Challenges of metals recycling

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Introduction

The metals in the earth's crust have clustered in certain locations in much higher concentrations than average due to geothermal processes. This great ecoservice provided by nature has made it possible for society to produce metals. However, the earth has its boundaries and in that sense the amount of metals is limited. Nevertheless, many predictions of the availability of metals have failed as they have been based on the known and predicted ore reserves at that time. Here the definition of metal ore is important: ore is a mineralization from which it is economically feasible to produce metals. Thus the price of metals and even more the technology with which the metal is extracted from the ore play a very important role.

The Brundtland Report [BRUN] devotes Chapter 2 to discussing the "Interlocking Crisis," alluding to the complex systems that connect our activities to nature. Resource efficiency can be improved significantly by recycling, not only through the reuse of non-renewable resources through making end-of-life products available as a resource, but it can also significantly increase the availability of various metals (some presently critical, which could have ended in landfill) contributing to the sustainability-enabling infrastructure. Significant metal will be required for sustainability-enabling technology such as in energy (e.g. solar, wind, smart grids), water purification (e.g. various technologies to enhance water quality such as sensors, filter materials, smart water systems), transport (e.g. electric cars, planes), building (e.g. various materials in eco-cities), to name a few [REU1]. The Brundtland definition for sustainability [BRUN] as stated in paragraph #27 is: *"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"*. In Chapter 8 the Brundtland report discusses *"Industry: Producing More With Less"*, which is at the heart of recycling. This key theme was taken up by the World Business Council on Sustainability Development as *"Doing more with less"* [WBCSD]. Key issues of importance to achieve the transition to this vision are "Phasing out landfill", "Closing the loop", "Four to tenfold increase in resource efficiency", while also highlighting the importance of materials in the interlocking system of our society to achieve sustainability in the world. Of particular importance is "Resource Efficiency", i.e. the decoupling of welfare and environmental impact by the World Council on Sustainable Development.

Resource efficiency through recycling can be explained as follows: *"Resource efficiency means reducing the environmental impact of the consumption and production of goods and services over their full life cycle. The 'doing more with less' slogan indicates the focus on more outputs with fewer impacts (fewer resources, less pollution, fewer impacts on the conditions of poor people). Efficiency gains do not however guarantee that the overall outcome stays within the ecological carrying capacity of the Earth. Influencing the demand side is therefore another prerequisite for sustainable development. It will only be by a combination of resource efficiency and resource sufficiency measures that the ultimate goal of sustainable consumption and production patterns can be achieved."* [UNEP1]. The recyclability of metals makes it possible for future generations to use the same metals that have already been used, therefore providing a service to our descendants by mining the ore and refining it to metal. It may be pointed out that in the future mining and metals extraction will not be as energy intensive as today, but metal is needed today and will continue to be needed in the future and recycling will help to reduce the footprint.

Some restrictions concerning metals recycling

Table 1 shows simplistically the global recycling rates of some metals. The values given in Table 1 are low compared to the political targets of recycling 100% of the material contained in the products. One of the reasons for this is that the recycling rates (recollecting) of End-of-Life (EoL) products remain low, because the motivation to return expensive EoLs is still low and also the global collection systems are not yet ready to absorb all the material that could be available for recycling. This is increasingly important today, when the lifetime of products is shorter and shorter. Society should prevent these materials ending up in municipal solid waste and landfill, from where the recovery of the metals is possible, but laborious due to the complex “landfill mineralogy”.

A simplistic description of recycling for metals is depicted in **Figure 1** [UNEP2], which is also often the basis for describing the various recycling rates used for metals. While this approach to recycling gives an indication of the recycling rates of commodity metals (which are often used to a large extent in relatively simple but important applications, e.g. various alloys of steel (incl. stainless) and aluminum, copper etc.), this abstraction fails in relation to multi-material products with a large number of elements in functional proximity [REU1-3]. This primary resource-based approach is discussed here as the metal/material centric view of recycling.

