Strategic metal recycling: adaptive metallurgical processing infrastructure and technology are essential for a Circular Economy

By Markus A. REUTER
Director Helmholtz Institute Freiberg for Resource Technology
and Antoinette VAN SCHAIK
Director/owner/founder Material Recycling and Sustainability (MARAS) B.V.

Recycling forms the heart of the Circular Economy (CE) system. Ultimately all products will have to be recycled at their End-of-Life (EoL). Maximizing the recovery of materials and also especially strategic elements from EoL products requires a deep understanding of the fundamental limits and the dynamics of the evolving system, thus an adaptive processing and metallurgical infrastructure is critical to recover all metals and materials. Paramount is the quantification of the "mineralogy", the complex and interlinked composition of products, to trace and quantify specifically all the losses of materials, metals, alloys, etc. due to thermodynamic and other non-linear interactions. We named this product centric recycling. The recycling potential and performance must be quantified and demonstrated for products, collection systems, waste separation and recovery technologies, and material supply. Emphasis is also placed on informing the consumer through iRE i.e. informing Resource Efficiency in an easy-to-understand way. System Integrated Metal Processing (SIMP) using big-data, multi-sensors, simulation models, metallurgy, etc. links all stakeholders through Circular Economy Engineering (CEE), an important enabler to maximize Resource Efficiency and thus iRE.

Circular Economy (CE)

The EU has recently published its ambitious plan on Circular Economy (CE) (EU, 2015). Recycling plays a key role in CE. If all products were constructed from one material and recyclates were 100% pure CE would be an easy endeavour. However, if society would reduce drastically its consumption, the complicating issues of a CE will become trivial, in fact a CE could become irrelevant. However, present reality is that consumer products are complex, creating complex recyclates, have an often short life span and are intensively produced and consumed.

In addition, variability of products and materials demands a dynamically changing processing infrastructure. For metals, this means that for a CE, to be realized requires for example a high-tech adaptive metallurgical infrastructure that interlinks all materials processing industries (i.e. all carrier metals infrastructures must - for example in the EU - be able to interchange materials if there is an economic incentive to do so).

Realizing the full potential, challenges and fundamental innovations to achieve a CE system requires an understanding of the social, technological, economic and environmental opportunities and limits thereof. The innovations, tools and challenges to move towards a CE include among others:

- The use of minerals and metallurgical processing know-how and tools in the analysis of the CE system. The innovation lies in further developing these tools for recycling and linking these to the already established tools used for optimizing metallurgical systems (REUTER, 1998; VAN SCHAIK and REUTER, 2010, MENAD et *al.*, 2016). We have called this product centric recycling (REUTER and VAN SCHAIK, 2012).
- Quantifying the data of the CE for both products and recycling in a manner that acknowledges the complexity of a product centric approach, that takes all materials of the consumer product (i.e. from the Urban Mine) into consideration, much like a complex mineral from a Geological Mine. This approach captures the full non-linear effects

of the recovery and losses of all materials, elements, strategic & critical raw materials (CRMs) (EU 2014) etc. on each other (as well as the contamination of the materials on each other). This is analogous to processing of polymetallic complex minerals from geology and ensuring all elements, metals and gangue are processed to economically valuable to environmentally benign final products such as slag.

- Recyclates have to be quantified so that thermodynamic and physical properties can be used in industry linked simulation (REUTER et *al.*, 2015) to optimize the complete system. Properties of the recyclate particles and flows include enthalpy, entropy & exergy, alloy and material composition, conductivity, colour, magnetic susceptibility, density, shape, odour, near infrared properties, interlinkages of materials in scrap particles, brittleness, ductility, etc.
- A real-time feedback loop, that links product design and recycling system configurations to real-time grade monitoring of recyclates with suitable multi-sensors (to estimate possible contaminants and valuables in them) while linking this to high quality material and metal production processing – thus Design for Resource Efficiency (DfRE).
- Use of real-time data to calibrate recycling and CE system models that provide a basis to optimise the processing chain and providing the necessary detail to calculate Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) as well as the environmental footprint. This simulation basis provides the true economic potential of CE as it rigorously maps all recoveries, losses and costs due to these losses.
- Determining the baseline recovery rate and potential for specific products based on a product centric approach. This permits the understanding of what actions to take to innovate in the CE system (REUTER, 1998; VAN SCHAIK and REUTER, 2014). Industry calibrated simulation models are key to optimizing the system i.e. methods will be applied to quantify both of quality and recovery, as well as opportunities and limits of recycling complex product material mixtures.
- On the basis of these rigorous adaptive CE models (REUTER and VAN SCHAIK, 2012), innovative circular business models can be developed that will design a closed loop system for material use preventing the loss of materials from the economy and into the environment including innovations to producer responsibility and new product ownership models. These models provide a basis to develop innovative collection and organisational approaches to increase the amount of sorted, collected and reported EoL goods and their subsequent reuse, recovery and closed loop recycling gleaning from the feedback from limits and critical issues in recycling learned from industry process simulation (UNEP, 2013).
- Involving end-users (consumers and businesses) in both the design of collection to maximise their participation in the testing of potential approaches and their acceptance to recycled and reused products.

