SOCRATES Zero Waste
EU MSCA-ETN

Policy Brief

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The EU’s metallurgical infrastructure is a cornerstone of the EU Green Deal and the Agenda 2030 realization

The European metallurgical industries are the enablers for the realization of the goals of the EU Green Deal and the Agenda 2030 for Sustainable Development. The realization of these goals requires a metallurgical industry that is even more resource-efficient, eco-friendly and responsible than it is today. Accordingly, the metallurgical industry and system must be protected and strengthened, rather than having its socioeconomic importance undermined because of misconceptions about its residue generation, energy consumption, and environmental impacts. To understand and quantify the opportunities and limits associated with creating more circular and sustainable metallurgical infrastructure systems, rigorous digitalization is imperative. The European Training Network SOCRATES has taken this up by developing ground-breaking metallurgical processes for the valorization of industrial intermediate products. Additionally, this project quantified the impact of its developed metallurgical processes on the sustainability of the current material and metal supply chain through the creation of large simulation-based digital twins of the metallurgical system.

Key takeaways:

1. **Agile metallurgical industry is a key enabler of the European and international policy roadmaps. It enables the Energy transition, Mobility transition, and Digital transitions, for example, through the supply of materials and metals, as well as the Circular Economy transition through the recycling of products, materials, and metals.**
2. **Intermediate products will always be generated during metal and material production and recycling, even in a fully implemented Circular Economy. Losses of useful elements/metals are inevitable and governed by the laws of thermodynamics.**
3. **Digital twins of metallurgical infrastructures are required to quantify today’s losses (see 2.) (in the status quo) and the future opportunities and solutions. To do so, the Circular Economy system simulations (digital twins) require detailed databases that include full mineralogical and compositional information of the raw materials, products and residues.**
4. **Industrial dialogue and alliances, which include all stakeholders, are required to develop sustainable solutions for the intermediate products generated during metal production and recycling. Digital twins (see 3.) are the tool to assess the sustainability of the solutions quantitatively. The ultimate goal is to reach the Circular Economy’s performance limits in a socially, economically and environmentally responsible and feasible way.**

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The role of metallurgy in the Green Deal & Agenda 2030

The ambitious European Union (EU) Green Deal (COM(2019) 640 final) and the United Nations' Agenda 2030 (A/RES/70/1) have articulated the essential role of metallurgy in our society. The roadmaps require a wide variety of technology metals to achieve their objectives. Silicon, indium, tellurium, selenium, gallium and rare earth elements are essential for manufacturing renewable energy technologies. These metals will enable a transition to a carbon-neutral Europe and realize the Sustainable Development Goals (SDG) 7 and 13 on affordable and clean energy and climate action. Lithium, cobalt and nickel used in batteries are cornerstones of energy storage and smart mobility that SDG 11 on sustainable cities and communities aims for. The metallurgical industry systems produce and recycle these metals, enabling responsible production and consumption (SDG 12) and the EU's Circular Economy Action Plan (COM(2020) 98 final).

Digitalization is one of Europe's key challenges in realizing its New Industrial Strategy (COM(2020) 120 final). It is also a triple challenge for the metallurgical industry as it must:

(i) **deliver** the base and technology metals (often over 60) required to manufacture IT devices and to build and operate the infrastructure for 5G networks, cloud computing, and communications;

(ii) **close-loop recycle** the products at End-of-Life (EoL) and unravel the complex designed functional material mixtures into high-quality alloys, materials for use in the same products[1];

(iii) **digitalize** its processes and value chains using a simulation-based digital twin that can be used for quantification and optimization of techno-enviro-economic performance.

Figure 1 below depicts the versatility of agile metallurgical systems to process complex primary and secondary raw materials (left) to recover a wide range of technology metals. They are produced as by-products from base metals processes such as the zinc and copper production (middle). However, the complex composition of the raw materials leads to the creation of intermediate products during metal production (right), e.g. slags and hydrometallurgical residues. These are landfilled if further processing or use is not economically feasible. Any metals contained in the intermediate product are then lost to the Circular Economy (CE).