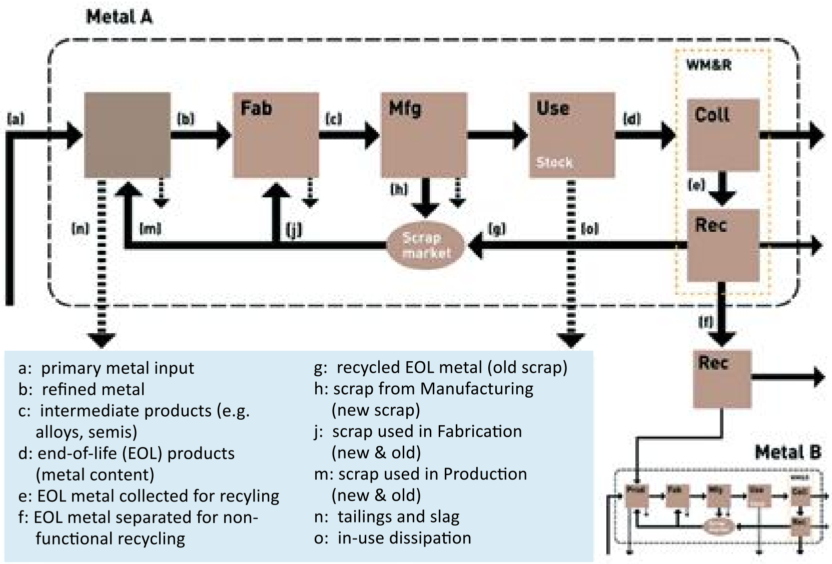


Figure 1. *A metal/material-centric view of recycling: Linear and sequential representation of recycling for non-complex metal application such as in construction, packaging etc. [UNEP1]*

Metal	**Global recycling rate, %**
Aluminum	40
Copper	38
Iron/steel	47
Lead	47
Nickel	34
Zinc	36

Table 1. *Indicative global recycling rates of some metals – values depend on the measure used and should usually be defined as a range due to the complexity of recycling systems ([NOR] & [REU2])*

An important restriction on recycling is that the availability of the metallic materials to be recycled is much lower than the annual metal consumption. The use of metals is increasing with a rate that is higher than ever. This rate increase, however, is still mainly based on material use in construction, durable goods, machinery and other installations, the lifetime of which is long, meaning the material will only return for recycling after a relatively long period of time. Thus the amount of what is called stock of material in use is increasing. For example, for aluminum the total aluminum in use (including the stocks in municipal solid waste (MSW) facilities) in 2006 was 586 million metric tons and the annual net addition to that stock was 24.4 million metric tons. From that amount only 7.8 million metric tons of aluminum was recycled. It must be noted that the amount of non-recycled (wasted) aluminum was 3.9 million metric tons, which is alarming [MEN]. This means that there is simply not enough material to be recycled. Most of the materials entering stock in use are in China. The same happened in the US after the Second World War, when more than 70% of the world’s annual copper production entered stock in use in that country.

Many consumer products are much more complex than those described in Figure 1. In contrast to a material centric approach to recycling, a product-centric view of recycling is more representative of the recycling of complex consumer goods, which is evident from the complexity shown in Figure 2, which also explains the low recycling rates that are achieved.

Figure 2 depicts the complexity of recycling, especially the fact that all

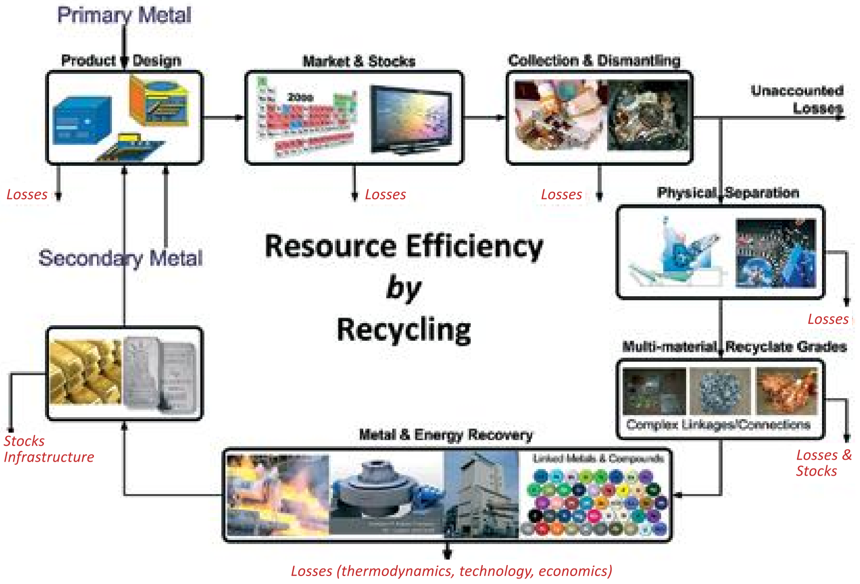


Figure 2. *A product-centric view of recycling: A multi-dimensional dynamic first-principles view to quantify the resource efficiency of all elements over the life cycle of simple and complex products simultaneously. [REU3]*

elements in products have to be considered simultaneously. Thus, it is a truly complex multi-dimensional dynamic problem, to be optimized in its entirety in order to reach minimum losses, i.e. to maximize resource efficiency. It is pointless simplifying it to one-metal-at-a-time metal flows, which do not include the physics of their connections or consider all the chemical/thermodynamic interactions (alloys, compounds etc.) that take place while hydro- and/or pyrometallurgically treating the recyclates. In other words, it should be self-evident that the Resource Efficiency of metals is not only to be considered in a one-dimensional manner (Figure 1); instead, complex interactions as shown in Figure 2 are at the heart of optimizing recycling. The degree of recycling is determined and limited by the quality of the scrap that is fed into what the "normal" operation of a smelting or melting unit operation allows as well as by the chemical/thermodynamic interactions.