In other words, business models will need to be connected to material science, underpinning policy with physics and economics creating the field of Circular Economy Engineering. Ultimately energy and material efficiency should be optimized as a function of product and recycling and processing infrastructure design to fully reveal the opportunities and limits of the CE system. This is the key challenge to understand the role of an adaptive infrastructure and process technology to innovate the true potential of CE thinking. This adaptive infrastructure is called "System Integrated Metal and Materials Processing".

System Integrated Metal and Materials Processing (SIMP)

A substantial challenge for realizing CE is the production of clean recyclates that can provide the physical material properties that impart the required functional properties in the consumer products these are applied. Complexity of recyclates and the complex mix of material properties, etc.: all affect the final recovery during physical and metallurgical processing.

While metals can be refined to high purity metal alloys during metal refining, plastics have a limit to how much recyclate (containing a mix of more or less of all other metals and materials in the EoL product) can be added to virgin plastics to produce high quality plastics once again. Just think of rheological, mechanical, thermal, visual properties of recyclates that could affect their usage in high performance electronic applications! (Figure 1 provides an overview of this interaction and the effect on quality on metals and plastics respectively). Creating the highest quantity and quality of recyclates for all materials at the same time is the "simple" task that CE should achieve, but it gives no indication of the complexity of the task at hand.

The linkage of all technologies and systems from product design to metal recovery we call System Integrated Metal and Materials Processing (SIMP) can help achieve these challenging goals. This requires new rules for physical recycling tied to product design and design for recycling linked via process metallurgy to high grade metal based materials. This involves reconsideration and where necessary redesigning the whole value chain to minimise material losses and reducing the unnecessary mixing of materials to reduce energy use and costs. Various base metals, steel, plastics etc. are the carriers to be understood to quantify interaction and recovery possible of all materials in the product as among others shown by the metal wheel (VERHOEF et *al*., 2004). Digitalizing the CE and specifically the metals processing through SIMP is a key to recovering all materials (CRMs among others) from EoL products.

In SIMP, real-time data and big-data analysis will be used to calibrate the simulation models that will be used to quantify and provide the data for the business models and plans to innovate the CE system. Included must be environmental assessment linked to simulation as shown by Reuter et *al.* (2015). Crucial in innovating in the CE system is the comprehension of the baseline on a fundamental physics basis to innovate the future. Essential to SIMP and CE is a close communication and cooperation

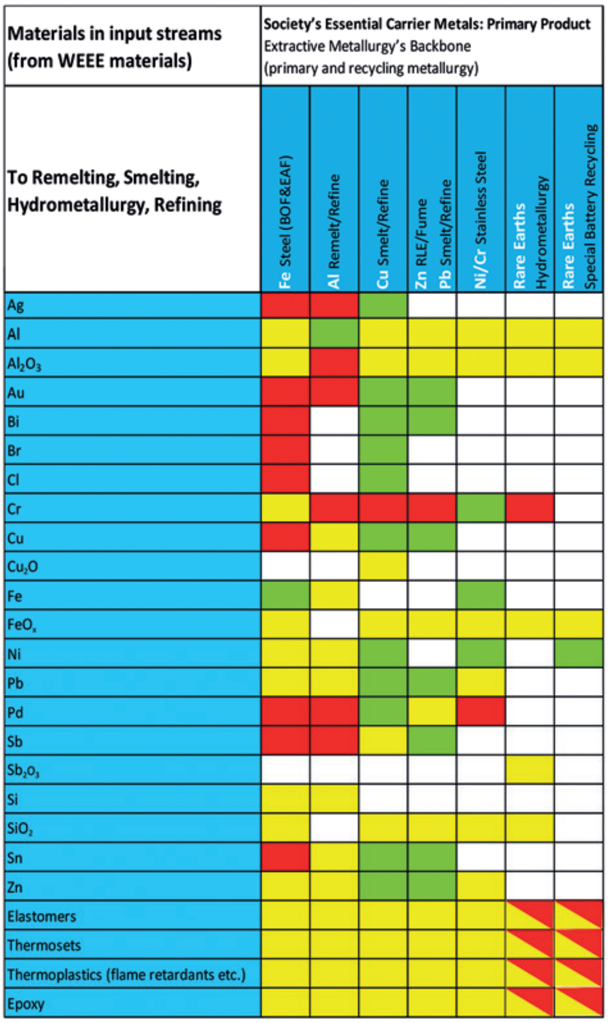

Figure 1: Interaction between Plastics and Metals: Miscibility charts (Van Schaik and Reuter, 2014) of different metal and polymer types.

