham diagram) and in reaction 1 there is a net production of 1 mole of gas (slope of ΔG_T^0 versus T curve similar in magnitude as for most metal oxides, but opposite in sign). This means that at sufficiently high temperatures CO becomes more stable than many major metal oxides. Hence the key role that carbon plays in the production of metals. CO has a high calorific value: it is further oxidized to CO_2, the combustion heat being used, for example, to produce electric power, but this is at the cost of the unavoidable production of CO_2, which makes the C-based production of steel (and other metals) in the mid-term ecologically unsustainable.

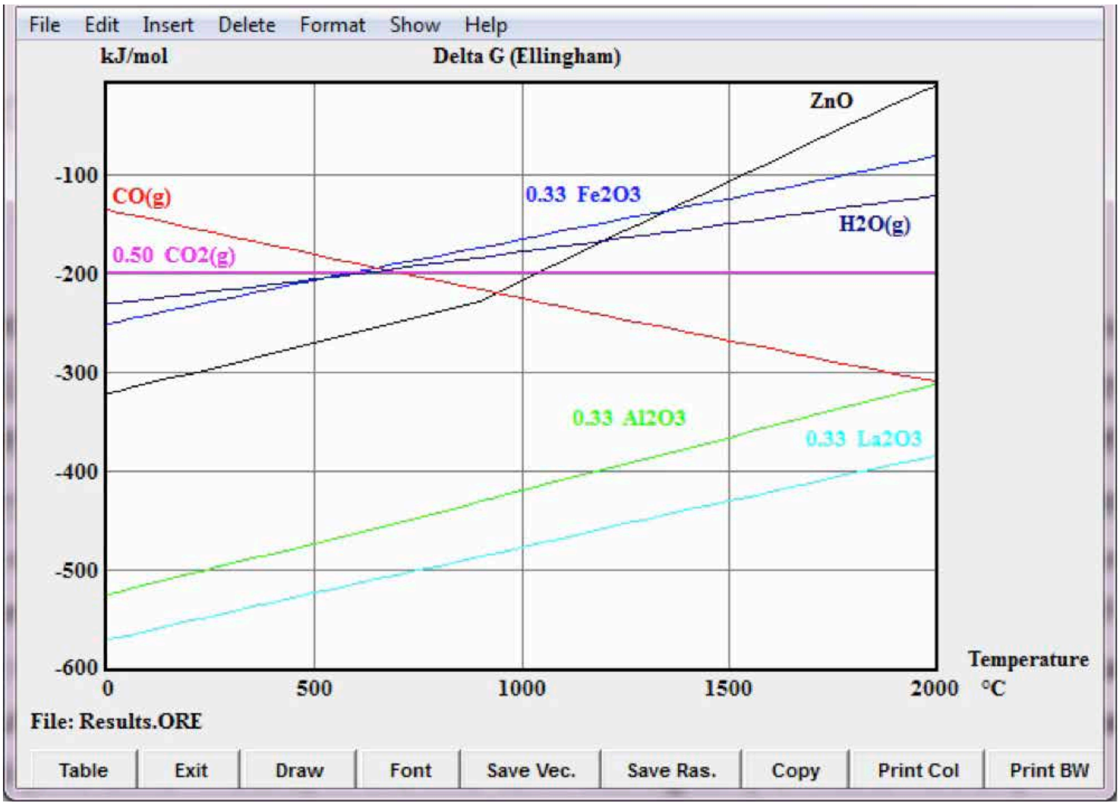


Figure 127: The use of C (red line producing CO(g)), CO(g) (magenta line producing CO_2(g)) and H_2(g) (dark blue line producing H_2O(g)) as reductants kJ/mol (HSC Chemistry 7, 1974 – 2011).

13.4 H_2 as alternative reductor

From the diagram (Figure 127) we also see that H_2 is an interesting reductor, forming simply H_2O as reaction product. From an ecological point of view, it would be great to have access to cheap and vast amounts of hydrogen, but there are not that many solutions. Using renewable solar energy to produce H_2 by the electrolytic dissociation of H_2O is worth further investigation and evaluation.

13.5 Very stable oxides

Very low in the diagram (Figure 127) we find the lines of very stable oxides, including LiO_2, MgO and Al_2O_3. They are so stable that, at acceptable temperatures, C cannot be used for reducing them to produce the corresponding metals. For the production of Al, for example, the major industrial Hall-Héroult process is commonly used. It involves dissolving alumina in molten cryolite, and electrolysing the molten salt bath to obtain pure aluminium metal. The production of aluminium metal from primary ore requires about ten times as much energy per kg as the production of iron from its primary ore. Hence, remelting well-recycled aluminium scrap is much cheaper in terms of energy consumption.

13.6 Desired purity levels

The chemical potential of an element i in a liquid or solid solution can be expressed as

$$\mu_i = \mu_i^0 + RT \ln a_i$$

As the activity of i, ai, is proportional to the mole fraction of i, xi, the chemical potential decreases strongly at very low concentrations of i. The chemical potential being a measure for the amount of energy needed to remove remaining i from the given solution, it is clear that metal refining can be very expensive in terms of energy and that it is mandatory to avoid unwanted mixing of elements during recycling.

13.7 Slag chemistry and phase diagrams

Typical components in a slag are summarized in Table 47. Their melting points clearly show which compounds have to be controlled in order for the melting temperature not to become too high.

When mixed and molten in a furnace, they usually have lower melting points than the individual compounds as shown in Table 48 and also by the phase diagrams of Figure 128 and Figure 129. Note the importance of a low Fe/SiO_2 ratio (Row 1 and Row 2) in controlling a low melting temperature. Also note that a bit of lime can bring down the melting temperature (Row 3) but too much is detrimental (Row 4).

Table 47: Common compounds in a slag and their melting points (HSC Chemistry 7). Note that due to various crystalline forms of SiO_2 a lower value of 1600 °C is given. For CaO a value of 2572 °C is reported showing some variations in data.

Slag compound	Name	Melting Point (°C)
FeO	Iron oxide (Fe: iron & O: oxygen)	1377
SiO_2	Silica (Si: silicon & O: oxygen)	1723
CaO	Lime (Ca: calcium & O: oxygen)	2899
MgO	Magnesia (Mg: magnesium & O: oxygen)	2832
Al_2O_3	Alumina (Al: aluminium & O: oxygen)	2054
ZnO	Zinc Oxide (Zn: zinc & O: oxygen)	1975
PbO	Lead Oxide (Pb: lead & O: oxygen)	887

Table 48: Common compound mixtures in a slag (see Figure 128 and Figure 129) and their melting points and Fe/SiO_2 ratios (HSC Chemistry 7).

Slag compound	Mass % Mixture & Ratio	Melting Point (°C)
FeO + SiO_2 ($2FeO \cdot SiO_2$ – fayalite)	29.5 % SiO_2 and 70.5 % FeO (Fe/SiO_2 = 1.86)	1217
FeO + SiO_2	37 % SiO_2 and 63 % FeO (Fe/SiO_2 = 1.32)	1187
CaO + FeO	19.6 % CaO and 80.4 % FeO	1059
CaO + SiO_2 ($CaSiO_3$)	49.7 % SiO_2 and 48.3 % CaO	1540

The data in Table 47 and Table 48 can be best visualized in triangular phase diagrams a simplified version of which is given by Figure 128. The shaded area in the diagram shows the large molten slag area at 1300 °C, a good operating temperature for a non-ferrous smelting furnace. This slag composition is targeted:

- To enable operation at lower temperatures.
- To reduce refractory damage and fuel usage, maintaining the slag composition within this region to ensure the slag is fluid for effective furnace operation and easy tapping.
- To achieve the target composition, silica, iron ore and limestone fluxes are used.

Figure 128 is very useful for determining the operating area, limits and constraints of the system. From this diagram, we can observe the following:

- Straight dotted lines on the diagram represent targets relating to slag composition. Maintaining the slag composition on this operating line provides the greatest operational flexibility (i.e. small changes in slag composition can be absorbed by the system without the occurrence of operational difficulties).
- Key targets are the FeO/SiO_2 ratio and the quantity of lime in slag.
- It is necessary to control the slag composition within these maximum and minimum target values to ensure the slag remains fluid.

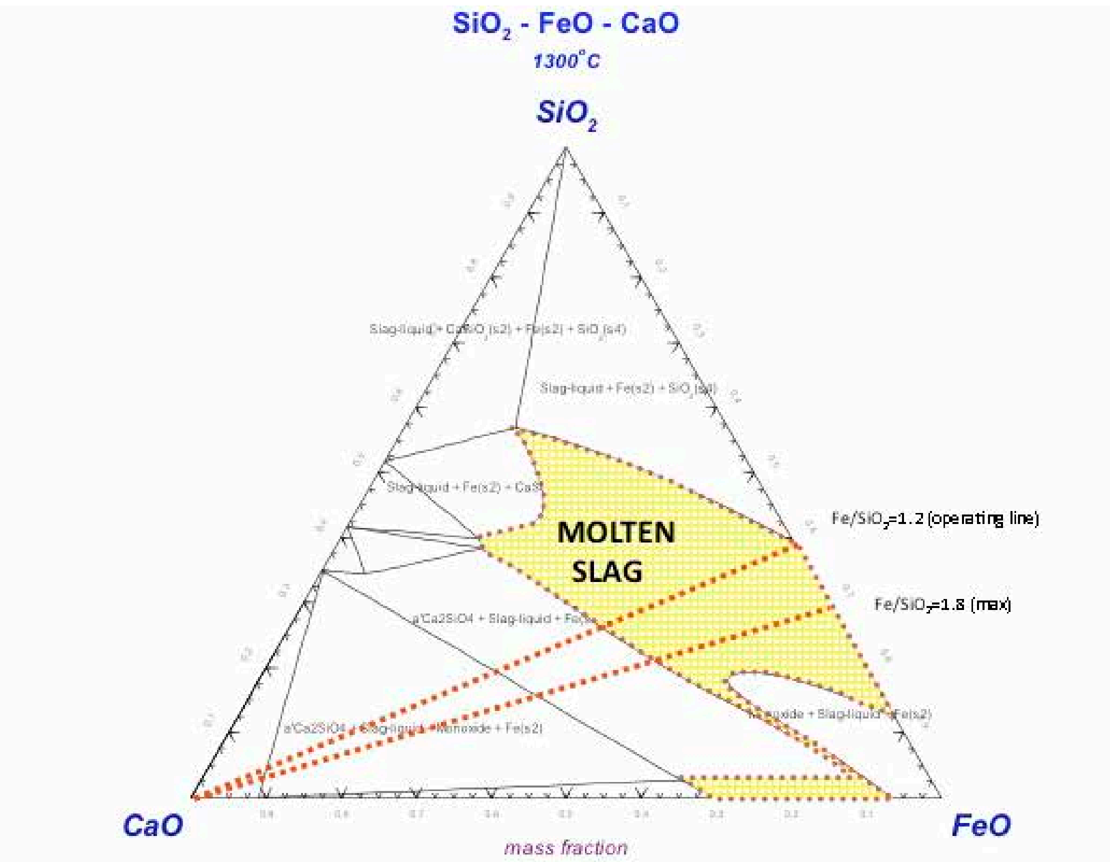
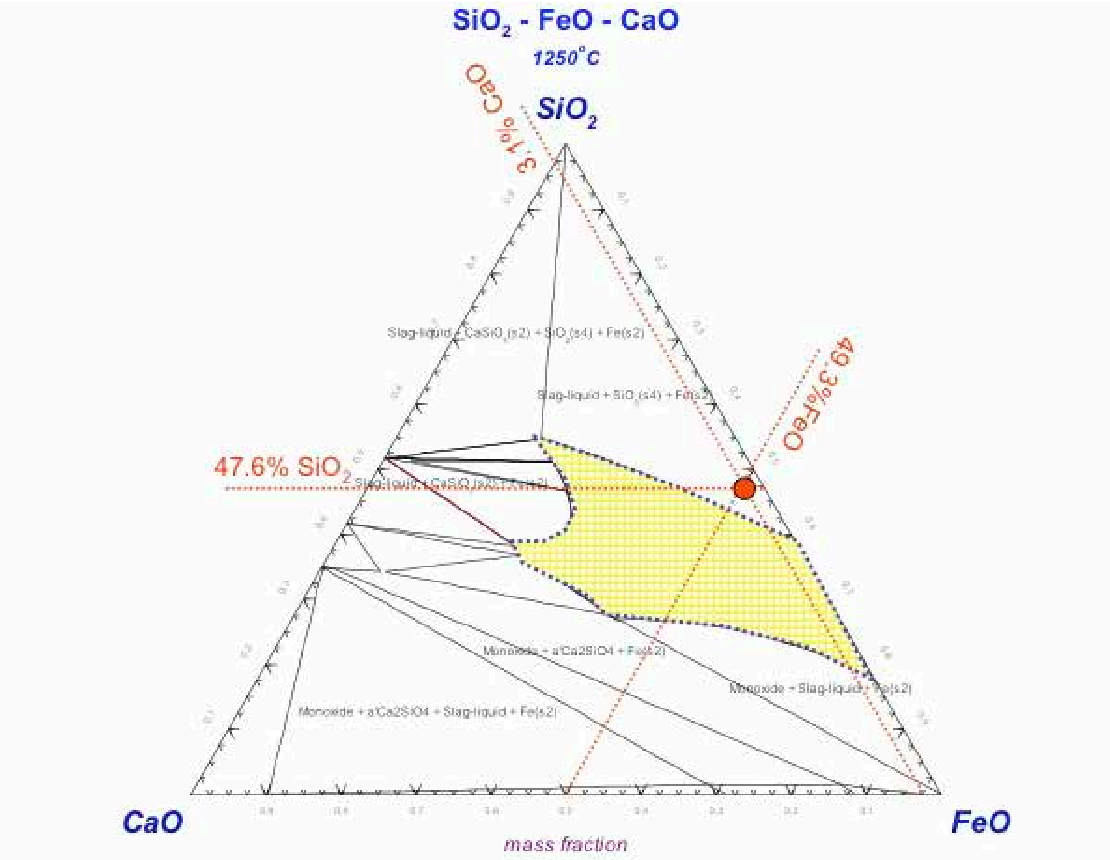


Figure 128: A simplified SiO_2-FeO-CaO phase diagram showing the area that is molten at 1300 °C with an industrially safe range of Fe/SiO_2 as shown (FACT Sage).

First, note that all analyses on a triangular phase diagram add up to 100 %. If the composition 49.3 % FeO, 47.6 % SiO_2 and 3.1 %CaO is drawn on the phase diagram as shown by Figure 129, it is clear that, since the operating point lies outside the yellow which is undesirable, the furnace may have an only partially molten slag.

Figure 129:

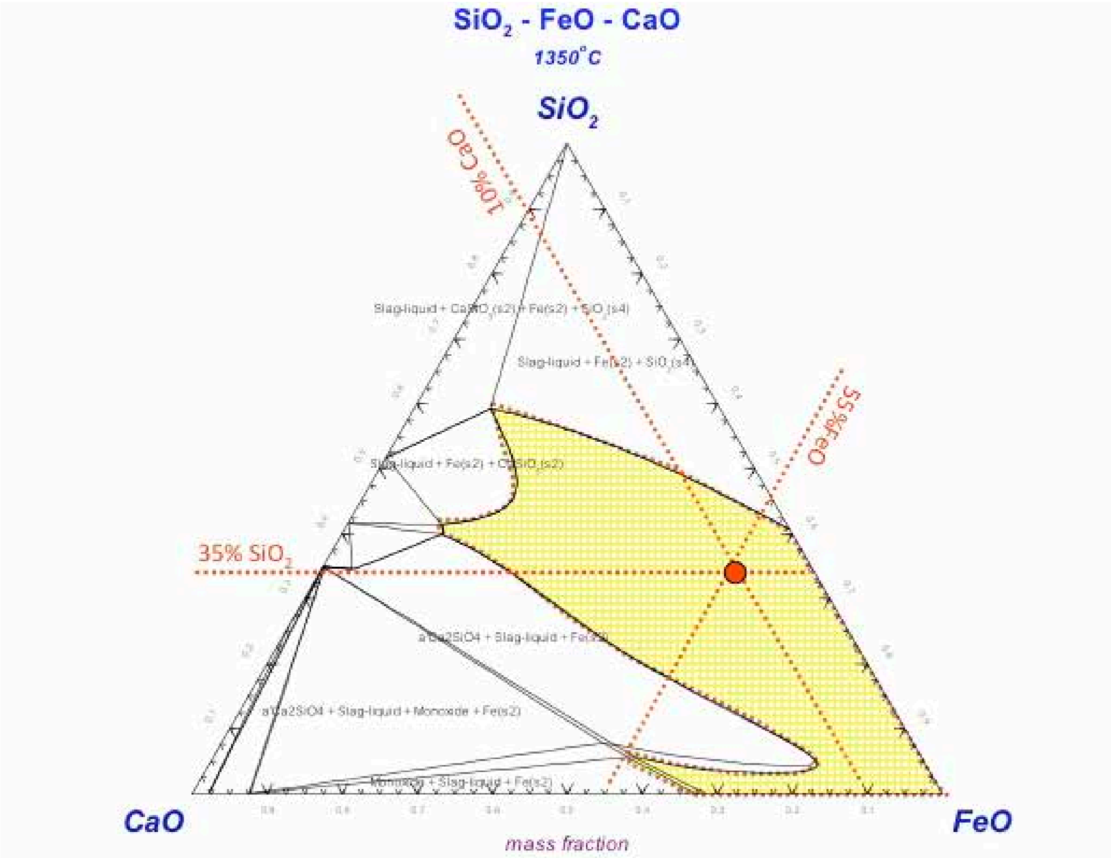
A simplified SiO_2-FeO-CaO phase diagram showing the area that is molten at 1250 °C and the operating point (FACT Sage).