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[1] *M.A. Reuter, A. van Schaik, J. Gutzmer, N. Bartie, A. Abadías Llamas (2019): Challenges of the Circular Economy - A material, metallurgical and product design perspective. Annual Review of Materials Research, 49, 253-274.*

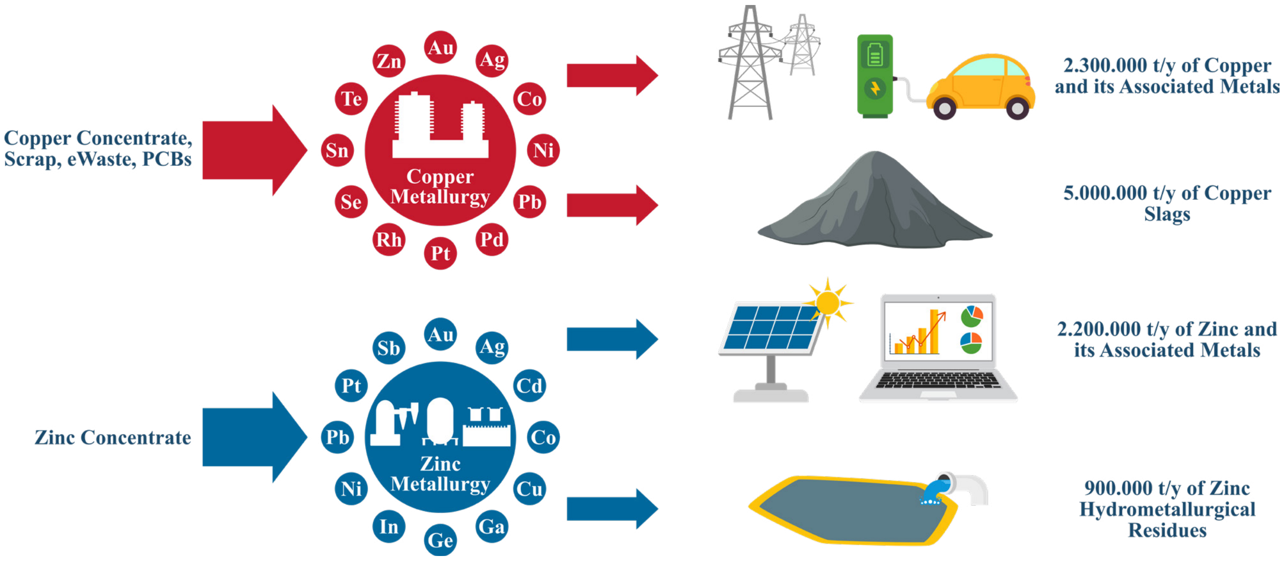

Figure 1. Processing routes for Cu and Zn concentrates

Intermediate products are inevitable in a circular economy

Let's take an in-depth look at the intermediate products and what is done with them today.

Base metals such as copper or zinc are produced from ores containing up to 20 different elements or from EoL products containing hundreds of materials such as plastics, metals or ceramics. Some of these materials are recovered because of their economic importance, e.g. silver or gold in copper production. Other metals are recovered because of their technological importance, such as indium and germanium in zinc production.

Figure 2 (right) shows the Metal Wheel[2] . It depicts in detail which metals (green in the Metal Wheel), can be recovered within the base metal industry as metal commodities. The metals, in the form of compounds, that leave the process as an intermediate product are labelled in yellow. The metals that are not recovered are shown in red. These metals are captured in complex intermediate products. The Metal Wheel also depicts how the interconnected metallurgical system permits the treatment of intermediate products from one base metal process in another base metal process to transform these into high-value products. This maximizes the material recovery and thence resource efficiency, lowering the quantity of intermediates going to landfill. For example, Boliden's[3] interconnected zinc, lead, copper and nickel plants exchange metal-containing intermediate products. Zinc-containing intermediates produced in the copper and lead plants are treated in the zinc smelters to recover zinc and associated elements. In return, zinc plants supply copper, nickel and cobalt-containing intermediate products to the copper and nickel smelters for their recovery.

The Metal Wheel does not provide sufficient details about the intermediate products. The **Residue Wheel** (**Figure 2, left**) depicts the intermediate products and their full compositional detail generated within the metallurgical systems, complementing the Metal Wheel. For each base metal process, the intermediate products are shown, with their (mineralogical) composition. Compounds and metals for solid intermediates, e.g. slags, drosses, sludges, and ions for wastewater and solutions, are depicted in yellow. A systemic evaluation of the CE system, using a (simulation-based) digital twin, is required to assess if there is a sustainable solution for the intermediate products, converting its constituents into useful products. If so, then the label is green; otherwise, it will be red. Still, it has to be noted that the processing of each intermediate product will create both useful products and new intermediate products (residue).