between the original equipment manufacturers (OEMs) and the recycling industries (both recyclers and metallurgical and plastic recycling industries) in the value chain. Key enablers of System Integrated Materials Processing are:

- **Adaptive metallurgical infrastructure:** To maximize metals and CRMs from diverse changing EoL products requires a high-tech metallurgical infrastructure. Only where there are "holes" in the system should technology innovation take place, system innovation should be paramount and policy should be an enabler.
- **Metallurgical system optimization**: Optimal recycling routes supported by innovative developments in separation and real-time digitalization (i.e. on-line measurement technologies) are key: they will minimise the inclusion of contaminating materials affecting the properties of recyclates, hence enhancing the quality and uptake of secondary/recycled materials into new products.
- **Quantification of recycling rates - The recycling Index (RI):** Physics based rigorous process simulation tools to quantify and predict recycling rates and limits thereof for current and future products/systems will be calibrated based on the industry trials and real-time data derived from innovative sensor based measurements. This quantifies the limiting factors and options for improvements in resource efficiency/reduction and reduction of generation of residual waste (See Figure 2)
- **Real-time big-data acquisition and analysis**: Based on detailed insights derived from real-time data acquisition and quality control and simulations, the physical limits of recycling can be translated into technology and industry driven Design for Recycling innovations of various products. Redesigns and innovated recycling routes will be addressed and quantitatively assessed on improved recyclability (i.e. process data are linked via simulation to computer aided design (CAD) supporting both product and process redesign for improved resource efficiency).
- **Criticality of process infrastructure:** Maintaining, innovating and simulating the metallurgical and recycling processing infrastructure enables the maximum recovery of all metals from the EoL products. This facilitates the redesign of the value and supply chain supplying CAPEX and OPEX data for the whole system, the basis for evaluating the business potential of CE.
- **Cross-sectorial symbiosis:** Incorporating quantifiable targets for measuring sustainable recovery, recycling and re-use of resources (including energy and material qualities) in the overall material flow chain from resources to consumer products in a data format which can be applied for all stakeholders allows for quantified symbiosis between different sectors.
- **Eco-innovative system analysis** is realised by the improvement of recycling and uptake of recycled materials into products. The relationships between stakeholders along the material and product value chain (such as collection systems, producers, recyclers and processers) are linked with quality monitoring and environmental life cycle assessment.
- **Quantification of regulatory barriers** will become evident through the systemic integrated approach in which critical and limiting issues (as well as physics based limits to recycling and resource efficiency) are pinpointed. As the product centric approach addresses recovery of both commodities (materials and metals), as well as CRMs and other materials (such as plastics and other non-metals), regulatory barriers are addressed as a trade-off between these, taking cognisance of functional product specifications.
- **Improve environmental assessment (LCA) methodology:** The detailed analysis and simulation of all streams in terms of compounds, recyclates, residue mineralogy etc. provides the detail to improve LCA methodology as well as environmental databases (REUTER et *al.*, 2015).
- **iRE - informing Resource Efficiency** requires both a rigorous analysis of energy and material efficiency. Analysis is based both on material and energy flow, entropy (exergy) in addition to life cycle assessment tools.
- **Redesigning of collection and sorting systems for CE**: Understanding on how to minimise contamination and losses during recycling (e.g. critical issues in processing and decreased recyclate quality due to undesired material mixtures) that limit the recycling and arise as a consequence of product mixtures provides direct input to redesign the way EoL materials and products are collected and treated. This will result in well-designed collection

and sorting of the CE system with physical separation and thermodynamic as well as metallurgical and plastic processing options. This includes quality requirements of recyclates and materials.

Resource efficiency can be quantified and optimised for products by applying an innovative and unique combination of industrial model calibration, sensor based quality measurement and a rigorous simulation basis, which are key to realizing SIMP. This provides a quantitative, dynamic and predictive basis for reducing material losses in the chain as well as a reference for measuring improvements against the status quo. This allows to rigorously and systemically link product design with collection, recycling, processing and the effectiveness thereof from a plastic and metal quality point of view and required innovations to move towards circularity.