If for example the slag composition is 55 % FeO, 35 % SiO_2 and 10 % CaO (effective), the operating point falls well in the molten slag area as shown by Figure 130.

Figure 130:

A simplified SiO_2-FeO-CaO phase diagram showing the area that is molten at 1300 °C with the operating point well within the molten slag area (FACT Sage).



13.8 Thermodynamic costs and benefits of recycling

The benefits of recycling are usually uncontested: it saves natural resources and is better for the environment. However, these benefits depend very much on the performance of the recycling processes involved and, in reality, neither of the two potential benefits are necessarily realized. The environmental performance of recycling processes is best assessed using the Life-Cycle Assessment methodology (see above). Depending on technical circumstances, material composition and efficiency of the processes involved, recycling might perform better or worse in terms of environmental burdens when compared with primary production. Concerning metals, recycling often compares favourably with primary production (see for instance the Ecoinvent database for Life-Cycle Assessment, www.ecoinvent.ch).

Regarding resource consumption, one could naively argue that recycling in all cases saves natural resources: natural ores can remain in the ground when recycled materials are used instead. However, even in this category producing metals from recycled sources can be more resource consuming than primary production. This is the case when the target metals can only be extracted from the waste stream with large efforts, as is the case for highly mixed fractions or with chemically or metallurgically challenging material feeds. In these cases, while ores are being saved, other resources, mainly energy carriers, have to be consumed in recycling the target material. In terms of physics, you cannot "upgrade" one resource without causing other resources to be "downgraded" by at least the same amount.

This is essentially the meaning of the second law of thermodynamics (Kondepudi and Prigogine, 1998), which is why it is a perfect starting point to discuss the aggregated resource consumption of recycling processes. In the context of this law, the concept of entropy is used for measuring the downgrading of resources. Interpretation of the second law in terms of resource consumption is simple: the more resources are consumed, the more entropy is produced (Gößling, 2001; Gößling-Reisemann, 2008a; 2008b; 2008c; 2011; Gößling-Reisemann et al., 2011). Entropy production is thus the most general form for measuring the physical aspects of resource consumption and the concept can be applied to all processes where materials and energy are transformed (Hinderink et al., 1996).

Entropy production occurs in many forms. Converting high-quality energy carriers to low-temperature heat is one of the most prominent examples, as the mixing of materials produces entropy. As a rule of thumb, whenever a process results in making material and energy flows less available for further processing, entropy is produced. The higher the loss in availability of the transformed material and energy flows, the higher is the entropy production. The availability of energy stored within material and energy flows is also known by another name: **exergy** (Szargut, 2005). As one can easily guess, entropy production and exergy loss are highly correlated. In fact, in most cases they are proportional and can easily be converted into one another via a simple formula (the Gouy-Stodola equation).

The most important fact about the second law of thermodynamics is that it describes a one-way situation: entropy is created in every process, it is never destroyed. Only in the unrealistic case of perfect reversibility can the overall entropy be conserved. In other words, resources that were consumed can never be regained. It should be obvious now that "saving resources" with recycling processes is impossible in general. One can save one resource, but only at the cost of consuming others; somewhere, entropy is always produced. What we really do in recycling is spending energy and consuming materials, i. e. we produce entropy for the separation and transformation of recycled materials, increasing their technical and economic value.

As we can see, the thermodynamic costs of recycling can be equated with entropy pro-

duction, but what about the benefits? In the same manner that mixing material streams increases their entropy, "unmixing" does the opposite. In reality, the mixing entropy contributes only little to the overall entropy of a material flow. However, to decrease this mixing entropy, comparatively huge efforts are necessary that in themselves produce large amounts of entropy through resource consumption. To avoid confusion, unmixing does not destroy entropy; it is just transferred somewhere else, usually to the surroundings as waste heat. In addition, unmixing usually consumes energy and materials and thus produces even more entropy. Nevertheless, the unmixing of materials is really at the core of recycling. Especially for metals, it is the ultimate service delivered by recycling processes. In this respect, the local and metal-specific entropy decrease between recycling materials (wastes, discards, obsolete products) and recycled metals is the quantifiable benefit of recycling (Gößling-Reisemann et al., 2011; Rechberger, 1999; Rechberger et al., 2008; Rechberger and Brunner, 2002).

13.9 Recycling performance: effectiveness and efficiency (exergy)

Viewed from a thermodynamic perspective and related to the topic of recycling, entropy production (or exergy loss) can be seen as the most general cost of producing materials, whether from primary ore or from recycling sources. At the same time, the benefit of metal recycling lies in the separation of metals from unwanted materials and the separation (un-mixing) of mixed metal streams; this benefit can be quantified by a decrease in the entropy of mixing. The more the mixing entropy decreases, the more effective is the recycling process. However, the less entropy is produced in this process, the more efficient is the process.

When we consider a typical metal-recycling situation, we usually have multiple input flows containing metals in various forms: as pure metals, as metal mixtures, as part of chemical compounds, and so on. In each input flow, the situation might be different: one contains only a mixture of pure metals or alloys, while another contains various metal oxides or other compounds. For each input flow, we can calculate the total mixing entropy by applying the text book formula:

$$S_{\text{mix}} = -R \sum_j n_j \ln(y_j)$$

where R is the universal gas constant (8.314472 J·K-1·mol-1), nj are the molar amounts of component j (compound or element) and yj are the molar concentrations.

By simply disaggregating the sum, we yield an expression for the partial mixing entropy of each component, e. g. each metal-bearing compound (Gößling-Reisemann, 2008c; Gößling-Reisemann et al., 2011):

$$s_{\text{mix,j}} = -R n_j \ln(y_j)$$

The mixing entropy of a specific metal X in this input flow is then simply the sum of all partial mixing entropies of compounds that contain X:

$$s_{mix,X} = \sum_{\{j \text{ contains } X\}} s_{mix,j}$$

Adding the contributions from all input flows (1..k) for a metal X, we arrive at the incoming mixing entropy for metal X into the recycling process:

$$s_{mix,X}^{in} = \sum_{\{input\ flows\}} s_{mix,X}$$

We can calculate the same for output flows and we can compare the two mixing entropies to measure the metal-specific absolute effectiveness of the process:

$$\Delta S_{mix,X} = s_{mix,X}^{out} - s_{mix,X}^{in}$$

is negative when the process reduces the mixing of metal X, i. e. when metal X is concentrated. It is positive when metal X is dissipated, i. e. when its mixing across the output flows is larger than it was across the input

flows. Relating the change in metal-specific mixing entropy to the incoming entropy as a base line, gives the relative metal-specific effectiveness of the process:

$$\eta_{mix,X} = \Delta S_{mix,X} / s_{mix,X}^{in}$$

In recycling practice, usually only some metals will be of economic interest and are then concentrated, while others might get dissipated. In evaluating the whole recycling smelting process, it is instructive to look at all metals that enter the process. The aggregated relative effectiveness then gives a measure for the balance between concentration vs. dissipation:

$$\eta_{mix} = \frac{\sum_X \Delta S_{mix,X}}{\sum_X s_{mix,X}^{in}}$$

In an ideal case, a perfect recycling process (or chain of processes) would decrease all metal-specific mixing entropies to zero, i. e. it would produce pure fractions, and the relative effectiveness would then be one. These fractions do not need to be pure metals, though. As a fictive example, a process that separates a mixture of say Fe, FeO, and Fe_2O_3 into three pure fractions would also have an effectiveness of one, even though the resulting fractions are far from what you would expect from a recycling process. In another fictive process, carbon might be added to the mixture, and pure fractions of Fe and CO_2 could be produced. Again, the effectiveness as defined above is the same, but the quality of the product is different! However, the improved quality comes at a price, i. e. carbon has to be added. Thus, to fully evaluate process performance, effect has to be compared with cost and product quality has to be considered as well. For all practical matters, of course, an effectiveness of one cannot be achieved; there are always losses of metals or metal compounds to other material flows (slags, dust, offgas, etc.) such that the relative effectiveness is below one.

However, when aiming for a sustainable metals management, effectiveness should be as high as possible, and, within the limits imposed by economics and technology, entropy-based measures can help identifying the most effective solutions by considering multiple metals at the same time.

As said before, effectiveness is not everything: for a complete evaluation we must consider the costs. Economic and energetic costs are relevant factors for market success and environmental performance, and are thus usually analysed sufficiently well. However, resource consumption, as introduced at the beginning of this chapter, is usually not considered in the same detail. A complete picture of the recycling process in terms of thermodynamic performance emerges when the thermodynamic effect is compared with the thermodynamic cost, i. e. the decrease in overall mixing entropy is compared with overall entropy production. We can do this by analysing the entropy flows into and out of the process over a typical process cycle to get the entropy change of the system (Gößling-Reisemann, 2008b, 2008c). This entropy change can be decomposed into an exchange term and an internal production term. The first captures the entropy exchanged with the surroundings by heat, material and radiation transfer. The internal production part is due to irreversibilities inside the process and forms the actual resource consumption as discussed above:

$$\Delta S_{sys} = \Delta_e S_{sys} + \Delta_i S_{sys}.$$

For steady-state processes, or for a complete cycle in a batch process, the system entropy change ΔS_{sys} is zero: no entropy is accumulated inside the system. The internal entropy production $\Delta_i S_{sys}$ can then be calculated from the entropy exchange of material, heat and radiation with the surroundings $\Delta_e S_{sys}$ (Gößling, 2001; Gößling-Reisemann et al., 2011):

$$\Delta_i S = \int \left(\underbrace{\sum_l \frac{e_{q,l}^{out}}{T_{q,l}} - \sum_l \frac{e_{q,l}^{in}}{T_{q,l}}}_{\text{Heat balance}} + \underbrace{\sum_j \frac{4}{3} \frac{e_{s,j}^{out}}{T_{s,j}^{out}} - \sum_j \frac{4}{3} \frac{e_{s,j}^{in}}{T_{s,j}^{in}}}_{\text{Radiation balance}} + \underbrace{\sum_k s_k m_k^{out} - \sum_k s_k m_k^{in}}_{\text{Material balance}} \right) dt$$

with heat flow e_q at temperature T_q, radiation flow e_s at temperature T_s, specific entropies s_k, and material flows m_k.

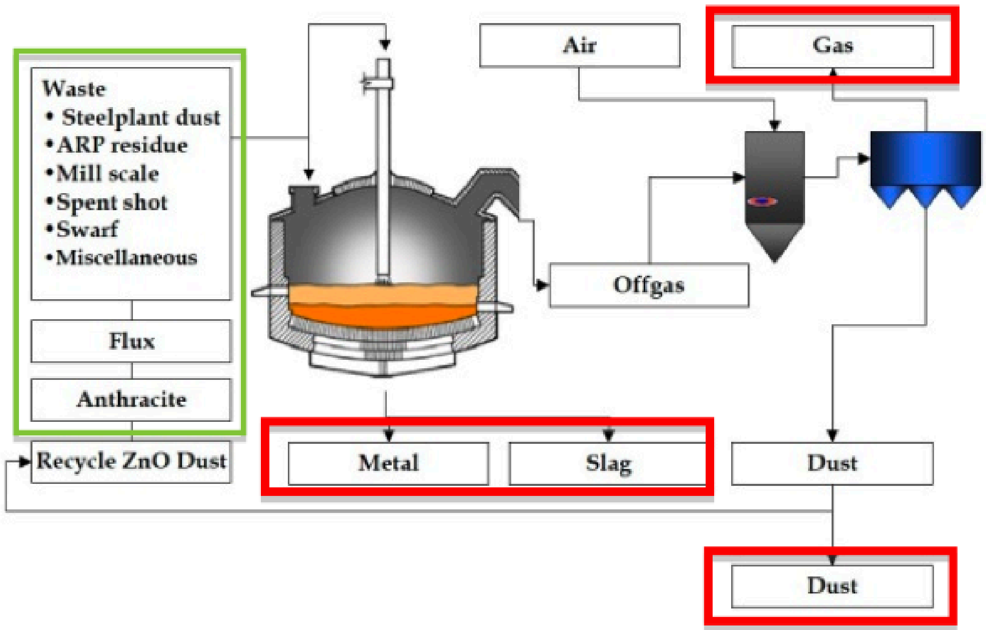
Box 25:

Exergy of a smelter

For illustrating the above assessment methods, we consider a real-life example (Gößling-Reisemann, 2011). The basis for the assessment is detailed material flow data, including chemical analysis of the components. Thus, the data requirements of the methods are quite high, and application depends on their availability. A well-described process in the literature is the Enviroplas process by Mintek, RSA (Denton et al., 2005), mainly used for recycling Electric Arc Furnace (EAF) dust. The target metals are zinc and iron, but nickel, chromium and molybdenum are also of commercial interest, the latter two even considered "critical" by some sources. The flowsheet is shown in Figure 131. Please see also Cebulla and Bernard (2010) for more details on metal-specific mixing entropy flows.

Figure 131:

General flowsheet of the Mintek Enviroplas process (Input flows are in green, output flows in red) (Denton et al., 2005).



Box 25:_b

Fe, Ca and Zn are well concentrated, consistent with the main economic incentive. Other metals are only concentrated slightly like Al, Cr, and Mg, and Mn, Mo, Ni, and Ti are even slightly dissipated. Compared to the concentrating effect on zinc, the overall performance in terms of metal concentration is only medium (-33%), but in terms of economics it is probably sufficient since zinc and iron are the main motivation for operating the whole process.

The entropy production of the Enviroplas process has not yet been analysed in detail, but by using the data in Denton et al. (2005) and with the help of GEMIS and Ecoinvent, two life-cycle assessment databases, one can roughly estimate the entropy production to be in the range of 90 MJ/K per tonne of metal produced. The entropy-based efficiency can then be calculated to be in about 0.001 (or 0.1%). Without a benchmark, however, this number does not say very much about the maturity of the process. All one can say, is that probably much room exists for improvement, either in decreasing the resource consumption or by improving the overall metal concentration.

Viewed from a sustainability perspective, the Enviroplas process can be improved. Just by how much is not clear from the above analysis, which shows that choosing certain technologies for concentrating target metals affect the possible dissipation of non-target metals. To approach a closed-loop metals economy, we must consider these side effects and design recycling flowsheets that capture the widest range of metals, without too much dissipative loss.

13.10 Solution thermodynamics

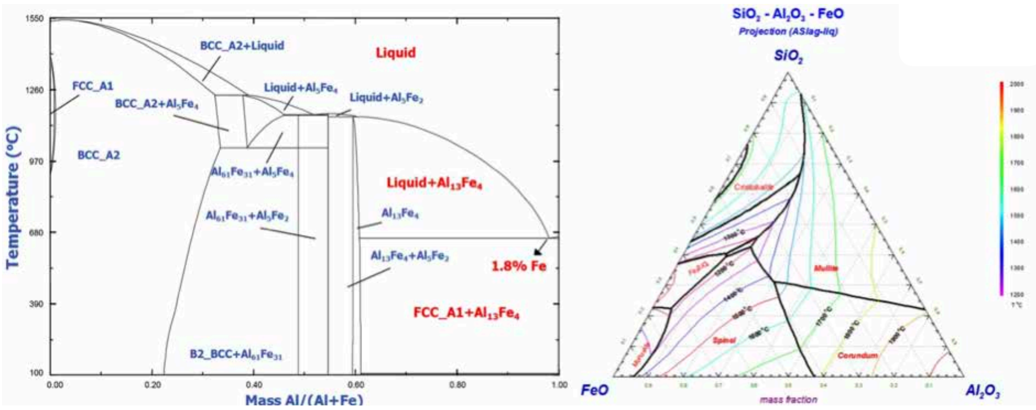
The three boxes of the following section briefly present examples in pyro- and hydrometallurgical solution chemistry, which is of critical importance for predicting the destination of elements between different phases and therefore their recovery throughout the metal production system.