Driver for Recycling?

Finland has been a benchmark for recycling, e.g. glass milk and other bottles as well as paper have been recycled in the country for over half a century. The motivation to do this has been the refund or reward related to the return of the object or material. Strictly speaking, the return of bottles in the early days would be categorized today as reuse and the return of paper waste would be categorized as recycling (if the paper is targeted for a paper mill instead of an incineration plant). Metals have also been recycled effectively throughout history; cannons have been cast from bronze statues (and vice versa). It has been calculated that around 80% of the copper ever produced is still in use. The motivation for recycling may be different but the main issue is that metals are easy to recycle and almost 100% recyclable if 100% collected and in PURE form! As metallic scrap has a monetary value, this is an obvious incentive for metals recycling.

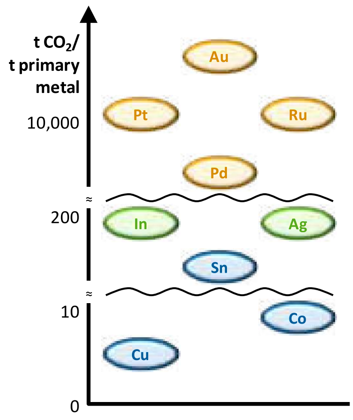
Therefore, if metal scrap is available for remelting and it is economically viable to do so, a metallurgical (hydro- and/or pyro-) plant will process it on the back of its normal operation. The scrap price may be directly or indirectly influenced by the metal price, which is related to the physics of recovery. In other words, this also implies that if less energy is used, therefore at lower cost, the system will be more profitable and more resource efficient. To illustrate this consider the following: **Figure 3** shows the average tonnes of CO_2 that are created during the primary production of metals *(compare to 30,500 Mt CO_2 in total produced in 2010)*. Recycling of metals is often "simply" a remelting operation with a fraction of the emissions quoted in Figure 3. For example, it has been estimated that the energy consumption in Europe to produce steel from primary raw materials is in the range of 20-42 GJ/ tonne of steel and the same using recycled raw material is in the range of 9-13 GJ/t of steel. This means a dramatic saving in energy costs but also savings in relation to carbon dioxide emissions, which in this example would decrease from 1.4 tonnes CO_2 to 0.55 metric tonnes CO_2 per tonne of steel [STEEL], with correspondingly less impact on nature, thus implying a higher resource efficiency. However, this value will increase as scrap becomes more complex, if compounds of metals or metal mixtures in complex products are recycled simultaneously, which in turn will increase energy consumption and require a more sophisticated approach to recycling as will be shown below. The transport of scrap and its carbon footprint also play a role.

Where economics has failed to drive recycling, important legislation has been implemented e.g. recycling is motivated by directives such as 2008/98/EU [EU4] , which forms the basis for Finland's new Waste Act (01.05.2012). In this the waste hierarchy is determined to be the prevention of waste, reuse of waste, recycling of waste, other recovery such as energy production via incineration, and at the bottom the disposal of waste.

Therefore, some key questions can be asked: Are the relatively simple metal/material-centric recycling rates that underlie Figure 1 a metric revealing the rich details of multi-dimensional complexity and physics (and the related economics) of the system? Is this enough detail to facilitate improved resource efficiency? We will now discuss and shed some light on the issues that have to be surmounted in order to improve the performance of the recycling system.

Resource Efficiency through Best Available Technology (BAT)

Scrap metals, and also metals and their compounds in End-of-Life (EoL) goods, often have to be either smelted (i.e. with chemical change) or simply remelted (if in metal and alloy form and not contaminated by contained and attached materials) to bring them back into the cycle. The importance of extractive metallurgy as enabling, "loop-closing" technology is therefore self-evident as also reflected in Figure 2, showing that the product (and the material it contains) cycle rests on the "Metal & Energy Recovery" block. Metallurgical ingenuity has helped the industry to drive the resource efficiency of ferrous and base metals (e.g. steel, stainless steel, aluminum, copper, zinc, lead, nickel, tin) using Best Available Technology (BAT) ever nearer the limits that are permitted by physics, although the industry's in some cases continuing use of non-BAT technologies leaves room for improvement. Remelting scrap arising from relatively "simple" products such as packaging, infrastructure metals/alloys, transport, die-castings, etc., using large quantities of bulk metal/alloy, is carried out routinely today, provided that the scrap quality is within the bandwidth required/permitted by the market. Usu-