Innovative redesign of recycling systems and processes (e.g. metallurgical processing) will need to be combined with Design for Resource Efficiency for Circular Economy by developing and integrating product design, collection, processing, economics and environmental performance on the basis of industry calibrated system models and applying these to innovate and quantify new concepts, processes, technologies, designs and structure. We call this discipline, with its comprehensive engineering toolbox, Circular Economy Engineering.

Design for Recycling and Resource Efficiency

System Integrated Metal & Materials Processing (SIMP) will result in an innovative eco-innovative systemic approach producing improved resource efficiency in the complexly interlinked CE system. Digitalization will link and visualize the complexity of interactions between consumers, Producer Responsibility Organisations, collectors, recyclers and processors, and producers and (re-)manufacturers. SIMP will provide a real-time as well as predictive (in future) quantification of the physical and economic limits of recycling and more specifically of critical technology elements.

Key to SIMP is to quantify design and inefficiency in separation cross-contaminated recyclates. It will quantify where metals and critical raw materials disappear into the wrong material, recyclate or waste flows and how recovery of all materials could be optimised, i.e. ensuring that for example plastic quality (i.e. purity) is maximized. SIMP goes beyond state of the art as it:

- establishes a technological and economic baseline for increased materials (plastics, metals and CRMs) recovery to maximise the opportunities for resource efficiency;
- acknowledges and includes the technological, economic and physics detail of all recycling, metallurgical and processing technology in the chain;
- provides the framework against which improvements in redesign, collection and recycling will be established, measured and quantified and provides a rigorous and measurable basis for innovation and business models for a CE, now and in future;
- uses a product centric recycling system approach taking into account the innovation potential of the main actors and stakeholders in the material processing value chain;

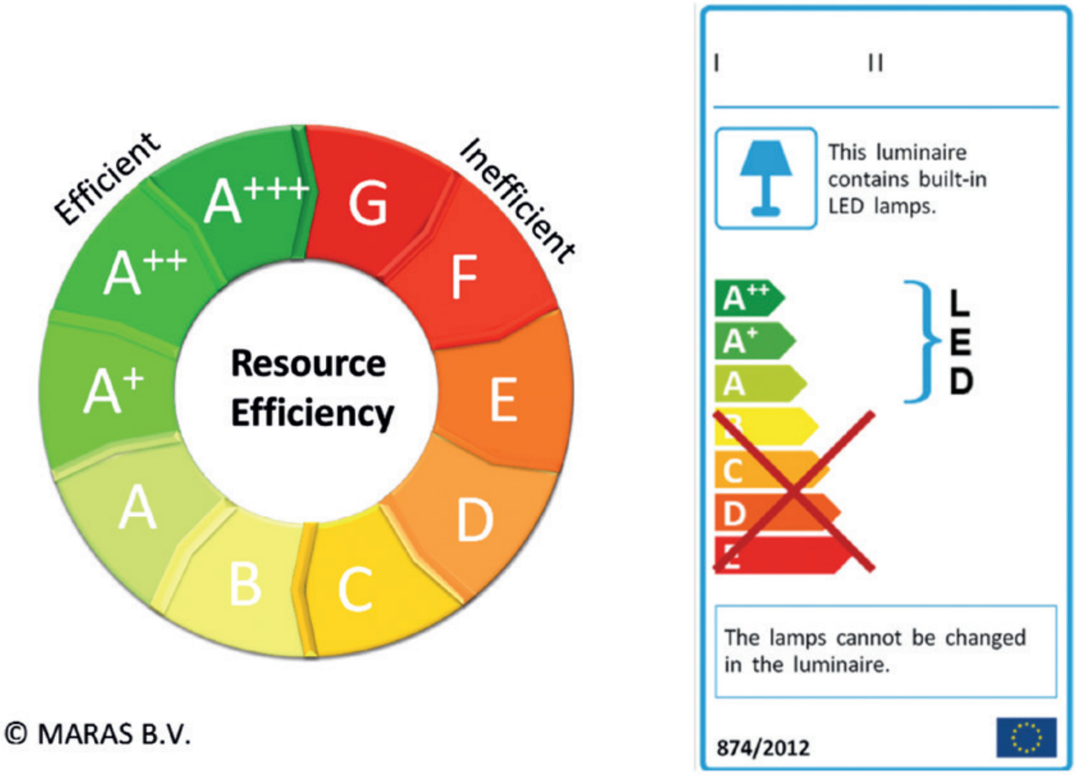

Figure 2: SIMP permits the optimization of both material and energy efficiency, thus providing the complete detail of informing Resource Efficiency (iRE), the sum of the Recycling Index (Reuter et al., 2015) and the accepted Energy Efficiency calculation (EU, 2012).