Box 26:

Pyrometallurgy: maximal recovery of materials into a valuable liquid metal phase
To separate metals from other metals and optimally recover metals from their metal oxides from slags (mixture of molten oxides), a theoretical understanding of phase relationships is required. In Figure 132 (left-hand) the effect of iron dissolved in molten aluminium is shown, showing that a large number of inter-metallic compounds are created, which makes the removal of Fe from Al very difficult, while also noting the eutectic at around 1.8 % Fe. Figure 132 (right-hand) shows a ternary phase diagram defining the melting points of all possible mixtures of FeO-SiO_2-CaO. From this figure it is evident that aluminium oxidized to alumina (Al_2O_3) and dissolved in slag markedly increases the melting point of slag. Excess aluminium in the feed should thus be avoided in scrap that goes to a non-ferrous smelter. The latter has to operate with a liquid and low-viscosity slag to operate well and recover the metals from the slag into a metal phase. Aluminium in the feed reduces process functionality and thus metal recovery in a non-ferrous smelter.

Box 26_b:

Figure 132: Phase relationship in molten metal alloy and multi-oxide slag (ternary diagram) (FACT Sage; Castro et al., 2004; Castro et al., 2005; Reuter, 2011a; Reuter, 2009).



To maximize separation in metallurgical smelting, the slag must be suitably molten for optimal recovery of the reduced metal, which implies that the molten slag must have a sufficiently low viscosity, i. e. the temperature must be sufficiently high. However, molten slag mixtures of CaO-FeO-SiO_2-Al_2O_3-MgO-metal oxides are complex high temperature liquids that, depending on the composition, will have a complex liquidus profile. Figure 133 clearly shows the marked influence of alumina (Al_2O_3) on the melting point of slag as also shown in Figure 132 for different conditions. Usually, alumina is created from aluminium in e-waste in a non-ferrous copper smelter. Removal of aluminium from e-waste is thus beneficial for smelting as well as being desirable because of aluminium's reduced energy footprint during remelting and refining.

Figure 134 shows the relative stability of some indium and tin oxides in the ratio used for flat-panel TV screens. The thermodynamics-based figure shows that this stability has a direct effect on their recovery and recycling rate due to various different compounds In and Sn can appear in when processed. This is attributable to their oxidation states, vapour pressure, etc. Obviously, a proper understanding of the thermodynamics within this technological/economic context will determine how well indium and tin are recovered in suitable phases for further processing. Usually, BAT operators do this very well in a most resource efficient manner, as they have a good understanding of the physics involved. The example in Figure 134 shows the various compounds of indium and tin and their behaviour under different temperatures and different carbon-starting values (i. e. with little carbon it is more oxidizing and with more it is more reducing). It is clear that under more reducing conditions more indium metal is produced, while tin oxide is readily reduced to metal. Various volatile species of indium oxide and tin oxide exist and, depending on the gas flow through the system, more or less of these are removed to the gas phase and then oxidized to flue dust.

Figure 135 shows that if the lime (CaO) content in the slag changes for given experimental conditions, the distributions are affected and will complicate matters further.

Box 26_c:

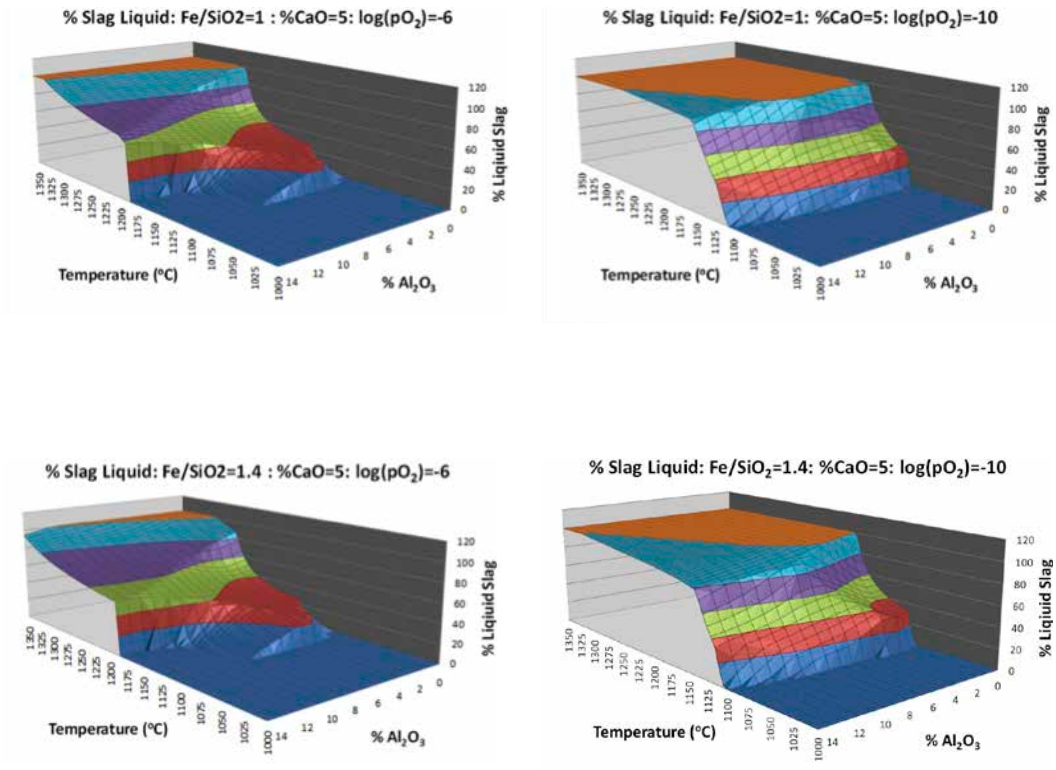


Figure 133:

The effect of different alumina levels (from aluminium in e-waste) on the slag liquidus temperature, on solids in solution as a function of temperature, and on oxygen partial pressure of a typical slag (FACT Sage; Reuter et al., 2011b).

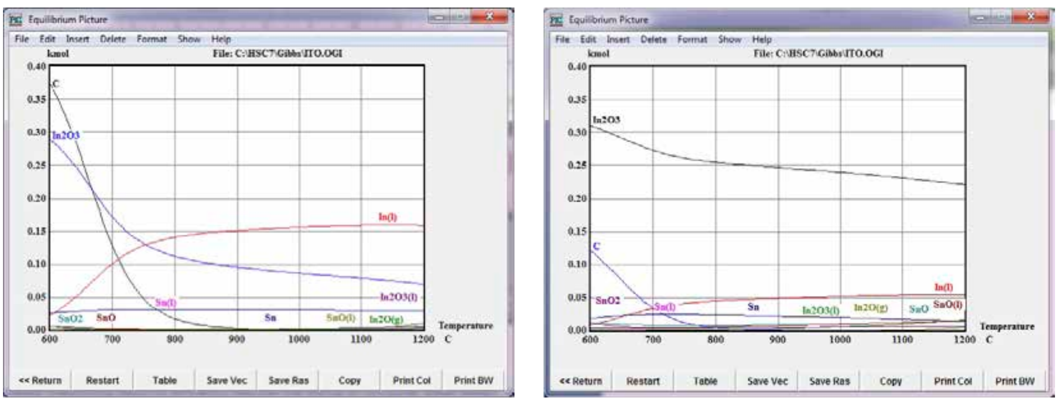


Figure 134:

The stability of some of tin (Sn) and indium (In) oxides under different operating conditions: (a, left) shows more reducing conditions while (b, right) shows more oxidizing conditions (HSC Chemistry 7, 1974–2013; Outotec).

Box 26_d:

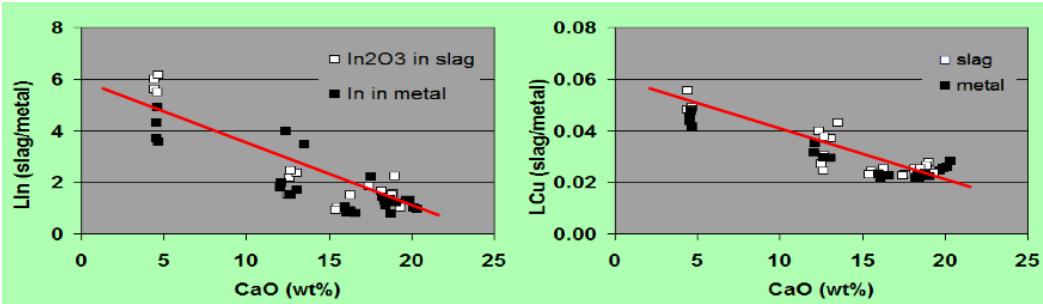


Figure 135: The distribution of indium and copper between metal and slag as a function of lime addition at 1300 oC, Fe/SiO_2 = 1.1-1.2 and log(pO_2) = -7 (Anindya et al., 2011).

Figure 136 shows Gibbs Free Energy (Ellingham) graphs for various oxides as a function of temperature. This so-called Ellingham diagram shows the relative stability of oxides and how easily these can be reduced to metal. SnO_2/In_2O_3 are easiest to reduce, while various REO are extremely difficult to reduce with, e. g., carbon and hydrogen, requiring the use of hydrometallurgy for refining.

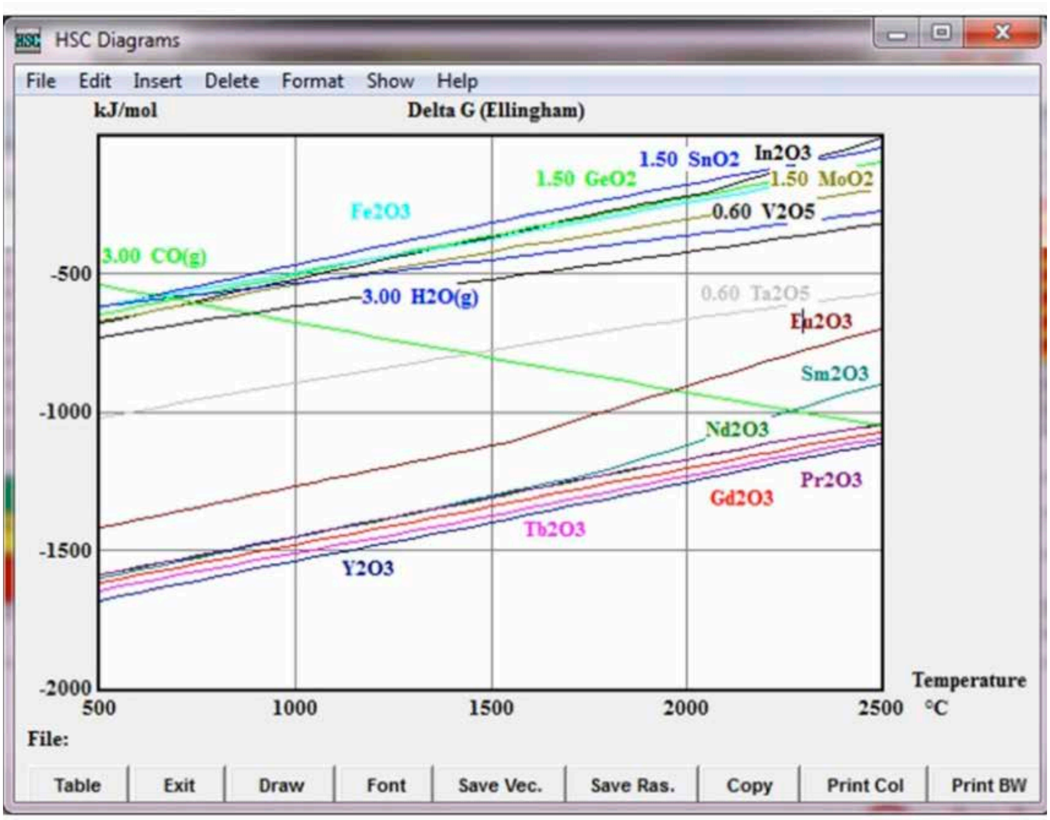


Figure 136: Ellingham Diagram for the Stability of various compounds in e-waste – the bottom compounds being the most stable (HSC Chemistry 7, 1974–2013; Outotec).

Box 27:

Hydrometallurgy: maximal recovery of materials into a valuable aqueous phase

As for pyrometallurgy, hydrometallurgy requires a keen understanding of the thermodynamics of aqueous solutions. Similar to phase diagrams at different temperatures for different partial oxygen pressures, Eh-pH diagrams (Figure 137) provide an indication of which different phases are stable in aqueous electrolytes. Ultimately, the 'critical' elements at some stage go through hydrometallurgy to create pure metals and compounds.

Note that during for example leaching of printed wire boards entropy is increased considerable when numerous metals (and compounds) go into solution as mg/l and g/l and then having subsequently to clean the solutions to recover pure compounds and metals (thus decreasing entropy again). Careful analysis of thermodynamics and associated economics are required to evaluate its suitability for this. This analysis is especially important as a hazardous heavy metal containing printed wire board remains, which will incur landfill and/or other/further treatment costs. Usually an economic dictated balance between pyro- and hydrometallurgy is required to best recycle printed circuit boards.

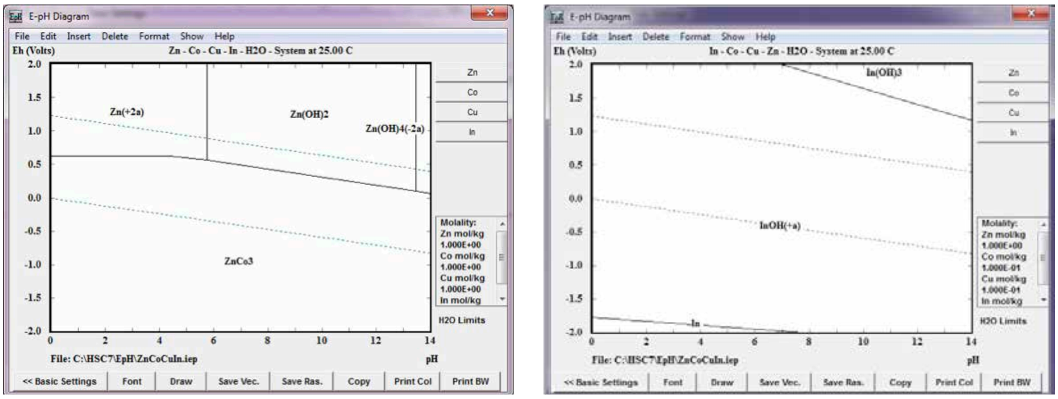


Figure 137:

Eh-pH diagram for an aqueous electrolyte showing the behaviour of different dissolved elements, which are subsequently recovered by various refining processes (HSC 1974 – 2013).

Box 28:

Recycling of gallium-arsenide on a printed wire boards vis-à-vis steel beverage can recycling

The successful recycling of steel beverage cans can be explained by various "simple" recycling-rate-calculation definitions, which are close to a Material (& Metal)-Centric recycling view.

On the other hand, the recycling of gallium (Ga) and arsenic (As) from a gallium-arsenide component on printed wire boards (PWB) in electronic products is far more difficult. Due to its functional linkages, using simple Material (& Metal)-Centric recycling-rate-calculation definitions is not possible. A Product-Centric recycling view takes note of the sophisticated physics that is required for separating Ga and As from all the other 50+ elements in some End-of-Life products, producing pure GaAs for reuse on PWBs. However, GaAs may be present as traces and may well be locked up in, for example, environmentally benign slag. In this case, recycling of these elements makes no economic sense, but it is important to have a system that can take care of all these element mixes while maximizing metal recovery, profit and minimizing ecological damage.

13.11 Distribution of elements in specific reactor types – the effect of transfer processes

It is evident from the above theoretical considerations that a truly Product-Centric view of recycling is required for the economic separation of complex EoL recyclates into high purity metals, compounds, etc. In addition to the above theory, tools such as computational fluid dynamics that describe mass, momentum and energy-transfer processes, provide a good understanding of reactor furnaces such as the TSL type (Figure 47). Huda et al. (2012) showed the flow and transfer phenomena in this type of furnace and described to which phase elements will report, i. e. metal, matte, slag, speiss, flue dust, etc. (Figure 138).