Metals used in EEE	Demand for EEE	Primary production intensity	CO_2 emissions	Source, data year
	t/a	t CO_2/t metal	Mt/a	
Gold	327	16,991	5.56	GFMS, 2010
Platinum	8	13,954	0.11	JM, 2011
Ruthenium	16	13,954	0.22	JM, 2011
Palladium	30	9,380	0.28	JM, 2011
Silver	4,917	144	0.71	GFMS, 2010
Indium	717	142	0.10	Roskill, Metal Pages, 2010
Tin	129,708	16	2.09	ITRI, RESOLVE, 2010
Cobalt	16,470	8	0.13	CDI, 2010
Copper	7,174,000	3	24.39	GFMS, 2010
CO_2 total [Mt/a]			**33.58**	

Figure 3. *Carbon footprint of selected elements in EEE (Electrical and Electronic Equipment) goods [EU2] compared to 30,500 Mt/a global emission in 2010. [Umicore, UNEP3]*

ally these scrap types arise as bulky and well-defined materials or well sorted/dismantled parts or liberated materials from complex products.

Modern products and hence the associated resource cycles and efficiencies are becoming increasingly complex e.g. modern multi-material (electric) cars, electrical and electronic equipment, solar cells, planes, windmills (**Figure 4**) and various other sustainability-enabling products, to name just a few. Product design has engineered a large variety of different materials into close proximity with one another for reasons of functionality for example, resulting in EoL scrap becoming increasingly impure and contaminating the traditional commodity metals and their alloys. This has large implications for metal purity and recovery, as all of the elements in some or other way affect each other during physical processing and metallurgical recovery, demanding a more detailed and sophisticated approach. If product design brings thermodynamically compatible materials in close proximity, then metallurgical technology can deal with them well, hence true Design for Recycling.

The BAT of extractive metallurgy and its underlying physics and associated mineralogy are captured in the Metal Wheel (**Figure 5**). It is organized by main commodity Carrier Metals. Each slice within the Metal Wheel shows the Carrier Metal, i.e. the metal used in large quantities for commodity products. The carrier metal minerals are the principal components in an ore/mineral and concentrate (the inside ring that drives the mining of the ore). Each metal wheel slice shows the elements associated geologically (and hence thermodynamically) with them. Over the years, the recovery of each valuable element has been optimized by various BAT technologies, often in one metallurgical complex, while the ultimate loss of elements (compounds) to the outside green ring has been minimized at the lowest possible energy consumption (hence highest efficiency), the ultimate goal of resource efficiency. Metallurgical plants processing scrap produced from "simpler" commodity products can operate comfortably within the thermodynamic, technological and resulting economic constraints of a single slice of the Metal Wheel. Obviously, if complex multi-material products have metals (and their alloys and compounds) that fall into more than one slice of the Metal Wheel, the extractive metallurgy based on one slice of the Metal Wheel will run into problems as the thermodynamics of the different elements and their compounds are incompatible. This suggests that the metallurgy, physics and the infrastructure to process these materials have to fall into more than one slice of Carrier Metals (Alloy) in order to be able to process these products and contained metals (and their compounds & alloys) well, while at the same time operating with economies of scale to remain profitable. In short, where steel recycling has to cope with Cu, Sn and Sb and generally operates comfortably within a single

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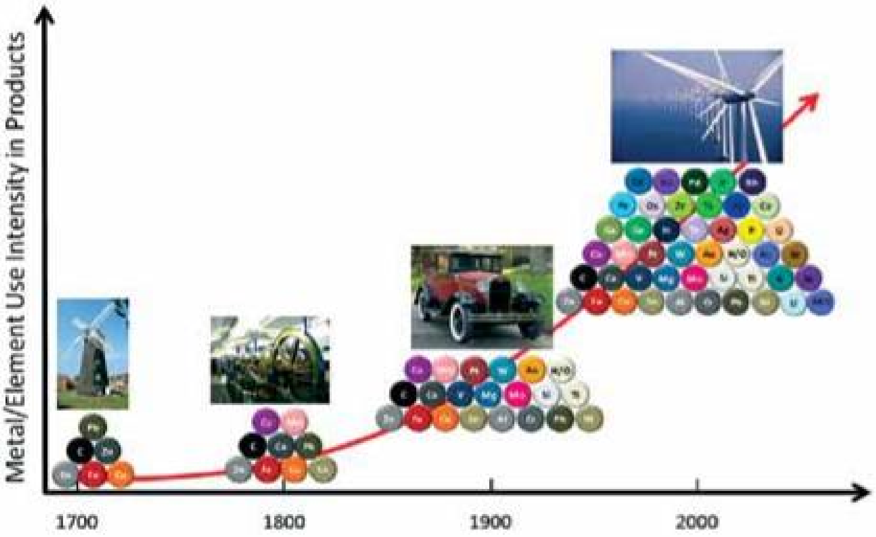