- improves recycling performance and recyclate quality via the development of optimised and new technologies and processes, sensor technologies, dynamic quality control and data interaction in simulation tools as well as the optimisation of the value chain via innovative business models;
- pinpoints and quantifies techno-economic limits to recycling and a CE;
- links CAD software, sensor-based measurement and recycling simulation tools to predict recycling rates and recyclates qualities to maximise plastic inclusion based on material properties affected (e.g. by CRMs and other materials) in the product;
- links different actors together into one harmonized business model which will require significant innovation in business science and approaches;
- creates data structures using common formats which can be communicated easily between designers and recyclers, thus compatible with common thermodynamic and material properties data formats; and
- enhances interaction between stakeholders in the value chain, in particular between manufacturers, producer compliance schemes, collectors, recyclers, legislators, consumers etc. to ensure sufficient information and intelligence sharing on product composition, material use, and product use, reuse and recycling.

In summary, SIMP leads to innovative product designs for recycling, processes, processing routes and sensor based real-time measurements linked to and integrated in predictive simulation tools. Figure 2 provides the present status of developing a Recycling Index-RI (REUTER et al., 2015) combined with the accepted energy label for products (EU, 2012). Combining these two symbols will be a key to informing the consumer and guiding CE development. This will help also to harmonize and integrate energy efficiency into the wider resource efficiency discussion. SIMP is thus a rigorous engineering toolbox that permits the calculation of a RI as well as RE, informing business models with the required depth to quantify disruptive and innovative CE business models.

Summary: Circular Economy Engineering

SIMP, the basis of Circular Engineering, provides the tools that will quantify evidence-based knowledge for enabling framework conditions (such as the regulatory or policy framework) to facilitate a broader transition to the CE.

Circular Economy Engineering (CEE) thus provides the engineering and economic tools that will help innovate the CE system.

The outcome of CEE is to join energy and material efficiency into one symbol (Figure 2) that informs the consumer and thus also guides the development, innovation and business models of the CE system.

We call this outcome of informing the consumer on a rigorous basis : iRE, thus Informing Resource Efficiency with engineering based tools providing a rigorous basis for developing new CE business models.

References

EU (2011): European Commission DG ENV, Plastic Waste in the Environment, Specific contract 07.0307/2009/545281/ETU/G2 under Framework contract ENV.G.4/FRA/2008/0112, Revised final report April 2011, 171p.

EU (2012): COMMISSION DELEGATED REGULATION (EU) No 874/2012 of 12 July 2012, supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of electrical lamps and luminaires.

EU (2014): COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative, Brussels, 26.5.2014 COM (2014) 297 final.

EU (2015): COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, Closing the loop - An EU action plan for the Circular Economy, Brussels, 2.12.2015 COM (2015) 614 final.

MENAD (N.), KANARI (N.), MENARD (Y.) & VILLENEUVE (J.) (2016): Process simulator and environmental assessment of the innovative WEEE treatment process, International Journal of Mineral Processing (in press).

REUTER (M.A.) (1998): The simulation of industrial ecosystems: Minerals Engineering, 11(10), 891-917.

REUTER (M.A.) & VAN SCHAIK (A.) (2012): Opportunities and limits of recycling: A dynamic-model-based analysis, Material Research Society BULLETIN, 37(4), 339-347.

REUTER (M.A.), VAN SCHAIK (A.) & GEDIGA (J.) (2015): Simulation-based design for resource efficiency of metal production and recycling systems, Cases: Copper production and recycling, eWaste (LED Lamps), Nickel pig iron, International Journal of Life Cycle Assessment, 20(5), 671-693.

UNEP (2013): REUTER (M.A.), HUDSON (C.), VAN SCHAIK (A.), HEISKANEN (K.), MESKERS (C.) & HAGELÜKEN (C.): United Nations Environmental Protection (UNEP) Report "Metal Recycling: Opportunities Limits Infrastructure" report: http://www.unep.org/resourcepanel/Publications/MetalRecycling/tabid/106143/Default.aspx

VAN SCHAIK (A.) & REUTER (M.A.) (2014): Chapter 22: Material-Centric (Aluminium and Copper) and Product-Centric (Cars, WEEE, TV, Lamps, Batteries, Catalysts) Recycling and DfR Rules. In: Handbook of Recycling (Eds. WORREL (E.) , REUTER (M.A)), Elsevier, 307-378.

VERHOEF (E.), DIJKEMA (G.) & REUTER (M.A.) (2004): Process knowledge, system dynamics and metal ecology, Journal of Industrial Ecology, 8(1-2), 23-43.