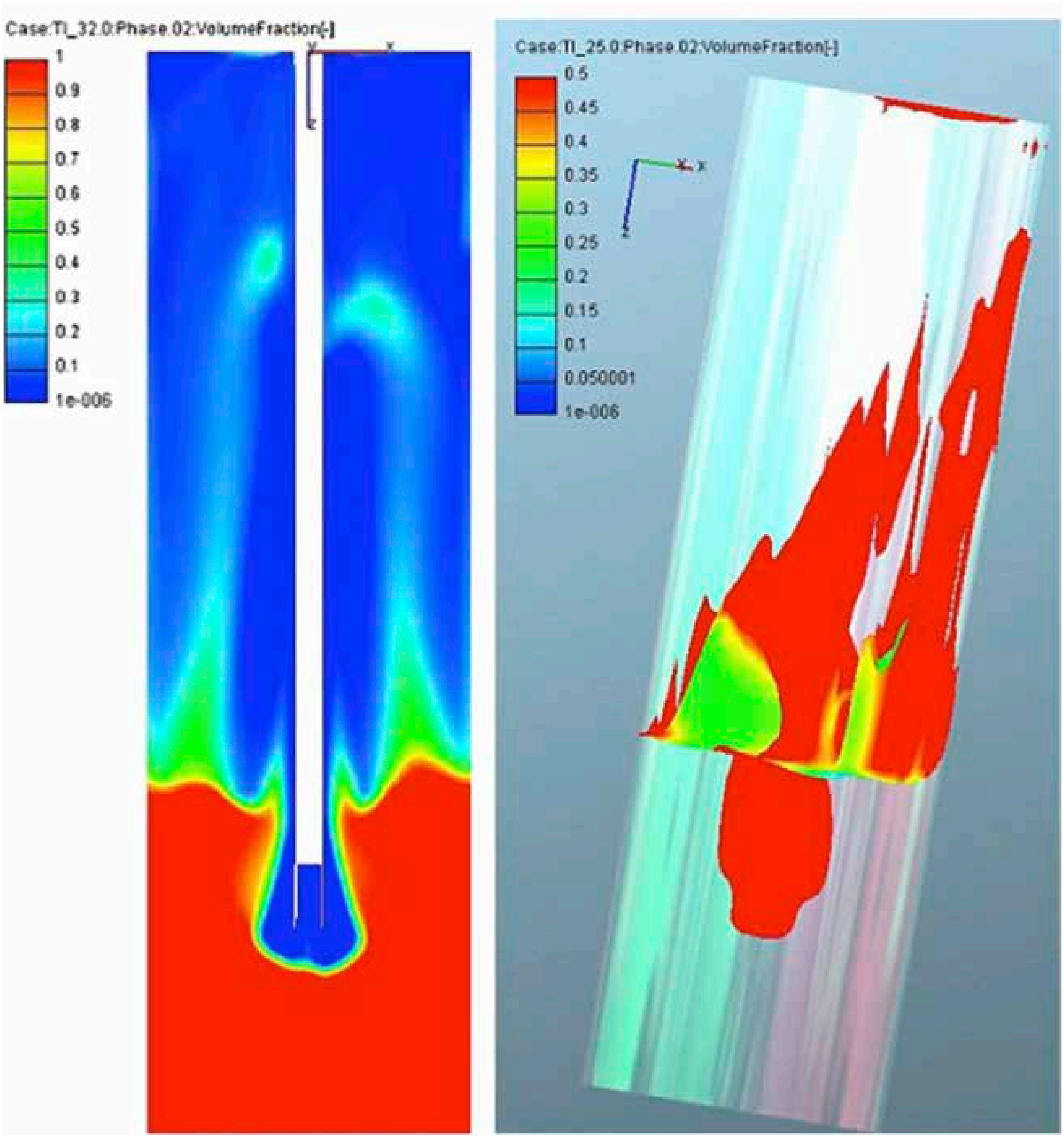


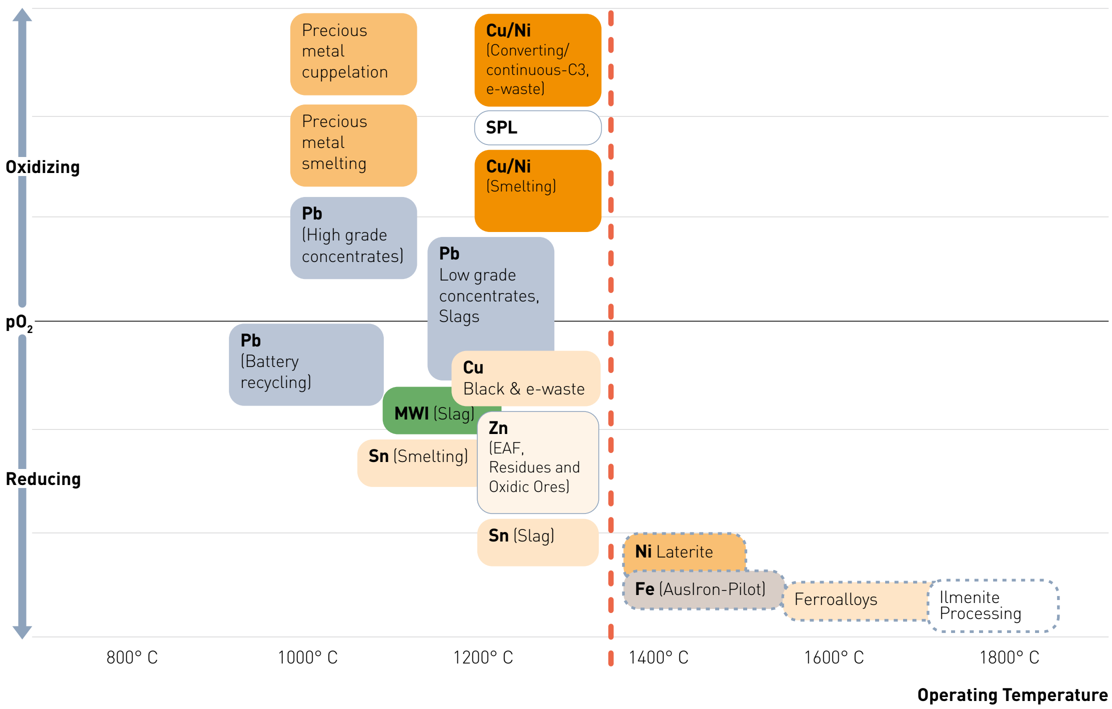
Figure 138: Using computational fluid dynamics for optimizing conditions within furnaces (which can be 10–40 m high) – this drives process understanding to its limits and maximizes resource efficiency (Huda et al., 2012).

The "element radar chart" (Figure 64) graphically shows how easy or difficult it is to separate metals within various mainstream-metal (Carrier Metal) reactor types (Nakajima et al., 2009; 2011; Hiraki et al. 2011) for primary production. The chart shows how metals (and their compounds) split between metal, slag and flue dust, and therefore whether they are recoverable in the indicated reactor types (note that this tells us nothing about the downstream processes). The theoretical aspects discussed above determine the distribution of all these elements in a specific reactor. For example, alloying elements for steel such as nickel, tungsten, molybdenum, and cobalt are stable in molten iron. This thermodynamic feature usually leads them to stay in metallic iron, where they are lost for other uses and become impurities in the steel, which cannot be removed by conventional recycling systems of steel, aluminium or magnesium. The radar chart shows this, indicating that removing impurities and/or extracting valuable scarce metals is easier for the other metal processes shown. This illustrates that the level of impurities in metal produced by conventional steel, aluminium and magnesium recycling depends upon the purity of the input. With some impurities, like tin and copper in steel, the metal will become substandard. Tin dissolves in the molten steel and, on cooling, solidifies on the steel-grain boundaries, thereby destroying the steel phase-structure necessary for steel's strength and durability. Copper above 0.25 % by weight in scrap input for steel making, will cause the steel to become brittle or soft ("hot shortness"), prohibiting the manufacture of high quality products from such scrap.

Ultimately the distribution of elements between the different phases within a metallurgical reactor are among others functions of the technology but also how well the temperature and partial oxygen pressure can be manipulated to achieve the best economic goal.

Figure 139:

Manipulating conditions within a TSL to achieve desired metal production and energy recovery, recycling and waste processing (www.outotec.com).



13.12 Recycling a cup of coffee, a modern consumer product – how to do it economically?

As a final thought, please solve the problem below and appreciate truly the issues of recycling.

Box 29:

A final example – recovery of all constituents from a cup of coffee
Now try to answer the question posed at the start of this report:

As a final thought experiment please develop a flow sheet and estimate the costs for producing pure water, milk, sugar, coffee from a cup of coffee.

This illustrates the complexity of recycling, the effect of dissolution of metals in each other and then separating them into pure or alloy products of economic value.

Box 30:

A final example - recycling of lithium ion batteries
Figure 140 clearly shows that recycling is useful to recover lithium. As an exercise develop a an economically viable route that maximially recovers all metals and materials from a Lithium-Ion battery.

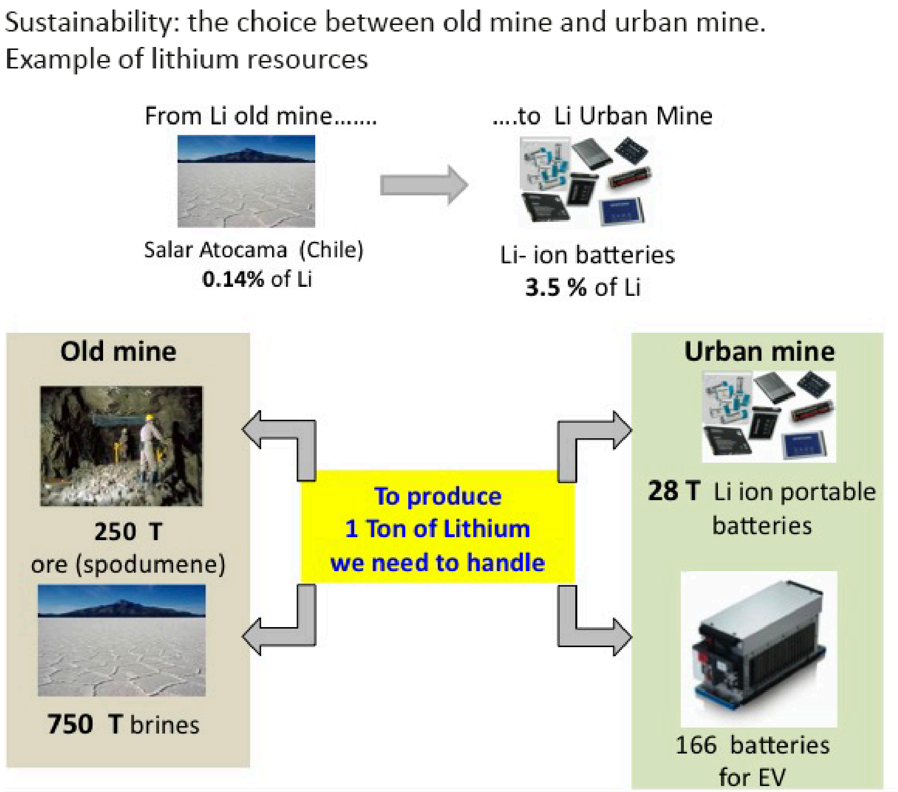


Figure 140: Recycling lithium-ion batteries (Recupyl SAS).

References

1. Abelson, P. H. A potential phosphate crisis. Science, vol. 283, No.5410 p. 2015 (1999).

2. Achzet, B., Reller, A.: Powering the Future (pre-publication) (2011).

3. Van Acker, K., Verpoest, I.: Is CFRP an environmentally friendly alternative for transport? – LCA of the entire life cycle of CFRP, GO Carbon Fibre 2011, Seattle, Washington, October 5–6, 2011.

4. AEB Amsterdam. Facts and Figures. Available from: http://www.amsterdam.nl/aeb/english/about-us/facts-figures/ (accessed December 7th, 2012).

5. Agricola, G. De Re Metallica, p. 439p. (1556). Translated by H.C. Hoover & L.H. Hoover, Dover Publications, New York, p. 638 (1950).

6. Alfantazi, A.M., Moskalyk, R.R.: Processing of indium: a review. Minerals Engineering, vol.16, No. 8, pp. 687–694 (2003).

7. Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E.: Material efficiency: A white paper. Resources, Conservation and Recycling, vol. 55, pp. 362–381 (2011).

8. Amini, S. H. Remmerswaal, J. Castro, M.B. and Reuter, M.A., Quantifying the quality loss and resource efficiency of Recycling by means of exergy analysis. Journal of Cleaner Production, vol. 15, pp. 907–913 (2007).

9. Anastas, P.T., Breen, J.J.Design for the environment and green chemistry: the heart and soul of industrial ecology. Journal of Cleaner Production, vol. 5(1–2), 97–102 (1997).

10. Angerer, G. Raw materials for emerging technologies; The case of Lithium, Eco-efficient Economy, Presentation, Linkoping, November 2009, Available from: http://isi.fraunhofer.de/isi-en/service/presseinfos/2010/pri10-02.php (accessed December 7th, 2012).

11. Anindya, A., Swinbourne, D., Reuter, M.A., Matusewicz, R. Indium distribution during smelting of WEEE with copper scrap, European Metal Conference, EMC 2011, GDMB (Goslar), Düsseldorf, Germany (June 26th – 29th, 2011), 1, 3–14 (2011).

12. ARN – Auto Recycling Nederland. Recycling Process. Available from: http://www.arn.nl/english/ARN-Recycling/Process (accessed December 7th, 2012).

13. Aspen Plus: AspenTech (1994–2011) Available from: www.aspentech.com (accessed December 7th, 2012).

14. Aurubis www.aurubis.com (accessed December 7th, 2012).

15. Ayres, R.U. Metals Recycling: economic and environmental implications. Resources, Conservation and Recycling, vol. 21, pp. 145–173 (1997).

16. Baker, E., Bournay, E., Harayama, A. and Rekacewisz, P. Vital Waste Graphics. Basel Convention Secretariat/UNEP-GRID. Available from: http://www.grida.no/publications/vg/waste/ (2005).

17. Basson, L., Petrie, J. A critical systems approach to decision support for process engineering. Computers and Chemical Engineering, vol. 31, pp. 876–888 (2007). Basel Secretariat, 2012. Origins of the Convention. Available from: http://www.basel.int/convention/basics.html#1 (accessed December 7th, 2012).

18. Befesa www.befesa-steel.com (accessed December 7th, 2012).

19. Bernardes, A.M., Espinosa, D.C.R., Tenório, J.A.S. Recycling of batteries: a review of current processes and technologies. Journal of Power Sources, vol. 130, pp. 291 – 298 (2004).

20. Bertram, M., Martchek, K.J., Rombach, G. Material Flow Analysis in the Aluminum Industry. Journal of Industrial Ecology, vol. 13(5), pp. 650 – 654 (2009).

21. Bertuol, D.A. et al.: Spent NiMH batteries: Characterization and metal recovery through mechanical processing. Journal of Power Sources, vol. 160, pp. 1465 – 1470 (2006).

22. Biddle, M.B., Dinger, P., Fisher, M.M. An Overview of Recycling Plastics from Durable Goods: Challenges and Opportunities. IdentiPlast II Conference, Brussels (April 1998).

23. BIR, Bureau of International Recycling www.bir.org (accessed December 7th, 2012).

24. Bodénan F., Hanrot F., Moulin I., Poirier J., Rose J., Piantone P. et al. Recycling physically sorted steelworks slag for the metallurgical and cement industries: conclusions of the ORLA research project. Proceedings of the 12th European Congress and Exhibition on Advanced Materials and Processes (Euromat 2011). Session C52, 12 – 15 sept 2011, Montpellier, France (2011).

25. Boin, U.M.J., Bertram, M.: Melting Standardized Aluminum Scrap: A Mass Balance Model for Europe, Journal of Metals, vol.46, pp. 26 – 33 (2005).

26. NewBoliden. Available from: www.boliden.se (accessed December 7th, 2012).

27. Boni, H. and R. Widmer: Disposal of Flat Panel Display Monitors in Switzerland, EMPA, March 2011.

28. Bosmans, A., et al. Enhanced Landfill Mining: a crucial role for Waste-to-Energy technologies. Journal of Cleaner Production (2012).

29. Boustead, I., Hancock G-F.Handbook of Industrial Energy Analysis. Ellis Horwood Ltd., 1979.

30. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Raw Materials Group (2010). Available from: http://www.bgr.bund.de (accessed December 7th, 2012).

31. Briffaerts, K. Spirinckx, C., Van der Linden, A., Vrancken, K.: Waste battery treatment options: Comparing their environmental performance, Waste Management, vol. 29, pp. 2321 – 2331 (2009).

32. Brunner, P.H., Rechberger, H. Practical Handbook of Material Flow Analysis, Lewis Publishers, Boca Raton, FL, ISBN 1566706041, p. 336 (2004).

33. Brundtland Report: Our Common Future, Oxford: Oxford University Press. ISBN 0-19-282080-X, 1987. Available from: http://www.un-documents.net/wced-ocf.htm (accessed December 7th, (2012).

34. Buckminster Fuller, R. Critical Path, St. Martin's Press, New York, p. 471 (1981).

35. McDonough, W., Braungart, M. Cradle To Cradle Remaking the Way We Make Things, North Point Press, New York, p. 193 (2002).

36. Castro, B., Remmerswal, H., Boin, U., Reuter, M.A. A thermodynamic approach to the compatibility of materials combinations for recycling. Resources, Conservation and Recycling, vol. 43(1), pp. 1 – 19 (2004).

37. Castro, B., Remmerswal, H., Brezet, H., Van Schaik, A., Reuter, M.A. A simulation model of the comminution-liberation of recycling streams: Relationship between product design and the liberation of materials during recycling. International Journal of Minerals Processing. vol. 75 (3–4), pp. 255–281 (2005).

38. Chancerel, P.; Meskers, C.; Hagelüken, C.; Rotter, S. WEEE: metals too precious to ignore. Recycling International November, pp. 42–45 (2008).

39. Chancerel, P., Meskers, C.E.M., Hagelüken, C., and Rotter, V.S.: Precious metal flows during the preprocessing of electronic waste. Journal of Industrial Ecology, vol. 13(5), pp. 791–810 (2009).

40. Chancerel, P., Rotter, S. Recycling-oriented characterization of small waste electrical and electronic equipment, Waste Management, vol. 29, pp. 2336–2352 (2009a).