Figure 4. *The ever-increasing use of complex mixtures of metals in products: this has a key effect on the recyclability of metals as the designed element combinations start spilling outside the constraints of thermodynamically compatible separation as shown in the Metal Wheel (Adapted from [ACH]).*

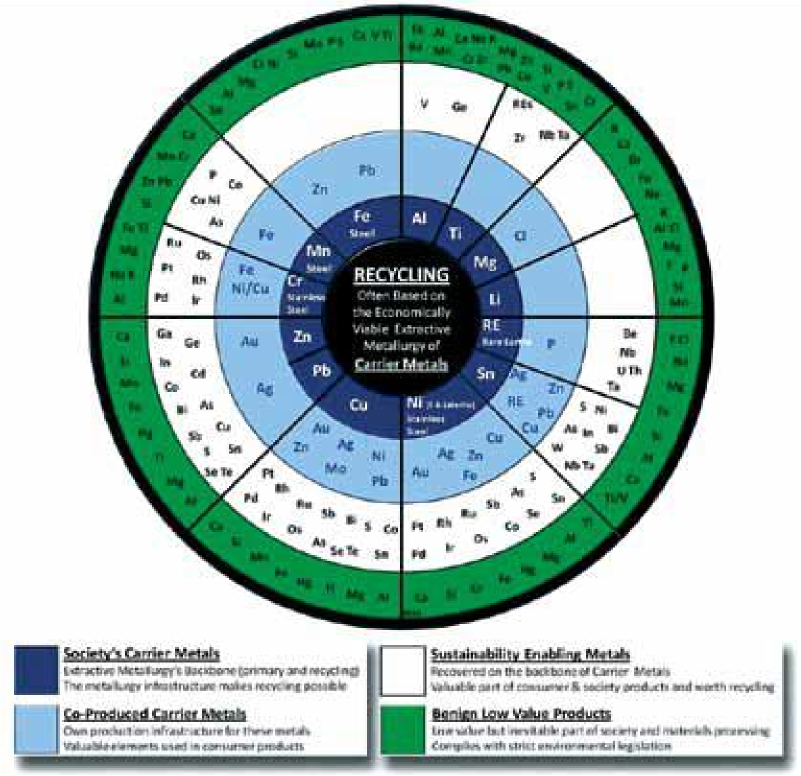


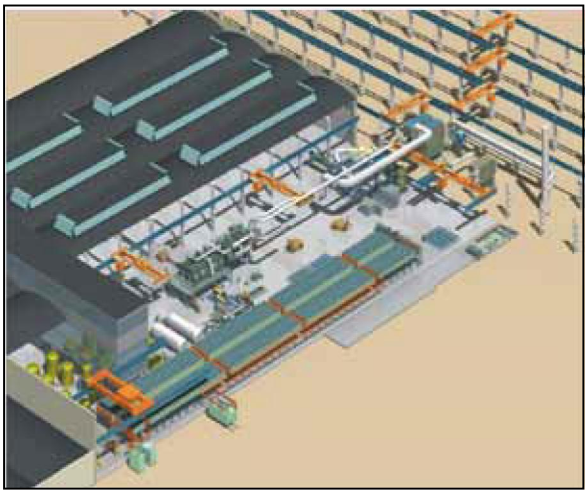
Figure 5. *Recycling Metal Wheel reflecting that knowledge of recovering carrier elements (commodity/base metals/alloys) is implicitly linked to the recovery/recycling of minor elements i.e. base and minor metal extractive metallurgy. Metals in the green band may, as compounds, substitute natural resources: e.g. slags substitute natural sand. [Updated from the original REU 1]*

slice of the Metal Wheel, complex post-consumer scrap such as e-Waste may have to account for 50+ elements at the same time. While the former already poses a formidable complex metallurgical problem to create steel qualities for high tech applications, the 50+ elements are an even larger process metallurgical, thermodynamic and economic puzzle to solve. This is a daunting task, and lies at the heart of resource efficiency.