41. Chancerel, P., Rotter, V.S. Assessing the management of small Waste Electrical and Electronic Equipment through Substance Flow Analysis – The example of gold in Germany and the USA. Proceedings of the ISSST International Symposium on Sustainable Systems and Technology, 18–20 May 2009, Phoenix (2009b).

42. Chancerel, P. Substance flow analysis of the recycling of small waste electrical and electronic equipment – An assessment of the recovery of gold and palladium. Doctoral thesis, Technische Universitaet Berlin, Germany (2010). Available from: http://opus.kobv.de/tu-berlin/frontdoor.php?source_opus=2590 (accessed December 7th, 2012).

43. Cebulla, B.: Beschreibung der Recyclingeffienz und -effektivität mittels thermodynamischer Maße anhand zweier ausgewählter metallurgischer Prozesse. Bachelor thesis. Advisor: Stefan Gößling-Reisemann. University of Bremen, Faculty of Production Engineering, Division of Technological Design and Development (Prof. A. von Gleich) (2010).

44. Chemconserve, Nederland (2011). Available from: www.chemconserve.com (accessed December 7th, 2012).

45. Chi, X., Streicher-Porte, M., Wang, M.Y.L., Reuter, M.A. Informal electronic waste Recycling: A sector review with special focus on China, Waste Management, vol. 31, pp. 731–742 (2011).

46. Copper Development Association. Copper Info. Available from: http://www.copperinfo.co.uk/alloys (accessed November 2, 2012).

47. Copper, International Copper Association. Available from: http://www.arcat.com/arcatcos/cos37/arc37309.html (accessed December 7th, 2012).

48. Choi, B., Shin, H., Lee, S., Hur, T. Life Cycle Assessment of a Personal Computer and its Effective Recycling Rate. International Journal of LCA, vol. 11(2), pp. 122–128 (2006).

49. Christen, K., Closing the phosphorus loop. Environmental Science and Technology, vol. 41, p. 2078 (2007).

50. Cowell, S.J., Wehrmeyer, W., Argust, P.W., Robertson, J.G.S. Sustainability and the primary extraction industries: theories and practice. Resources Policy, vol. 25, pp. 277–286 (1999).

51. Cui, J., Forssberg, E. Mechanical Recycling of waste electric and electronic equipment: a review. Journal of Hazardous Materials, B99, pp. 243–263 (2003).

52. Cui, J., Zhang, L. Metallurgical recovery of metals from electronic waste: A review. Journal of Hazardous Materials, vol. 158, pp. 228–256 (2008).

53. Damanhuri, E. Post-Consumer Waster Recycling and Optimal Production, Published by InTech Janeza Trdine 9, 51000 Rijeka, Croatia, 306p. (2012). Available from: http://www.intechopen.com/books/post-consumer-waste-recycling-and-optimal-production (accessed November 2, 2012).

54. Denton, G. M., Barcza, N. A., Scott, P. D., Fulton, T. EAF Stainless Steel Dust Processing. Mintek, Pyrometallurgy Division. Randburg, South Africa. Mintek Technical Papers (2005).

55. DEFRA. Department for Environment, Food and Rural Affairs. Trial to establish waste electrical and electronic equipment (WEEE) protocols, p. 104 (2007).

56. Deubzer, O. Explorative Study into the Sustainable Use and Substitution of Soldering Metals in Electronics. Doctoral thesis, Delft University of Technology, Delft, the Netherlands (2007).

57. Dewulf, J., Van Langenhove, H. Integrating industrial ecology principles into a set of environmental sustainability indicators for technology assessment. Resources Conservation and Recycling, vol. 43, pp. 419 – 432 (2005).

58. Dewulf, J., Van der Vorst, G., Denturck, K., Van Langenhove, H., Ghyoot, W., Tytgat, J., Vandeputte, K. Recycling rechargeable lithium ion batteries: critical analysis of natural resource savings. Resource Conservation Recycling, vol. 54, pp. 229 – 234 (2010).

59. Dodbiba, G., Takahashi, K., Sadaki, J., Fujita, T.: The Recycling of plastic wastes from discarded TV sets: comparing energy recovery with mechanical Recycling in the context of life cycle assessment. Journal of Cleaner Production, vol. 16, pp. 458 – 470 (2006).

60. U.S. Department of Energy (2010): Critical Materials Strategy. Available from: http://energy.gov/sites/prod/files/edg/news/documents/criticalmaterialsstrategy.pdf (accessed November 2, 2012)

61. DOWA. Available from: www.dowa.com (accessed December 7th, 2012).

62. Dubreuil A, Young SB, Atherton J, Glora TP. Metals recycling maps and allocation procedures in life cycle assessment. International Journal of Life Cycle Assessment, vol.15, pp. 621 – 634 (2010).

63. Duflou, J.R., Seliger, G., Kara, S., Umeda, Y., Ometto, A., Willems, B.Efficiency and feasibility of product disassembly: A case-based study. CIRP Annals – Manufacturing Technology, vol. 57, pp. 583 – 600 (2008).

64. Duflou, J.R., Deng, Y., Van Acker, K., Dewulf, W., Do fiber-reinforced polymer composites provide environmentally advantageous benign alternatives? – An LCA-based study. MRS Bulletin Sustainability issue (to be published) (2012).

65. Durao Jr., W.A. et al., Mercury reduction studies to facilitate the thermal decontamination of phosphor powder residues from spent fluorescent lamps. Waste Management, vol. 28, pp. 2311 – 2319 (2008).

66. European Aluminium Association, Aluminium Recycling in Europe. The Road to High Quality Products, p. 52 (2006).

67. Edwards, R., Pearce, D. The effect of prices on the recycling of waste materials. Resources Policy, pp. 242 – 248 (December 1978).

68. Integrated Pollution Prevention and Control (IPPC) Reference Document on Best Available Techniques in the Non Ferrous Metals Industries December 2001 (Next Version Due 2012).

69. European Commission DG ENV.E3, Heavy Metals in Waste, Final Report, February 2002. Available from: www.ec.europa.eu/environment/waste/studies/pdf/heavy_metalsreport.pdf (accessed December 7th, 2012).

70. European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. OJ L365, Brussels, Belgium.

71. European Parliament and Council Directive 1999/31/EC of the European parliament and of the council of 26 April 1999 on the landfilling of waste. Official Journal of the European Communities 1999; L182:1 – 19, Brussels Belgium.

72. European Parliament and Council Directive 2000/53/EC of the European Parliament and the council of 18 September 2000 on end of life vehicles, Official Journal of the European Communities, 21-10-2000, Brussels Belgium.

73. European Parliament and Council Directive 2002/96/EC of the European parliament and of the council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Official Journal OJ L 37 of 13.02.2003, Brussels Belgium.

74. European Parliament and Council Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS). Official Journal OJ L 37 of 13.02.2003, Brussels Belgium.

75. REACH (Registration, Evaluation, Authorisation and Restriction of Chemical substances), REACH is the European Community Regulation on chemicals and their safe use (EC 1907/2006). Available from: http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm (accessed December 7th, 2012).

76. Staff Working Paper Accompanying the proposal for a directive of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE) (recast) – Impact Assessment {COM(2008) 810 final} {SEC(2008) 2934}.

77. European Lamp Companies Federation. Environmental aspects of lamps. Brussels, 2nd edition, p. 17 (April 2009). Available from: http://www.elcfed.org/documents/090811_elc_brochure_environmental_aspects_lamps_updated_final.pdf (accessed December 7th, 2012).

78. Ellen McArthur Foundation (2012), Towards the circular Economy. Economic and business rationale for an accelerated transition, p. 99 (2012). Available from: http://www.thecirculareconomy.org/. (accessed December 7th, 2012).

79. Elker. Available from: http://www.elker.fi (accessed December 7th, 2012).

80. Critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials, Enterprise and Industry Directorate General, p. 85 (2010). Available from: http://ec.europa.eu/enterprise/policies/raw-materials/documents/index_en.htm (accessed December 7th, 2012).

81. COM 699. Communication from the commission to the European Parliament and the Council. The Raw Materials Initiative – Meeting our critical needs for growth and jobs in Europe, Brussels (2008).

82. United Nations University. Review of Directive 2002/96 on Waste. Electrical and Electronic Equipment – Study No. 07010401/2006/442493/ETU/G4, p. 347 (2007).

83. European Commission DG Environment: Gather, process, and summarize information for the review of the waste electric and electronic equipment directive (2002/96/EC). Synthesis report. Final version September 21, 2006. [ENV.G.1/FRA/2004/0081, study no. 16], p. 293 (2006).

84. European Commission. Analysis of Existing Environmental Impact Assessment Methodologies for use in Life Cycle Assessment. In: European Commission, editor. ILCD Handbook – International Reference Life Cycle Data System. Joint Research Centre (EC-JRC), Institute for Environment and Sustainability, Ispra (Italy) (2010).

85. European Commission. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on waste electrical and electronic equipment (WEEE). Summary of the Impact Assessment, 2008a. Available from: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=SEC:2008:2934:FIN:EN:PDF (accessed December 7th, 2012).

86. European Commission. Recast of the WEEE Directive, 2012. Available from: http://ec.europa.eu/environment/waste/weee/index_en.htm (accessed December 7th, 2012).

87. European Topic Centre on Sustainable Consumption and Production. Waste from electrical and electronic equipment (WEEE) (2009). Available from: http://scp.eionet.europa.eu/themes/waste/#6 (accessed December 7th, 2012).

88. Eurometaux's proposals for the raw materials initiative, Darmstadt/Brussels (11th June 2010). Availabel from: http://www.oeko.de/oekodoc/1069/2010-115-en.pdf and appendix (accessed December 7th, 2012).

89. FACT Sage. Availabel from: www.factsage.com (accessed December 7th, 2012).

90. Fagan, J.E., Reuter, M.A. Langford, K.J. Dynamic performance metrics of integrated urban water systems. Resource Conservation Recycling, vol. 54, pp. 719 – 736 (2010).

91. Food and Agriculture Organization, FAOSTAT. Rome: Statistics Division, FAO, (2011).

92. Ferrão, P., Amaral, J. Assessing the economics of auto recycling activities in relation to European Union Directive on end of life vehicles. Technological Forecasting & Social Change, vol. 73, pp. 277 – 289 (2006).

93. Franz, K.A., Kehr, W.G., Siggel, A., Wieczoreck, J., Adam, W. Luminescent Materials. Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH Verlag GmbH & Co, KGaA, Weinheim, Germany, p. 41 (2010).

94. Froelich, D., Maris, E., Haoues, N., Chemineau, L., Renard, H., Abraham, F., Lassartesses, R. State of the art of plastic sorting and Recycling: Feedback to vehicle design. Minerals Engineering, vol. 20, pp. 902 – 912 (2007).

95. First Solar. Available from: www.firstsolar.com (accessed December 7th, 2012).

96. Futatsuka, T. Shitogiden, K. Miki, T. Nagasaka, T. and Hino, M. Dissolution behavior of nutrition elements from steelmaking slag into seawater. ISIJ International, vol. 44, pp. 753 – 761 (2004).

97. GaBi 4&5 LCA/LCE Software: PE International. Available from: www.pe-international.com (1989 – 2012) (accessed December 7th, 2012).

98. Gautier M., Poirier J., Franceschini G., Bodénan F. Influence of the cooling conditions on the nature and the size of the mineral phase in a BOF slag. WASCON Proceedings, Lyon (2009).

99. García-Serna, J., Pérez-Barrigón, L., Cocero, M.J. New trends for design towards sustainability in chemical engineering: Green engineering. Chemical Engineering Journal, vol. 133, pp. 7–30 (2007).

100. Geldermann, J., Treitz, M., Rentz, O. Integrated technique assessment based on the pinch analysis approach for the design of production networks. European Journal of Operational Research, vol. 171, pp. 1020–1032 (2006).

101. Global Steel Dust. Available from: www.globalsteeldust.com/steel_dust_recycling (accessed December 8th, 2012).

102. Gmünder, S. Recycling – from waste to resource: assessment of optimal manual dismantling depth of a desktop PC in China based on eco-efficiency calculations. Master Thesis: Swiss Federal Institute of Technology (ETH) and Swiss Federal Laboratories for Materials Science and Technology (EMPA), Zurich/St. Gallen Switzerland (2007).

103. Goede, M., Stehlin, M., Rafflenbeul, L., Kopp, G., Beeh, E. Super Light Car-lightweight construction thanks to a multi-material design and function integration. European Transport Reseach Review, vol. 1, pp. 5–10 (2008).

104. Goedkoop M, Spriensma R. The Eco-indicator 99: a damage oriented method for life cycle impact assessment. Consultants Amersfoort, P. The Netherlands. 2000. Available from: http://www.pre-sustainability.com/download/misc/EI99_methodology_v3.pdf (accessed December 8th, 2012).

105. Goosey, M., Kellner, R. A scoping study. End of life printed circuit boards. Supported by Department of Trade and Industry Intellect Shipley Europe Limited (2002).

106. Goosey, M., Kellner, R. Recycling technologies for the treatment of end of life printed circuit boards (PCBs). Circuit World, vol. 29/3, pp. 33–37 (2003).

107. Gößling, S. Entropy production as a measure for resource use: Method development and application to metallurgical processes. Dissertation, Hamburg (2001). Available from: http://www.sub.uni-hamburg.de/opus/volltexte/2004/1182/ (accessed December 7th, 2012).

108. Gößling-Reisemann, S. What Is Resource Consumption and How Can It Be Measured? Theoretical considerations. Journal of Industrial Ecology, vol. 12(1), pp. 10–25 (2008a).

109. Gößling-Reisemann, S.: What Is Resource Consumption and How Can It Be Measured? Application of Entropy Analysis to Copper Production. Journal of Industrial Ecology, vol. 12(4), pp. 570–582 (2008b).

110. Gößling-Reisemann, S. Entropy analysis of metal production and recycling. Management of Environmental Quality, vol. 19(4), pp. 487–492 (2008c).

111. Gößling-Reisemann, S. Entropy Production and Resource Consumption in Life Cycle Assessments. Thermodynamics and the Destruction of Resources. Bakshi, B., Gutowski, T., Sekulic, D., Eds. Cambridge University Press: New York (2011).

112. Gößling-Reisemann, S., von Gleich, A., Knobloch, V., Cebulla, B. Bewertungsmaßstäbe für metallische Stoffströme: von Kritikalität bis Entropie. In Methoden der Stoffstromanalyse: Konzepte, agentenbasierte Modellierung und Ökobilanz. Beckenbach, F., Ed. Stoffstromanalysen 1; Metropolis: Marburg (2011).

113. Graedel, T.E. On the Future Availability of the Energy Metals, Annual Review of Materials Science, vol. 41, pp. 323–335 (2011).

114. Graedel, T.E., Allenby, B.R. Industrial Ecology, 2nd Edition, Upper Saddle River, N.J., Prentice Hall, p. 363 (2003).

115. Grant R.M. Zinc concentrate and processing trends. World Zinc '93, ed.: Matthew I.G., the Australasian Institute of Mining and Metallurgy, pp. 391–397 (1993).

116. Guinée, JB., Gorrée, M., Heijungs, R., Huppes, G., Kleijn,R., de Koning A, et al. Life cycle assessment. An operational guide to the ISO standards. Part 3: Scientific Background. Ministry of Housing SPaEVaCoESC, Den Haag and Leiden, The Netherlands, 2001. Available from: http://media.leidenuniv.nl/legacy/new-dutch-lca-guide-part-3.pdf (accessed March 12th, 2013).

117. Habashi, F. Handbook of Extractive Metallurgy, III, WILEY-VCH Verlagsgesellschaft mbH, Weinheim, Deutschland, p. 2426 (1997).

118. Hagelüken, C. Secondary Raw Material Sources for Precious and Special Metals, R. Sinding-Larsen and F.-W. Wellmer (eds.), Non-Renewable Resource Issues: Geoscientific and Societal Challenges, International Year of Planet Earth, DOI 10.1007/978-90-481-8679-2_10, Springer Science+Business Media B.V. pp. 195–212 (2012).

119. Hagelüken C., Corti, C.W. Recycling of gold from electronics: Cost-effective use through 'Design for Recycling', Gold Bulletin, vol. 43(3), pp. 209–220 (2010).

120. Hagelüken, C., Meskers, C.E.M. Complex lifecycles of precious and special metals. In: Graedel, TE, van der Voet E (eds) Linkages of Sustainability. Strüngmann Forum Report 4. MIT Press, Cambridge, MA pp. 165–197 (2010).

121. Hagelüken C., Buchert, M., Ryan, P. Materials flow of platinum group metals in Germany, International Journal of Sustainable Manufacturing, vol.1(3), pp. 330–346 (2009).

122. Hagelüken, C. Recycling of Electronic Scrap at Umicore's Integrated Metals Smelter and Refinery. World of Metallurgy – Erzmetall, vol. 59(3), pp. 152–161 (2006).

123. Hagelüken, C. Improving metal returns and eco-efficiency in electronics recycling – a holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining. In proceedings of the IEEE International Symposium on Electronics & the Environment, 8–11 May, San Francisco, pp. 218–223 (2006).

124. Hagelüken, C., Buchert, M., Stahl, H. Materials Flow of Platinum Group Metals. Umicore AG & Co. KG and Öko-Institut e.V. London: GFMS Limited (2005).

125. Hauschild, M., Wenzel, H. Environmental Assessment of Products. Volume II – Scientific background. London (UK), Weinheim (Germany), New York (USA), Tokyo (Japan), Melburne (Australia), Madras (India): Champan & Hall (1998).

126. Hauschild, M., Potting J. Spatial differentiation in life cycle impact assessment – the EDIP2003 methodology. Environmental News no. 80. The Danish Ministry of the Environment, Environmental Protection Agency, Copenhagen, DK (2005).

127. Heiskanen, K. Particle Classification. Chapman & Hall, London, Great Britain. ISBN 0 412 493004 (1993).

128. Hester, R.E. and Harrison, R.M. Electronic Waste Management Design, Analysis and Application. London. Royal Society of Chemistry, ISBN 978-0-85404-112-1 (2008).

129. Hinderink, A.P., Kerkhof, F.P.J.M., Lie, A.B.K., De Swaan Arons, J. de, Van der Kooi, H.J. Exergy analysis with a flowsheeting simulator I. Theory; Calculating Exergies of material streams, Chemical Engineering Science, vol. 51(20), pp. 4693 – 4700 (1996)

130. Hischier, R., Wäger, P., Gauglhofer, J. Does WEEE Recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and Recycling systems for waste electrical and electronic equipment (WEEE). Environmental Impact Assessment Review, vol. 25, pp. 525 – 539 (2005).

131. Hischier, R., Weidema, B., Althaus, H-J., Doka, G., Dones, R., Frischknecht, R., et al. Implementation of Life Cycle Impact Assessment Methods. Swiss Centre for Life Cycle Inventories, St. Gallen, CH (2010).

132. Hiraki, T. Takeda, O. Nakajima, K. Matsubae, K. Nakamura, S. and Nagasaka T. Thermodynamic criteria for the removal of impurities from end-of-life magnesium alloys by evaporation and flux treatment. Science and Technology of Advanced Materials, vol. 12 (2011).

133. Hoang, J., Reuter, M.A., Matusewicz, R., Hughes, S., Piret, N. Top Submerged Lance Direct Zinc Smelting. Minerals Engineering, vol. 22, pp. 742 – 751 (2009).

134. Hoek van den, W.J., Luijks, G.M.J.F., Hoelen. C.G.H. Lamps. Ullmann's Encyclopaedia of Industrial Chemistry, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, p. 53 (2010).

135. Hogland, W., Hogland, M., Marques, M. Enhanced Landfill Mining: Material recovery, Energy Utilization and Economics in the EU (Directive) perspective. In: Jones, P.T., Tielemans, Y. (ed.) (2011).

136. Hieronymi, K. Is enough focus being given to designing-in recyclability in consumer electronics? Copper Recycling Conference, Brussels (11 – 13 June, 2012).

137. Huang, K., Guo, J., Xu Z. Recycling of waste printed circuit boards: A review of current technologies and treatment status in China. Journal of Hazardous Materials, vol. 164, pp. 399 – 408 (2009).

138. Huda, N., Naser, J., Brooks, G., Reuter, M.A., Matusewicz, R.W. Computational Fluid Dynamic Modeling of Zinc Slag Fuming Process in Top-Submerged Lance Smelting Furnace. Metallurgical Transactions B, vol. 43B(1), pp. 39 – 55 (2012).

139. HSC Chemistry 7 (1974 – 2011). Available from: http://www.outotec.com (accessed December 7th, 2012).

140. International Aluminium Institute, Improving Sustainability in the Transport Sector Through Weight Reduction and the Application of Aluminium. Available from: http://www.worldaluminium.org/media/filer/2012/06/12/fl0000307.pdf (accessed December 7th, 2012).

141. IChemE. The Sustainability Metrics: Sustainable Development Metrics, Institution of Chemical Engineers (IChemE), p. 29 (2001).

142. Ignatenko, O., Van Schaik, A., Reuter, M.A. Recycling system flexibility: the fundamental solution to achieve high energy and material recovery quotas, Journal of Cleaner Production, vol. 16, pp. 432–449 (2008).

143. Ignatenko, O., Van Schaik, A., Reuter, M.A. Exergy as a tool for evaluation of the resource efficiency of Recycling systems. Minerals Engineering, vol. 20, pp. 862–874 (2007).

144. Indaver (2011). Available from: www.indaver.com (accessed December 7th, 2012).

145. International Chrome Development Organization. Available from: http://www.icdacr.com (accessed December 7th, 2012).

146. International Zinc Association, Reuter, M.A. et al. Zinc College, Course Notes, International Zinc Association, ISBN 90-805644-5-1 (2001, 2002). Available from: http://www.zinc.org (accessed December 7th, 2012).

147. IP.com, "Method for the mixed recycling of lithium-based anode batteries and cells" (2007). Available from: http://ip.com/patapp/US20070196725 (accessed December 7th, 2012).

148. IPCC. IPCC Climate Change Fourth Assessment Report: Climate Change: Intergovernmental Panel on Climate Change (2007). Available from: http://www.ipcc.ch/ipccreports/assessments-reports.htm (accessed December 7th, 2012).

149. ISO. Environmental Management – Life Cycle Assessment – Principles and Framework. International Standardization Organization (ISO), European Standard EN ISO 14040, Geneva (Switzerland) (2006a).

150. ISO. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Standardisation Organisation (ISO), European Standard EN ISO 14044, Geneva (Switzerland) (2006b).

151. James, S.E. Recycling of zinc, Course Notes from Short Course presented before 4th International Symposium on Recycling of Metals and Engineered Materials, TMS (October, 2000).

152. Jahanshahi, S., Xie, D., Pan, Y., Ridgeway, P., Mathieson, J. Dry slag granulation with integrated heat recovery, Proceedings METEC, InSteelCon, Düsseldorf, 27th June – 1st July 2011, p. 7 (2011).

153. Jeswani, H.K., Azapagic, A., Schepelmann, P., Ritthoff, M. Options for broadening and deepening the LCA approaches. Journal of Cleaner Production, vol. 18, pp. 120–127 (2010).

154. Johnson-Matthey, PLATINUM 2011, p. 64 (2011). Avalable from: http://www.platinum.matthey.com/publications/pgm-market-reviews/archive/platinum-2011 (accessed December 7th, 2012).

155. Johnson, J., Reck, B.K., Wang, T., Graedel, T.E. The Energy Benefit of Stainless Steel Recycling. Energy Policy, vol. 36, pp. 181–192 (2008).

156. Jones, P.T., De Meyere, V. Terra reversa, de transitie naar rechtvaardige duurzaamheid, EPO/Jan Van Arkel, Berchem-Antwerpen, p. 359 (2009).

157. Jones, P.T. Landfill Mining: history and current status overview. In: Proceedings of the Global Landfill Mining Conference 2008 (1.1 – 1.4. 2008).

158. Jones, P.T., Geysen, D., Tielemans, S., Van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M., Hoekstra, N. Enhanced Landfill Mining in view of multiple resource recovery: a critical review, Journal of Cleaner Production (In Press, 2012).

159. Keller, M. Assessment of gold recovery processes in Bangalore, India and evaluation of an alternative recycling path for printed wiring boards, a case study. Master Thesis, Swiss Federal Institute of Technology (ETH) and Swiss Federal Laboratories for Materials Science and Technology (EMPA), Zurich/St.Gallen Switzerland (2006).

160. Kepplinger, W.L. Actual state of smelting-reduction processes in iron making. Stahl und Eisen, vol. 129(7), pp. 43 – 51 (2009).

161. Kim H.J., Kernbaum S., Seliger, G. Emulation-based control of a disassembly system for LCD monitors. The International Journal of Advanced Manufacturing Technology, vol. 40, pp. 383 – 392 (2009).

162. King, R.P. Modeling & Simulation of Mineral Processing Systems. Butterworth-Heinemann publications, Oxford, Great Britain. ISBN 0-7506-4884-8, p. 403 (2001).

163. Klauber, C., Gräfe, M., Power, G. Bauxite residue issues: I. Current management, disposal and storage practices. Hydrometallurgy, vol. 108, pp. 33 – 45 (2011a).

164. Klauber, C., Gräfe, M., Power, G. Bauxite residue issues: II. Options for residue utilization. Hydrometallurgy, vol. 108, pp. 11 – 32 (2011b).

165. Kondepudi, D., Prigogine, I. Modern thermodynamics: From heat engines to dissipative structures. Chichester, Wiley (1998).

166. Krinke, S., van Schaik, A. Reuter, M.A. Stichling, J. Recycling and DfR of multi-material vehicles (as part of 'Life cycle assessment and Recycling of innovative multimaterial applications'). In: Proceedings of the International Conference 'Innovative Developments for Lightweight Vehicle Structures'. May, 26 – 27th 2009, Wolfsburg, Germany (Volkswagen Head Office), pp. 196 – 208, ISBN 978-3-00-027891-4 (2009).

167. Kubo, H. Matsubae-Yokoyama, K. and Nagasaka, T., Magnetic separation of phosphorus enriched phase from multiphase dephosphorization slag. ISIJ International, vol. 50, pp. 59 – 64 (2010).

168. Kuo, T.C. The construction of a collaborative-design platform to support waste electrical and electronic equipment Recycling. Robotics and Computer-Integrated Manufacturing, vol. 26, pp. 100 – 108 (2010).

169. Krüger, J., Reuter, M.A. Kögler, C., Probst, T. Electrothermal Reactors, Ullmann's Encyclopaedia of Industrial Chemistry, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany (2005). (also consult chapters on all metals discussed in this document).

170. Lassner, E. and Schubert, W.-D. Tungsten: Properties, Chemistry, Technology of the Element, Alloys, and Chemical Compounds, Kluwer Academic/Plenum Publishers,New York, p. 422 (1999).

171. Li J., Gao S., Duan H., Liu L. Recovery of valuable materials from waste liquid crystal display panel. Waste Management, vol. 29, pp. 2033 – 2039 (2009).

172. Lidgren, K. The economics of recycling – matter of life or death for the recovery sector in the 1980s and 1990s. Resources and Conservation, vol. 12, pp. 175–192 (1986).

173. London Metal Exchange. Available from: http://www.lme.com (accessed December 7th, 2012).

174. Luidold, S. Process and product developments for niobium, tantalum, molybdenum and tungsten. World of Metallurgy – Erzmetall, vol. 62, pp. 91–99 (2009).

175. Luidold, S., Antrekowitsch, H. Red mud – hazardous waste or valuable raw material? In: Proceedings of EMC 2011, pp. 853–864 (2011).

176. Lupis, C.H.P., Chemical Thermodynamics of Materials, North Holland, New York, p. 134 (1983)

177. Lynas Corporation Ltd. Rare Earths – We touch them every day. Investor presentation, May 2011. Available from: http://www.lynascorp.com/content/upload/files/Presentations/Investor_Presentation_May_2011.pdf (accessed December 7th, 2012).

178. Manley, J.B., Anastas, P.T., Cue Jr., B.W. Frontiers in Green Chemistry: Meeting the grand challenges for sustainability in R&D and manufacturing. Journal of Cleaner Production, vol. 16, pp. 743–750 (2008).

179. Mäkelä, M. The Complexity of Mobile Phone Recycling, Developing user oriented design guidelines and future concepts for mobile phone Recycling, School of Art and Design, Aalto University, Helsinki (2011).

180. Matusewicz, R, Reuter, M.A. The role of Ausmelt's TSL in Recycling and closing the material loop. Proceedings REWAS2008, Cancun, Mexico, Ed. B. Mishra, C. Ludwig and S. Das, The Minerals, Metals & Materials Society (TMS) Warrendale, Pennsylvania, pp. 951–962, ISBN 978-0-87339-726-1 (2008).

181. Matlab. 1984–2011: The Language of Technical Computing, The MathWorks, Inc. Available from: http://www.mathworks.com (accessed December 7th, 2012).

182. Mathieux, F., Froelich, D., Moszkowicz, P. ReSICLED: A new recovery-conscious design method for complex products based on a multi-criteria assessment of the recoverability, Journal of Cleaner Production, vol. 16, pp. 277–298 (2008).

183. Matsubae-Yokoyama, K. Kubo, H. Nakajima, K. and Nagasaka, T., A material flow analysis of phosphorus in Japan – The iron and steel industry as a major source. Journal of Industrial Ecology, vol. 13, pp. 687–705 (2009).

184. Matsubae-Yokoyama, K., Kubo, H., and Nagasaka. T., Recycling Effects of Residual Slag after Magnetic Separation for Phosphorus Recovery from Hot Metal Dephosphorization Slag. ISIJ International, vol. 50, pp. 65–70 (2010).

185. May, G. The Evolution of the Lead/Acid Battery Market and the Effect of Changes in Automotive Technology on Battery Design, FOCUS Consulting, International Lead Zinc Study Group, Presentation, Lisbon (September 2011). Available from: http://www.ilzsg.org/generic/pages/list.aspx?table=document&ff_aa_document_type=P&from=1 (accessed December 7th, 2012).

186. McGill, I. Rare Earth Elements, Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, p. 46 (2010).

187. Mellor, W., Wright, E., Clift, R., Azapagic, A., Stevens, G. A mathematical model and decision-support framework for material recovery, recycling and cascaded use. Chemical Engineering Science, vol. 57, pp. 4697 – 4713 (2002).

188. Meskers, C., Reuter, M.A., Boin, U., Kvithyld, A. A fundamental metric for metal Recycling applied to coated magnesium. Metallurgical Transactions B, vol. 39(3), pp. 500 – 517 (2008).

189. Meskers, C.E.M., Hagelüken, C. et al. Impact of pre-processing routes on precious metal recovery from PCs. Proceedings of European Metallurgical Conference EMC (2009).

190. Meskers, C.E.M, Hagelüken, C. Salhofer, S. Spitzbart, M. Impact of pre-processing routes on precious metal recovery from PCs. Proceedings of European Metallurgical Conference EMC Innsbruck (28 June – 1 July 2009).

191. Metal Bulletin, Average values (2010).

192. Meurer, U. Gewinnung von Zinkoxid aus sekundären Rohstoffen – Neue entwicklungen in Wälzprozess, in: "Intensivierung metallurgischer Prozesse", ed.: Liese, F., GDMB, Clausthal-Zellerfeld, Germany, pp. 183 – 196 (2000).

193. Ministry of Environment and Forests of the Government of India (2011). E-Waste (Management and Handling) Rules 2011. Available from: http://moef.nic.in/downloads/rules-and-regulations/1035e_eng.pdf (accessed December 7th, 2012).

194. Ministry of Commerce of the People's Republic of China. Circular Economy Promotion Law of the People's Republic of China (2009). Available from: http://www.fdi.gov.cn/pub/FDI_EN/Laws/GeneralLawsandRegulations/BasicLaws/P020080919377641716849.pdf (accessed December 7th, 2012).

195. Müller, T., Friedrich, B. Development of a Recycling process for nickel-metal hydride batteries. Journal of Power Sources, vol. 158, pp. 1498 – 1509 (2006).

196. Münster, M., Lund, H. Comparing Waste-to-Energy technologies by applying energy system analysis. Waste Management, vol. 30(7), pp. 1251 – 1263 (2010).

197. Nakajima, K. Yokoyama, K. and Nagasaka, T., Substance flow analysis of zinc associated with the iron and steel cycle in Japan. ISIJ International, vol. 48, pp. 1478 – 1483 (2008).

198. Nakajima, K. Takeda, O. Miki, T. Nagasaka, T. Evaluation method of metal resources recyclability based on thermodynamic analysis. Materials Transactions, vol. 50, pp. 453 – 460 (2009).

199. Nakajima, K. Takeda, O. Miki, T. Matsubae, K., Nagasaka, T. Thermodynamic analysis for the controllability of elements in Recycling process of metals. Environmental Science & Technology, vol. 11, pp. 4929 – 4936 (2011).

200. Nakamura, S. and Nakajima, K. Waste input-output material flow analysis of metals in the Japanese economy, Materials Transactions, vol. 46, pp. 2550 – 2553 (2005).

201. Nakamura, S. Nakajima, K. Kondo, Y. and Nagasaka, T. The waste input-output approach to material flow analysis: Concepts and application to base metals. Journal of Industrial Ecology, vol. 11, pp. 50 – 63 (2007).

202. Nakamura, S., Kondo, Y. Input-output analysis of waste management. Journal of Industrial Ecology, vol. 6(1), pp. 39 – 63 (2002).

203. Nakamura, S., Kondo, Y. A waste input-output life-cycle cost analysis of the recycling of end-of-life electrical home appliances. Ecological Economics, vol. 57, pp. 494 – 506 (2006).

204. Nemry, F., Leduc, G., Mongelli, I., Uihlein, A. Environmental Improvement of Passenger Cars (IMPRO-car), Joint Research Centre Institute for Prospective Technological Studies JRC 40598 EUR 23038 EN ISBN: 978-92-79-07694-7, p. 216 (2008).