Therefore, successful e-waste processing facilities are based on two or more carrier metals. This is practiced by for example Boliden (Sweden), Umicore (Belgium), Dowa (Japan), and Aurubis (Germany), which have a combination of deep-rooted lead/zinc and copper primary smelting know-how and infrastructure, forming the basis for maximized recovery of metals from these products. Recycling of new products and material combinations, outside the existing infrastructure, requires the addition of smelting competence in other carrier metals.

The clever use of thermodynamics and appropriate technology reflected in the Metal Wheel by forward-looking innovative companies, within the constraints of economics, is driving this innovation. It is an example of exploring the limits and opportunities of recycling based on both existing and new infrastructures. The boundaries of resource efficiency are being pushed by a combined understanding of fundamental science, process technology and economics. It is clear that the thermodynamic basis of the Metal Wheel shows what is constraining traditional smelters and their recycling capability. It also shows the ingenuity that innovative smelters and their highly trained employees have come up with to expand their traditional core competences into a capability to process complex scrap and the multitude of metals, alloys and compounds of modern complex products. These visionary smelters understand the full implications of what the Metal Wheel expresses and use it for innovation.

Figure 6. *Outotec® MiniMill for copper-containing scrap.*



Various Outotec technologies exist to supply the metals required in sustainability enabling products. Recycling plays an extremely important part in ensuring that the supply of various metals meets the demands of a future sustainable society. Outotec has been in the recycling business for a very long time. One example of this is the "MiniMill" (**Figure 6**) supplied to a Russian customer "Novgorodsky Metallurgichesky Zavod," which included a 30t copper scrap smelting furnace, 180t anode furnace, M16 anode casting shop, anode preparation machine, stripping machine, copper electrolysis as well as installation supervision and commissioning services. In addition, aggregates for waste gas treatment, wasteless foul electrolyte processing, and waste water clean-up have been installed at the works.

Outotec has also delivered various smelting reactor solutions, as shown in **Figure 7**, for recycling copper and eWaste, lead-containing materials and batteries etc.

Resource Efficiency through Design for Recycling

In order to address the issue of Design for Recycling (DfR) correctly, it is important to distinguish between the Material-Centric view of recycling as one

E-Waste and Copper Recycling Dowa (Japan)

Boliden – Rönnskår Smelter (Sweden)

Lead Battery Recycling Recylex (Germany)

Xiangguang Yanggu Smelter (China)

GRM – Danyang Smelter (S. Korea)

Figure 7. *Versatile Outotec Smelting Technology accepting a range of feed types including copper, lead, various scrap, residues and eWaste (two left plants) .*

that operates mainly in one segment of the Metal Wheel and concerns the recycling of "simpler" products, while the product-centric view accommodates more than one segment for maximal recovery of a suite of metals (alloys/compounds) from complex products. Therefore, in order to understand the limits of recycling in terms of physics and therefore also its economics, it is very important to understand the material-centric and product-centric views of recycling and why these have to be considered together to maximize resource efficiency.

While the material-centric view of materials processing can happily exist only on a primary mined resource, recycling requires the metallurgical basis and core competence of the Carrier Metals to operate well, especially in capturing all the metals from complex products. It must be noted that a scarcity of certain elements forces society to recycle more, so the policy must take care to protect basic metallurgical core competence (and infrastructure), as it requires deep knowledge of the primary carrier metal metallurgy to recycle at BAT level and ensure that recycling can also take place in future. The losses that take place from the recycling system are related among other things to the thermodynamics of a slice of the Metal Wheel that cannot cope with the minor constituents that enter the system "out of place", hence decreasing resource efficiency. While a slice of the Metal Wheel has its thermodynamic limits, increasing resource efficiency implies breaking down the border between the slices. The number of different slices in which recyclates should be treated is affected by the efficiency of design (for recycling/sustainability), liberation/separation, and defining the remaining material combinations in different flows. The limiting ideal case is given when scrap can flow into the centre of the Metal Wheel (i.e. a system that connects all Carrier Metals) and then flows, as determined by physics and economics, into the appropriate slices, with the links between each slice connected smoothly. Although this is an utopian view, this understanding of the complete system is required to pinpoint the limitations of recycling, and hence understand fully the constraints on resource efficiency and unattainable Cradle-to-Cradle (C2C) approaches. The Metal Wheel also shows, that the ultimate Resource Efficiency is the minimization of metals/elements/compounds ending up in the outer green band of the Metal Wheel.