205. Nickel Institute. Available from: http://www.nickelinstitute.org (accessed December 7th, 2012).

206. Nokia. Available from: http://www.nokia.com (accessed December 7th, 2012).

207. Novak, E. Verwertungsmöglichkeiten für ausgewählte Fraktionen aus der Demontage von Elektroaltgeräten – Kunststoffe (Recycling possibilites for selected fractions from dismantling of waste electrical equipment – Plastics). Federal Ministry of Agriculture, Forestry, Environment and Water Management, Vienna, Austria (2001).

208. Ochsenkühn-Petropulu, M. et al. Recovery of lanthanides and yttrium from red mud by selective leaching. Analytica Chimica Acta, vol. 319, pp. 249 – 254 (1996).

209. OECD, Extended producer responsibility: A guidance manual for governments. Paris/France OECD (2001).

210. D. Schüler et al. Study on Rare Earths and Their Recycling Final Report for The Greens/EFA Group in the European Parliament. Öko-Institut e.V. Darmstadt, Germany, p. 140 (2011).

211. OMG Group. Available from: http://www.omgi.com (accessed December 7th, 2012).

212. Ongondo, F.O., Williams, I.D., Cherrett, T.J. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Management, vol. 31, pp. 714 – 730 (2011).

213. ORLA project for "Optimizing the recycling of solid by-products from steel works" (2008 – 2011) with the financial support of ANR (French Research Agency) under the Precodd 2007 program. BRGM coordinator with ArcelorMittal, LERM, CNRS/CEMHTI and CNRS/CEREGE partners (2011). Available from: http://orla.brgm.fr/ (accessed December 7th, 2012).

214. Orth, A., Anastasijevic, N., Eichberger, H. Low CO_2 emission technologies for iron and steelmaking as well as titania slag production. Minerals Engineering, vol. 20, pp. 854 – 861 (2007).

215. Owada, S. Tsuchiya, K. Takasugi, A. Kato, Y. Funakoshi, T. and Tanno, H. XRT and XRF sorting for the mutual separation of aluminum alloys to achieve "sash to sash" Recycling, Proceedings of the 11th International Symposium on East Asian Resources Recycling Technology (EARTH2011), Plenary Lecture, Kaohsiung, Taiwan (November 1, 2011).

216. Outotec. Available from: http://www.outotec.com. (accessed December 7th, 2012).

217. PE-International. Available from: http://www.pe-international.com (accessed December 7th, 2012).

218. Pietrelli, L. et al. Rare earths recovery from NiMH spent batteries. Hydrometallurgy, vol. 66, pp. 135 – 139 (2002).

219. Pimentel, D. Food Production and the Energy Crisis, Science, vol. 182, pp. 443 – 449 (1973).

220. Piret, N.Iron Stabilization by Pyrometallurgical Treatment, 3rd International Symposium on Iron Control in Hydrometallurgy, Short Course, Montreal (2006).

221. Plastics Europe. Available from: http://www.plasticseurope.org (accessed December 7th, 2012).

222. Prechthai, T., Padmasri, M., Visvanathan, C. Quality assessment of mined MSW from an open dumpsite for recycling potential. Resources, Conservation and Recycling, vol. 53, pp. 70 – 78 (2008).

223. Pruvost, P. Potential for increased aluminium recovery from bottom ashes in Europe, CEWEP-EAA Seminar Copenhagen (September 5 – 6, 2011).

224. Rabah, M.A. Recovery of aluminium, nickel-copper alloys and salts from spent fluorescent lamps. Waste Management, vol. 24, pp. 119 – 126 (2004).

225. Rabah, M.A. Recyclables recovery of europium and yttrium metals and some salts from spent fluorescent lamps. Waste Management, vol. 28, pp. 318 – 325 (2008).

226. Rebitzer, G. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment International, vol. 30, pp. 701 – 720 (2004).

227. RECHARGE aisbl, The European Association for Rechargeable Batteries, 168, Ave de Tervueren, box3. B-1150 Brussels, Belgium. www.rechargebatteries.org

228. Rechberger, H. Entwicklung einer Methode zur Bewertung von Stoffbilanzen in der Abfallwirtschaft, 1999. Wien: Technische Universität, Institute für Wassergüte und Abfallwirtschaft (Wiener Mitteilungen, 158).

229. Rechberger H., Brunner, P.H. A New, Entropy based method to support waste and resource management decisions. Environmental Science and Technology, vol. 36, pp. 809 – 816 (2002).

230. Rechberger, H, Brunner, P. H. Die Methode der Stoffkonzentrierungseffizienz (SKE) zur Bewertung von Stoffbilanzen in der Abfallwirtschaft, 2008. In: Hösel, G., Bilitewski, B., Schenkel, W., Schnurer, H. (Hg.): Müllhandbuch. Berlin: Erich Schmidt Verlag, 8506.1, pp. 1 – 18 (5/2002).

231. Reuter, M.A., Heiskanen, K., Boin, U., Van Schaik, A., Verhoef, E., Yang, Y. The Metrics of Material and Metal Ecology, Harmonizing the resource, technology and environmental cycles, Elsevier BV, Amsterdam, p. 706, ISBN: 13 978-0-444-51137-9 (2005).

232. Reuter, M.A. Limits of Design for Recycling and "Sustainability": A review. Waste and Biomass Valorisation, vol. 2, pp. 183 – 208 (2011).

233. Reuter, M.A. The simulation of industrial ecosystems. Minerals Engineering, vol. 11(10), pp. 891 – 917 (1998).

234. Reuter, M.A., Van Schaik, A., Ignatenko, O. Fundamental limits for the Recycling of end-of-life vehicles. Minerals Engineering, vol. 19(5), pp. 433 – 449 (2006).

235. Reuter, M.A., Van Schaik, A. Thermodynamic Metrics for Measuring the "Sustainability" of Design for Recycling. Journal of Metals, vol. 60(8), pp. 39 – 46 (2008).

236. Reuter, M.A. The Niche of Metallurgy in Design for "Recycling". World of Metallurgy – ERZMETALL, vol. 62(5), pp. 276 – 287 (2009).

237. Reuter, M.A., Van Schaik, A. Material and metal ecology, Encyclopedia of Ecology (Editors-in-Chief: Sven Erik Jorgensen and Brian D. Fath), 1st Edition, Elsevier, BV, Oxford, pp. 2247 – 2260 (2008).

238. Reuter, M.A., Matusewicz, R., Hughes, S., Wood, J. Secondary copper processing using Outotec's Ausmelt TSL process. Plenary Lecture, International Conference, Copper Metallurgy, 50th Anniversary of KGHM, Poland (2011).

239. Reuter, M.A. The simulation of industrial ecosystems. Minerals Engineering, vol. 11(10), pp. 891 – 917 (1999).

240. Reuter, M.A., Van Schaik A. Opportunities and Limits of recycling – A Dynamic-Model-Based Analysis. MRS Bulletin, vol. 37(4), pp. 339 – 347 (special edition on Sustainability) (2012a).

241. Reuter, M.A., Van Schaik A. Opportunities and Limits of WEEE Recycling – Recommendations to Product Design from a Recyclers Perspective. Proceedings for Electronics Goes Green 2012, Eds. Klaus-Dieter Lang, Nils F. Nissen, Andreas Middendorf, Perrine Chancerel, Berlin, Fraunhofer Institute for Reliability and Microintegration IZM, Berlin Technische Universität Berlin, Research Center for Microperipheric Technologies Paper A.5.3 (2012b).

242. Rhodia. Available from: http://www.rhodia.com (accessed December 7th, 2012).

243. Richard, A., van Schaik, A., Reuter, M.A. A comparison of the modelling and liberation in minerals processing and shredding of passenger vehicles. EPD Congress 2005, Edited by M.E. Schlesinger TMS (The Minerals, Metals & Materials Society), pp. 1039 – 1052 (2005).

244. Robinson, B.H. E-waste: An assessment of global production and environmental impacts. Science of the Total Environment, vol. 408, pp. 183 – 191 (2009).

245. Rombach E. et al. Altbatterien als sekundäre Rohstoffressource fur die Metallgewinnung. World of Metallurgy – Erzmetall, vol. 61(3), pp. 180 – 185 (2008).

246. Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Köhler, A., Larsen, H.F., MacLeod, M., Margni, M., McKone, T.E., Payet, J., Schuhmacher, M., van de Meent D., Hauschild, M.Z. USEtox – The UNEP-SETAC toxicity model: recommended characterization factors for human toxicity and freshwater ecotoxicity in Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, vol. 13, pp. 532 – 546 (2008).

247. Ruhrberg, M. Assessing the recycling efficiency of copper from end-of-life products in Western Europe. Resources, Conservation and Recycling, vol. 48, pp. 141 – 165 (2006).

248. Salhofer, S., Spitzbart, M., Maurer, K. Recycling of LCD Screens in Europe – State of the Art and Challenges, Proceedings: J. Hesselbach and C. Herrmann (eds.), Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd – 4th, 2011, DOI 10.1007/978-3-642-19692-8_78, Springer-Verlag Berlin Heidelberg (2011).

249. Sander, K., Schilling, S. Optimierung der Steuerung und Kontrolle grenzüberschreitender Stoffströme bei Elektroaltgeräten/Elektroschrott. Hamburg: Ökopol (2010). Available from: http://www.umweltdaten.de/publikationen/fpdf-l/3769.pdf (accessed December 7th, 2012).

250. Sayilgan, E., Kukrer, T., Civelekoglu, G., Ferella, F., Akcil, A., Veglio, F., Kitis, M. A review of technologies for the recovery of metals from spent alkaline and zinc-carbon batteries, Hydrometallurgy, vol. 97, pp. 158 – 166 (2009).

251. Saurat, M., Bringezu, S. Platinum group metal flows of Europe, part 1: Global supply, use in industry and shifting of environmental impacts. Journal of Industrial Ecology, vol. 12(5/6), pp. 754 – 767 (2008).

252. Van Schaik, A., Reuter, M.A., Boin, U., Dalmijn, W.L. Dynamic modelling and optimization of the resource cycle of passenger vehicles. Minerals Engineering, vol. 15(11), pp. 1001 – 1016 (2002).

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

254. Van Schaik, A., Reuter, M.A. The effect of design on Recycling rates for cars – Theory and practice. Proceedings of the International Automobile Recycling Congress, Geneva, Switzerland, March 10 – 13, 2004, p. 21 (2004b).

255. Van Schaik, A., Reuter, M.A., Heiskanen, K. The influence of particle size reduction and liberation on the Recycling rate of end-of-life vehicles. Minerals Engineering, vol. 17, pp. 331 – 347 (2004).

256. Van Schaik A., Reuter, M.A. The use of fuzzy rule models to link automotive design to Recycling rate calculation. Minerals Engineering, vol. 20, pp. 875 – 890 (2007a).

257. Van Schaik, A., Reuter, M.A. Calculating the Recyclability, Product Design is the Key to High Recycling Rates. Recycling Magazine, vol. 12, pp. 14 – 17. Internet version of Recycling Magazine published by Reed. Available from: http://www.Recycling-magazine.com (accessed December 7th, 2012) (2007b).

258. Van Schaik A., Reuter, M.A. Dynamic modelling of E-waste Recycling system performance based on product design. Minerals Engineering, vol. 23, pp. 192 – 210 (2010a).

259. Van Schaik, A., Reuter, M.A., Van Stokkom, H., Jonk, J., Witter, V. Management of the Web of Water and Web of Materials. Minerals Engineering, vol. 23, pp. 157 – 174 (2010b).

260. Van Schaik, A., Reuter, M.A. Shredding, sorting and recovery of metals from WEEE: linking design to resource efficiency, In: Waste electrical and electronic equipment (WEEE) handbook (Edited by V Goodship, University of Warwick, UK and A Stevels, Delft University of Technology, The Netherlands). Available from: http://www.woodheadpublishing.com/en/book.aspx?bookID=2385 (accessed December 7th, 2012) (2012).

261. Van Schaik, A. Kwantificering kritische grondstoffen in E-waste producten (in commission of Vereniging NVMP). 51p, 2011. Available from: http://www.producenten-verantwoordelijkheid.nl (accessed December 7th, 2012).

262. Van Schaik, A., Reuter, M.A. Modellhaftes Recycling. Recycling Magazine, vol. 04, pp. 26 – 29 (2009).

263. Schneider, W.D., Romberg, T., Schwab, B. Recycling von Zn-Pb-haltigen Reststoffen. Die notwendige Weiterentwicklung des IS-Prozesses, in: "Intensivierung metallurgischer Prozesse", ed.: Liese, F., GDMB, Clausthal-Zellerfeld, Germany, pp. 171 – 182 (2000).

264. Schweiz. Bundesrat. Ordinance of 14 January 1998 on the return, the taking back and the disposal of electrical and electronic equipment (ORDEE) (2004). Available from: http://www.bafu.admin.ch/abfall/01472/01478/index.html?lang=en (accessed December 7th, 2012).

265. Sepúlveda, A, Schluep, M, Renaud, F.G., Streicher, M., Kuehr, R., Hagelüken, C., Gerecke, A.C. A Review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India. Environmental Impact Assessment Review, vol. 30, pp. 28 – 41 (2010).

266. Seppälä, J., Posch, M., Johansson, M., Hettelingh, J-P. Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. International Journal of Life Cycle Assessment, vol. 11, pp. 403 – 416 (2006).

267. Singhal, P. Shaping consumers' behavior for responsible Recycling in India. Proceedings of Going Green Care Innovation, Vienna (November, 2010).

268. Sinha-Khetriwal, D., Kraeuchi P., Schwaninger M. A Comparison of electronic waste recycling in Switzerland and in India. Environmental Impact Assessment Review, vol. 25, pp. 492 – 504 (2005).

269. Sinha-Khetriwal, D., Widmer, R., Schluep, M., Eugster, M., Wang, Xuejun, Lombard, R., Ecroignard, L. Legislating e-waste management: Progress from various countries. Environmental Law Network International, vol. 1+2/06, pp. 27 – 36 (2006).

270. Sinha-Khetriwal, D., Kraeuchi, P., Widmer, R. Producer responsibility for e-waste management: Key issues for consideration – Learning from the Swiss experience. Journal of Environmental Management, vol. 90(1), pp. 153 – 165 (2009).

271. Skinner, A., Dinter, Y., Lloyd, A., Strothmann, P. The Challenges of E-Waste Management in India: Can India draw lessons from the EU and the USA? The Journal of Contemporary Asia, 117, pp. 7 – 26. (2010).

272. SLC – SuperLightCar, 6th framework EU project. Available from: http://www.superlightcar.com (accessed December 7th, 2012). Project leader Volkswagen (2005 – 2009). Project brochure available from: http://www.superlightcar.com/public/docs/SuperLIGHTCar_project_brochure.pdf (accessed December 7th, 2012).

273. SMS-Siemag. Available from: http://www.sms-siemag.com (accessed December 7th, 2012).

274. UNEP. Life Cycle Management: A Business Guide to Sustainability, ISBN 978 – 92-807-2772-2, p. 52 (2007).

275. Balkau, F., Sonnemann G. Managing sustainability performance through the value-chain. Corporate Governance, vol. 10(1), p. 46 (2010).

276. Stamp, A., Meskers, C.E.M., Reimer, M., Wäger, P., Althaus, H.-J., Scholz, R.W. Challenges for LCAs of Complex Systems: The Case of a Large-Scale Precious Metal Refinery Plant, in: Finkbeiner, M., (Ed.). Towards Life Cycle Sustainability Management. Springer Netherlands, pp. 247–258 (2011).

277. Stehlik, P. Contribution to advances in waste-to-energy technologies. Journal of Cleaner Production, vol. 17, pp. 919–931 (2009).

278. Szargut, J. Exergy method. Technical and Ecological Applications, WitPress, Southampton, Boston, p. 192 (2005).

279. Tam, V.W.Y., Tam, C.M. A review on the viable technology for construction waste recycling. Resource Conservation Recycling, vol. 47, pp. 209–221 (2006).

280. Tanskanen, P. Takala, R. A decomposition of the End of Life process. Journal of Cleaner Production, vol. 14, pp. 15–16, (2006).

281. Titech. Available from: http://www.titech.com (accessed December 7th, 2012).

282. Toxco. 2003. Available from: http://www.toxco.com/processes.html (accessed December 7th, 2012).

283. Toyota Tsusho Corporation, Toyota Tsusho Promotes Plan for Construction of Rare Earth Manufacturing Plant in India (2010). Available from: http://www.toyotatsusho.com/english/press/2010/12/20101208-3590.html (accessed December 7th, 2012).

284. Truttmann, N. Rechberger, H. Contribution to resource conservation by reuse of electrical and electronic household appliances. Resources, Conservation and Recycling, vol. 48, pp. 249–262 (2006).

285. Tuncuk, A., Stazi, V., Akcil, A., Yazici, E.Y., Deveci, H. Aqueous metal recovery techniques from e-scrap: Hydrometallurgy in recycling. Minerals Engineering, vol. 25, pp. 28–37 (2012).

286. Ullmann's Encyclopedia of Industrial Chemistry, Numerous Metal/Element/Compound/Alloy/Materials Chapters in Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany (2005).

287. Umicore/Rhodia: Press release. CP-2011-18-R Umicore and Rhodia develop unique rare earth Recycling process for rechargeable batteries. 16th June 2011 (2011). Available from: http://www.rhodia.com/en/news_center/news_releases/Umicore_rare_earth_160611.tcm (accessed December 7th, 2012).

288. Umicore. Umicore Technology. Brochure (May 2010). Available from: http://www.batteryrecycling.umicore.com/UBR/process (accessed December 7th, 2012).

289. Umicore, Belgium. Available from: http://www.umicore.com (accessed December 7th, 2012).

290. UNEP. StEP Report: Recycling – From E-waste to Resources. Berlin, Germany, p. 120 (2009). Available from: http://www.unep.org and www.step-initiative.org (accessed 6th December 2012).

291. UNEP. Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication, ISBN: 978-92-807-3143-9 (2011). Available from: http://www.unep.org/greeneconomy (accessed December 7th, 2012).

292. UNEP. Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel. Fischer-Kowalski, M., Swilling, M., von Weizsäcker, E.U.,

Ren, Y., Moriguchi, Y., Crane, W., Krausmann, F., Eisenmenger, N., Giljum, S., Hennicke, P., Romero Lankao, P., Siriban Manalang, A., Sewerin, S. (2011a).

293. UNEP. Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials, A Report of the Working Group on the Environmental Impacts of Products and Materials to the International Panel for Sustainable Resource Management. Hertwich, E., van der Voet, E., Suh, S., Tukker, A, Huijbregts M., Kazmierczyk, P., Lenzen, M., McNeely, J., Moriguchi, Y. (2010).

294. UNEP. 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., Alwood, J., Birat, J.-P., Reck, B.K., Sibley, S.F., Sonnemann, G., Buchert, M., Hagelüken, C., 2011b. Available from: http://www.unep.org/resourcepanel/Portals/24102/PDFs/Metals_Recycling_Rates_110412-1.pdf (accessed December 7th, 2012).

295. U.S. Geological Survey (USGS). Rare Earth Elements—Critical Resources for High Technology, USGS Fact Sheet 087-02 (2002). Available from: http://www.usgs.gov (accessed December 7th, 2012).

296. U.S. Geological Survey (USGS). The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective Scientific Investigations Report 2010. 5220 U.S. Department of the Interior U.S. Geological Survey. Reston, Virginia, p. 104. Available from: http://www.usgs.gov (accessed December 7th, 2012).

297. U.S. Geological Survey, Mineral commodity Summaries, Yttrium (2010b). Available from: http://www.usgs.gov (accessed December 7th, 2012).

298. U.S. Geological Survey, Mineral commodity summaries. U.S. Geological Survey, p. 193 (2010c). Available from: http://minerals.usgs.gov/minerals/pubs/mcs/. (accessed December 7th, 2012).

299. U.S. Geological Survey. Historical Statistics for Mineral and Material Commodities in the United States (2011). Available from: http://minerals.usgs.gov/ds/2005/140/#data (accessed December 7th, 2012).

300. Van der Zee, D.J., Achterkamp, M.C., de Visser, B.J. Assessing the Market Opportunities of Landfill Mining. Waste Management, vol. 24(8), pp. 795 – 804 (2004).

301. Fthenakis, V.M. End-of-life management and Recycling of PV modules, Energy Policy, vol. 28, pp. 1051 – 1058 (2000).

302. Veenstra, A., Wang, C., Fan, W. and Ru, Y. An analysis of E-waste flows in China. International Journal of Advanced Manufacturing Technology, vol. 47(5 – 8), pp. 449 – 459 (2010).

303. Venkateswaran, S. et al. W-Scrap Recycling by the Melt Bath Technique. International Journal of Refractory Metals & Hard Materials, vol. 14, pp. 263 – 270 (1996).

304. Vermeulen, I., et al. Automotive shredder residue (ASR): Reviewing its production from end-of-life vehicles (ELVs) and its Recycling, energy or chemicals' valorization. Journal of Hazardous Materials, vol. 190, pp. 8 – 27 (2011).

305. Verhoef, E., Dijkema, G., Reuter, M.A. Process knowledge, system dynamics and metal ecology. Journal of Industrial Ecology, vol. 8(1 – 2), pp. 23 – 43 (2004).

306. Volkswagen. Available from: http://www.volkswagen.com (accessed December 7th, 2012).

307. Voss, R. What new challenges confront the merchant and recycler today? Copper Recycling Conference, Brussels (11 – 13 June 2012).

308. Wäger, P.A., Hischier, R. Eugster, M. Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): A follow-up. Science of the Total Environment, vol. 409, pp. 1746 – 1756 (2011).

309. World Business Council of Sustainable Development WBCSD. Available from: http://www.wbcsd.org (accessed December 7th, 2012).

310. Wecycle, Nederland (2011). Available from: http://www.wecycle.nl (accessed December 7th, 2012).

311. Von Weizsäcker, E.U., Hargroves, K., Smith, M.H., Desha, C., Stasinopoulos, P. Factor Five – Transforming the Global Economy through 80 % Improvements in Resource Productivity, Earthscan, p. 448 (2009).

312. Welz,T., Hischier, R., Hilty, L.M. Environmental impacts of lighting technologies – Life cycle assessment and sensitivity analysis. Environmental Impact Assessment Review, vol. 31, pp. 334 – 343 (2011).

313. Widmer, R., Schluep, M., Denzler, S. The Swiss Global e-Waste Programme. Waste Management Conference (WasteCon2008). Durban, South Africa (2008).

314. Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H. Global Perspectives on e-waste. Environmental Impact Assessment Review, vol. 25, pp. 436 – 458 (2005).

315. Williams, E., Kahhat, R. Allenby, B., Kavazanjian, E., Kim, J., Xu, M. Environmental, Social, and Economic Implications of Global Reuse and Recycling of Personal Computers. Environmental Science & Technology, vol. 42, pp. 6446–6454 (2008).

316. Witik, R.A., Payet, J., Michaud, V., Ludwig, C., Månson, J-A. Assessing the life cycle costs and environmental performance of lightweight materials in automobile Applications. Composites: Part A, vol. 42, pp. 1694–1709, (2011).

317. World Steel Association, Sustainable steel at the core of a green economy, 2013. Available from: http://www.worldsteel.org/dms/internetDocumentList/bookshop/Sustainable-steel-at-the-core-of-a-green-economy/document/Sustainable-steel-at-the-core-of-a-green-economy.pdf (accessed April 10th, 2013).

318. Xiao, Y., Reuter, M.A. Recycling of distributed aluminium turning scrap. Minerals Engineering, vol. 15, pp. 963–970 (2002).

319. Xu J. et al. A review of processes and technologies for the Recycling of lithium-ion secondary batteries. Journal of Power Sources, vol. 177, pp. 512–527 (2008).

320. Xua, J., Thomas, H.R., Francis, R.W., Lumb, K.R., Wang, J., Liang, B. A review of processes and technologies for the Recycling of lithium-ion secondary batteries. Journal of Power Sources, vol. 177, pp. 512–527 (2008).

321. Yellishetty, M., Mudd, G.M., Ranjith, P.G., Tharumarajah, A. Environmental life-cycle comparisons of steel production and Recycling: Sustainability issues, problems and prospects. Environmental Science & Policy, vol. 14, pp. 650–663 (2011).

322. Yokoyama, K., Kubo, H., Mori, K., Okada, H., Takeuchi, S. and Nagasaka T. Separation and recovery of phosphorus from steelmaking slags with the aid of strong magnetic field. ISIJ International, vol. 47, pp. 1541–1548 (2007).

Acronyms and Definitions

ADP	Abiotic Depletion
AHSS	Advanced High Strength Steel
AOD	Argon Oxygen Decarburization (stainless steel converter)
ASR	Automotive Shredder Residue
BAT	Best Available Technique
BIR	Bureau of International Recycling
BIW	Body-in-White (term for basic structure of automobile)
BOF	Basic Oxygen Furnace (steel converter)
CAD	Computer-Aided Design
CAPEX	Capital Expenditure
C2C/CtC	Cradle-to-Cradle
Carrier Metals	Metals that form the backbone of recycling—commodity or base metals in industry jargon—and the basis of the complete metallurgical and technological infrastructure for the recovery of their various thermodynamically associated minor elements from the earth's minerals. Modern consumer products and their unique mixtures challenge this infrastructure due to their incompatibility with basic thermodynamics. Therefore for optimal resource efficiency, a network of carrier metal production facilities must be maintained at BAT level.
CO_2eq	Equivalent CO_2 (each Greenhouse gas is scaled relative to CO_2 and added to obtain the CO_2eq)
DfD	Design for Dismantling
DfE	Design for Environment
DfR	Design for Recycling
DfS	Design for Sustainability
DfRE	Design for Resource Efficiency
EoL	End of Life
EEE	Electrical and Electronic Equipment
EEP	European Environmental Protection
ELFM	Enhanced landfill management
ELV	End of Life Vehicle
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
ET	Ecotoxicity

EU27	EU 27 Membership Countries (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom)
EWM	Enhanced Waste Management
Exergy	The availability of energy stored within material and energy flows
HT	Humantoxicity
IRP	International Resource Panel (UNEP)
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LCI	Life Cycle Inventory
LCM	Life Cycle Management
LED	Light-Emitting Diode
LFM	Landfill Management
LIBS	Laser-Induced-Breakdown-Spectroscopy
LME	London Metal Exchange
Material Centric	Recycling that considers only single elements, i. e. one at a time without the non-linear interactions between all connected materials to that element. This is the basis for the data in the 1st UNEP report on recycling.
MFA	Mass Flow Analysis
Multiphysics	Studies that combine hitherto separate physical disciplines, to generate relational mathematical models and validate them with controlled experiments for enhancing the understanding of natural behaviour. A recycling system can only be understood with a full grasp of all physics describing it.
ODP	Ozone Layer Depletion Potential
OEM	Original Equipment Manufacturer
OLED	Organic Light-Emitting Diode
OPEX	Operating Expenses
PGM	Platinum Group Element
PM	Precious Metal
POCP	Photochemical Ozone Creation Potential
ppm	Part per million

Product Centric	Recycling that considers the entire product, including all non-linear interactions of materials on the recycling of all metals, elements and materials from complex products and their designer "minerals" similarly as is the basis for processing of geological minerals. To calculate this, requires detailed flowsheeting as well as considering the physics involved. This is the topic of the present report, in addition to defining multi-dimensional and non-linear definitions for recycling. This approach quite naturally leads to techniques for reuse, etc., for improving resource efficiency to be included in optimizing the recycling system.
PST	Post Shredding Technology
PWB	Printed Wire Board (also called Printed Circuit Board – PCB, but this may be confused with PCBs, the chemical)
Recyclate	Raw material sent to, and processed in, a waste recycling plant or materials recovery facility.
REE	Rare Earth Element
REO	Rare Earth Oxide
SHA	Small Home Appliance
SLC	Super Light Car (Volkswagen-led EU project)
tpa	tonnes per annum (metric)
UNEP	United Nations Environmental Programme (www.unep.org)
USGS	United States Geological Survey
WBCSD	World Business Council of Sustainable Development
WEEE	Waste Electrical and Electronic Equipment
WIO	Waste Input-Output
WtoE	Waste to Energy
XRF	X-Ray Fluorescence
XRT	X-Ray Transmission

Alphabetic list of all elements and their names, symbols and atomic numbers
Actinium Ac 89 – Aluminium Al 13 – Americium Am 95 – Antimony Sb 51 – Argon Ar 18 – Arsenic As 33 – Astatine At 85 – Barium Ba 56 – Berkelium Bk 97 – Beryllium Be 4 – Bismuth Bi 83 – Bohrium Bh 107 – Boron B 5 – Bromine Br 35 – Cadmium Cd 48 – Calcium Ca 20 – Californium Cf 98 – Carbon C 6 – Cerium Ce 58 – Cesium Cs 55 – Chlorine Cl 17 – Chromium Cr 24 – Cobalt Co 27 – Copper Cu 29 – Curium Cm 96 – Darmstadtium Ds 110 – Dubnium Db 105 – Dysprosium Dy 66 – Einsteinium Es 99 – Erbium Er 68 – Europium Eu 63 – Fermium Fm 100 – Fluorine F 9 – Francium Fr 87 – Gadolinium Gd 64 – Gallium Ga 31 – Germanium Ge 32 – Gold Au 79 – Hafnium Hf 72 – Hassium Hs 108 – Helium He 2 – Holmium Ho 67 – Hydrogen H 1 – Indium In 49 – Iodine I 53 – Iridium Ir 77 – Iron Fe 26 – Krypton Kr 36 – Lanthanum La 57 – Lawrencium Lr 103 – Lead Pb 82 – Lithium Li 3 – Lutetium Lu 71 – Magnesium Mg 12 – Manganese Mn 25 – Meitnerium Mt 109 – Mendelevium Md – 101 Mercury Hg 80 – Molybdenum Mo 42 – Neodymium Nd 60 – Neon Ne 10 – Neptunium Np 93 – Nickel Ni 28 – Niobium Nb 41 – Nitrogen N 7 – Nobelium No 102 – Osmium Os 76 – Oxygen O 8 – Palladium Pd 46 – Phosphorus P 15 – Platinum Pt 78 – Plutonium Pu 94 – Polonium Po 84 – Potassium K 19 – Praseodymium Pr 59 – Promethium Pm 61 – Protactinium Pa 91 – Radium Ra 88 – Radon Rn 86 – Rhenium Re 75 – Rhodium Rh 45 – Rubidium Rb 37 – Ruthenium Ru 44 – Rutherfordium Rf 104 – Samarium Sm 62 – Scandium Sc 21 – Seaborgium Sg 106 – Selenium Se 34 – Silicon Si 14 – Silver Ag 47 – Sodium Na 11 – Strontium Sr 38 – Sulfur S 16 – Tantalum Ta 73 – Technetium Tc 43 – Tellurium Te 52 – Terbium Tb 65 – Thallium Tl 81 – Thorium Th 90 – Thulium Tm 69 – Tin Sn 50 – Titanium Ti 22 – Tungsten W 74 – Ununbium Uub 112 – Ununhexium Uuh 116 – Ununoctium Uuo 118 – Ununpentium Uup 115 – Ununquadium Uuq 114 – Ununseptium Uus 117 – Ununtrium Uut 113 – Ununium Uuu 111 – Uranium U 92 – Vanadium V 23 – Xenon Xe 54 – Ytterbium Yb 70 – Yttrium Y 39 – Zinc Zn 30 – Zirconium Zr 40

International Resource Panel

As our economies have grown, so has the use of materials and resources. In an increasingly globalised economy, the challenge for policy-makers is to streamline actions for ensuring a more sustainable management of resources, both renewable and non-renewable. There are existing measures such as policies on climate change and biodiversity that tackle certain aspects of the global resource issues. However a holistic approach to resources management is needed to better identify their interlinkages and gaps in a systemic way.

The establishment of the International Resource Panel, or Resource Panel for short, is a first step towards addressing this need. Hosted at UNEP, the Resource Panel was officially launched in November 2007 to provide the scientific impetus for decoupling economic growth and resource use from environmental degradation.

The objectives of the Resource Panel are to provide independent, coherent and authoritative scientific assessments of policy relevance on the sustainable use of natural resources and in particular their environmental impacts over the full life cycle as well as to contribute to a better understanding of how to decouple economic growth from environmental degradation.

This work builds on and contributes to other related international initiatives, including the 10-Year Framework of Programmes on Sustainable Consumption and Production (10YFP) and the Green Economy Initiative.

Global Metal Flows Working Group

Economic development is deeply coupled with the use of metals. The growing demand for metals implies a permanent pressure on the resource base. Metals are resources that have a high value and in principle can be easily reused and recycled. Reuse and recycling activities of metals on a global scale can contribute to closing the loops, turn waste into resources, and are expected to thereby reduce environmental impacts, safeguard the availability of metals, minimize metal prices, and promote meaningful and safe jobs for poor people in developing countries.

The Global Metal Flows Working Group aims at contributing to the promotion of reuse and recycling of metals and the establishment of an international sound material-cycle society by providing scientific and authoritative assessment studies on the global flows of metals. Expected results include revealing potentials for increasing the resource efficiency of metal flows at the national and international level.

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 Global Metal Flows Group envisions a series of six reports, of which this is the second-b one addressing opportunities, limits and infrastructure for metal recycling. This report follows the IRP's first report on recycling, which has demonstrated the status quo of global recycling rates for sixty metals.

Product-Centric recycling is discussed in this report by acknowledged experts. This approach is considered to be an essential enabler of resource efficiency by increasing recycling rates. Due to complex functionality, modern products contain complex mixes of almost any imaginable metal, material and compound. This report provides a techno-economic, product design and physics basis to address the challenges of recycling these increasingly complex products in the 21st century.

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