Material-centric recycling - The present status of recycling

Agricola (1556) [AGR] described recycling of precious metals in the first metallurgical De Re Metallica, which highlights a simple fact – if a metal has economic value and it makes business sense to recycle it, it will be recycled. That was the case in the 16th century, and it is still the case now, only our metal-containing products are so much more complex than recycling simple gold jewellery or the alchemistic attempts to create gold from lead (recyclates). Industry's accomplishments already achieved in carrier metal recycling are remarkable considering the complexity of recycling. Various (carrier) metals associations are doing considerable good work to quantify recycling rates. It must be noted that recycling in a commodity metal centric world obviously works for commodity (Carrier) metals as applied in relatively "simple" applications implying few linkages of materials and/or linkages that can be easily separated with little contamination of impurities. Therefore, in a Material-Centric view of recycling:

- attempts to quantify the recycling mainly of commodity (carrier) metals and their alloys on their own with non-thermodynamic based material flow models work to an extent, due to the bulk application of commodity metals (alloys) for relatively uncomplicated linkages in "simple" products,
- recycling usually operates in the confines of a single sector or slice of the Metal Wheel and hence has issues with minor contaminating and alloying elements that do not "fit" the basic metallurgy of the sector,
- recycling metrics are used that do not include the complicating factors of multi-sector materials in the Metal Wheel, and
- discussions of material and energy efficiency of metals and alloys in "simple" products could lead to conclusions that do not necessarily hold true for many of the other elements in the periodic table nor for metals and alloys that are applied with many other materials in complex products.

While it can be postulated that a material-centric view is good enough for bulk metals such as steel and aluminum, scrap quality issues (created by complex products, poor sorting, metal linkages etc.) are an increasing problem as unwanted elements are slipping into the steel and aluminum sectors of the Metal Wheel, which can only be dealt with adequately by dilution with virgin metal produced from ore.

Product-centric recycling – Enabling future sustainability

The world is becoming ever more product-centric, where metals are mixed together into complex products that impart a functionality that in many cases will enable sustainability and change the way we live (Figure 4). This complex mixing in functionality-dictated complex designs is making the recovery of metals and materials increasingly difficult, as their recovery is affected not only by the physics of separation and sorting, but also in terms of thermodynamics, and the economic viability in BAT. This product-centric view of recycling obviously acknowledges the material-centric view and its accomplishments in recycling; however, it also forces us to discuss material and energy efficiency and recycling in a complex product setting, as shown by the very different consumer minerals. It is self-evident that these designed "minerals" are much more complex than thermodynamically compatible linkages of elements in geological minerals. These complex product "mineralogies" include a multitude of complexly linked materials:

- commodity materials (pure metal, alloys and compounds) such as steel, copper, aluminum, zinc, nickel, plastics, "critical" resources such as those identified by EU [EU2] through the EU Raw Materials Initiative [EU3], and
- various valuable minor elements (sometimes including toxic materials – which can be transformed into benign materials in appropriate process steps) that make Electrical and Electronic Equipment (EEE) work, are often closely linked as a result of functionality.

The product-centric view of recycling deals with the complexity depicted in Figure 2 to maximize Resource Efficiency. This figure also shows that pre-processing and sorting parts and materials into Metal Wheel compatible fractions helps considerably to maximize the recovery of metals and materials.

This gives Design for Recycling and Sustainability (DfR and DfS) as well as Life Cycle Management (LCM) a very prominent role, within a context that understands and integrates the complex physics of separation of all the metals and compounds from these complex products. In the context of this product-centric view, recycling often has to deal with in excess of 50 elements (unlike the "mere" 25 or so in concentrates) that are present as metals, alloys, compounds etc. in a complexly linked setting. During recycling, all these elements affect each other's recycling rate. Therefore, it is clear that the recycling metric for measuring current system performance of complex products can only be based on rigorous system models like the one depicted in Figure 2.

The Metal Wheel (Figure 5) makes one thing very clear: recycling is based mainly on the backbone of the Carrier (Commodity) Metals (alloys). It is this backbone, which must be present to recycle metals and their compounds efficiently. This implies that to optimize resource efficiency, careful consideration has to be given to first principles in order to harmonize the Material-Centric and the Product-Centric views of recycling. Numerous Product-Centric aspects are implicit and explicitly given by the visionary work of the World Business Council for Sustainable Development [WBCSD]. To realize these visions require considerable depth and detail to achieve; from a recycling perspective, this detail is reflected by Figure 2. The WBCSD speaks of "closing the loop" and "not a particle of waste", both of which thermodynamically impossible to achieve. However, with a deep understanding of the economics, technology and thermodynamics of recycling one may go a long way towards it. This requires acknowledgement of the complexity of material applications and then dealing with these complexities using the appropriate tools available to us.

Product-Centric Design for Recycling (DfR) and Life Cycle Management (LCM)

Figure 2 shows the product-centric view of recycling that considers the multitude of elements as alloys and compounds in the product ***all at the same time***. Predictive models have been developed that permit a rigorous analysis of complete systems and products to establish system requirements for the future. This view gives a true picture of recycling that provides the theoretical depth on which to base feasibility studies and subsequently build plants and systems. It provides insight into the limits and opportunities, it can show when recyclates have sufficient quality to warrant economically viable recycling, it can show what recyclates become waste, i.e. due to insufficient economic value, and where policy and legislation may have to step in.

The objective of the recycling industry is to produce pure metal, alloys and high quality compounds from diverse scrap and sell them at LME-related prices if they are traded on the LME or sold according to the price dictated by supply and demand. The crux of the total dynamic system is in fact the *"Metal and Energy Recovery"* block in Figure 2, which is the real closer of the material cycle, often also a primary producer of metal from concentrates that also processes recyclate feeds. The poorer the multi-material recyclates are, the more losses from the system there will be (see lower right arrow in Figure 2). On the other hand, if the metallurgical technology and infrastructure is not sophisticated enough, then the metals and materials cannot be separated well thereby creating losses. DfR and appropriately organized collection and pre-processing systems that ensure that metal, alloys and materials do not end up in the wrong slice/sector of the Metal Wheel are also of great importance. However, functionality forces elements together that are not necessarily compatible from a metallurgical point of view. In order to improve resource efficiency, the designer needs to be provided with tools/technology-driven guidelines to make the correct choices from a recycling point of view whenever possible, within the limits of design and product specifications and requirements.

By improving the product design using all the concepts of DfR and DfS [REU2], including Cradle-to-Cradle [C2C], it can be claimed that recycling and resource efficiency will increase. This may be true for simple products such as a chair, or a kettle; however, it is not easy to make an LED, fluorescent light, car, electronic product, integrated circuit (IC), etc. any simpler as the metals in close proximity provide the functionality that make them work. Indeed, one can also reuse ICs, capacitors, resistors etc., but modern technology is advancing extremely fast, putting a strain on the reuse especially of these types of components in more advanced and rapidly evolving products. Obviously complex linkages also create losses due to the physics of separation and the liberation of closely linked materials in complex multi-material products. These aspects can be addressed by DfR, sustainability and disassembly; however, the limits on changing design are driven by functionality, aesthetics, performance requirements, energy usage, and many other constraints such as crash tests, pedestrian safety for cars etc. Therefore, valuable (minor) metal losses are a fact of nature, i.e. physics. It is also clear from the Recycling Metal Wheel (Figure 5) that if there is insufficient metallurgical know-how and infrastructure then recycling from EoL to LME-grade metal will only happen with difficulty! A case in point is the Rare Earth (RE) industry, which, through poor foresight and vision has concentrated metallurgical technology in one geographical area, which is now limiting the recycling of REs in other parts of the world.

Summary

The product-centric view of recycling brings into play all the policy issues and legislation around products and their recycling, Life Cycle Management consumers (who will make increasingly informed purchasing decisions based on material types, their recyclability, footprints etc.) in addition to all the material and energy efficiency issues that are all part of metals processing. The product centric view also makes it clear that primary as well as recycling metallurgy and their infrastructure are a pre-requisite for recycling and must co-exist to produce the vast number of metals and materials from their multitude of combinations in modern sustainability-enabling products within a resource efficient society.

The above is partially based on the reference UNEP3's introduction (acknowledging herewith the given main authors' input to this) and work by the authors published in various academic journals.◣

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LYHENNELMÄ

Challenges of metals recycling

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Metallien kierrätyksellä on pitkät perinteet. Ajavana voimana on aina ollut saavuttaa korkea materiaali- ja resurssitehokkuus perustuen metallien kaupalliseen arvoon ja kierrätyksen helppouteen. Tällöin on ollut useimmiten kyseessä materiaalikeskeinen katsantokanta ja metallit on otettu talteen pääasiassa perustuen metallurgien perinteisiin prosesseihin. Tuotekeskeinen näkökanta kierrätykseen on kuitenkin monimutkaisempi johtuen mm. nykyaikaisten kierrätettävien tuotteiden lisääntyneestä kompleksisuudesta ja varsinkin siitä, että tuotteissa on yhdistelminä metalleja, jotka ovat fysikaalisesti vaikeasti erotettavissa ja toisaalta niiden talteenotto perinteisillä menetelmillä on jopa termodynamiikan vastaista. Artikkelissa käsitellään metallien kierrätystä sekä mahdollisuutena että varsinkin haasteena, johon ratkaisu täytyy löytää sekä metallurgian että tuotesuunnittelun keinoin. ◣

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