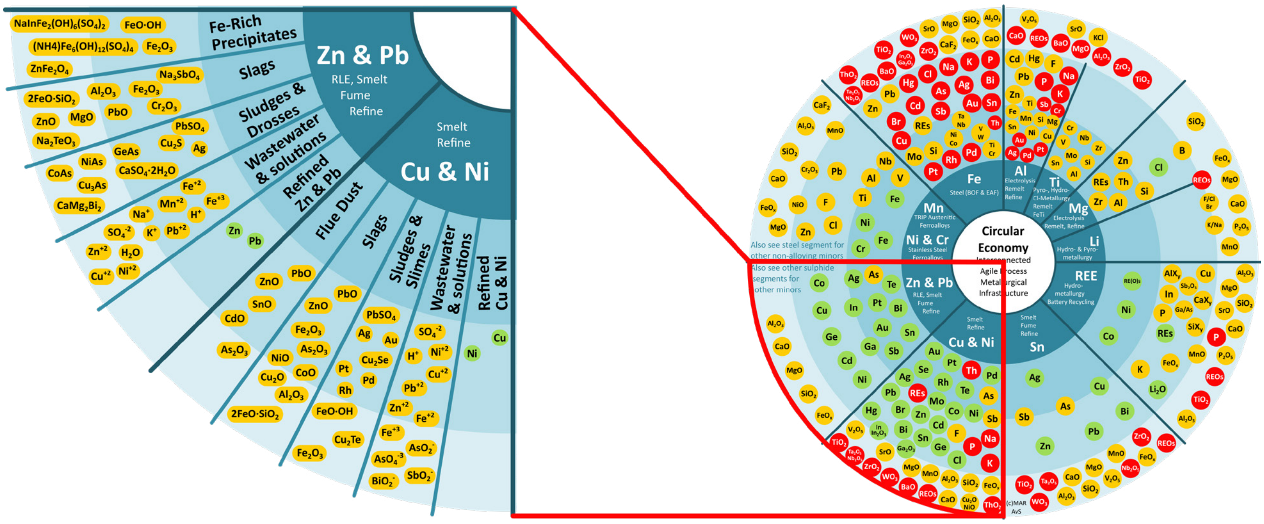

Figure 2. The Residue Wheel (left) and the Metal Wheel (right)

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[2] Verhoef E V, Dijkema G P J, Reuter M A, (2004), Process knowledge, system dynamics, and metal ecology, Journal of Industrial Ecology, 8(1–2):23–43.

[3] https://www.boliden.com/

Digital twin creation to find opportunities for intermediate products

To find the opportunities for the intermediate products, a systemic perspective of the different metallurgical value chains in the CE system is required (**Figure 3, left**). This perspective is obtained through the digitalization of the system - a digital twin – based on process simulation (**Figure 3, right**). The digital twin maps all the resources and the contained energy flowing through it at an element and compound level of detail[4] as depicted in the "Residue Wheel" (**Figure 2**) for all the products, by-products and intermediate products. The digital twin represents the complete system in terms of energy, materials, water and exergy linked to the energy infrastructure. The high level of detail used in the digital twin is imperative to 1) pinpoint solutions that improve the resource efficiency, environmental performance and sustainability and 2) describe the complex interactions that happen in the industrial ecosystems and alliances.

Highly detailed databases, which go well beyond those used for a typical material flow analysis, are required for the digitalization of the Green Deal industrial infrastructure. These digital twins create a rigorous quantitative baseline of the CE system's performance and quantify the benefits and impacts of potential improvements and solutions, thus allowing for benchmarking against the existing CE system.

The EU's New Industrial Strategy, aiming to create industrial alliances, requires this level of detail. The Circular Economy Action Plan also needs this detailed quantitative baseline to find solutions for the valorization of the intermediate products generated. Metallurgical companies require and use this level of detail to find an outlet for their intermediate products as they are already doing in the base metals infrastructure depicted in **Figure 3**.

Furthermore, this detailed information baseline and benchmarking, enabled by the digital twin, is also crucial for CE stakeholders during decision-making processes concerning the potential CE strategies. This information baseline supplies physics-based information on, among others, the quantity, composition, and mineralogy of residues landfilled near cities, potentially affecting people's welfare. Thus, it permits the analysis and simulation of the system to extract as many valuable elements and to reduce the amount of material leaving the cycle as economically as possible. Therefore, it informs the realization of the Green Deal's objectives and the SDGs with data that withstand an economic stress test.

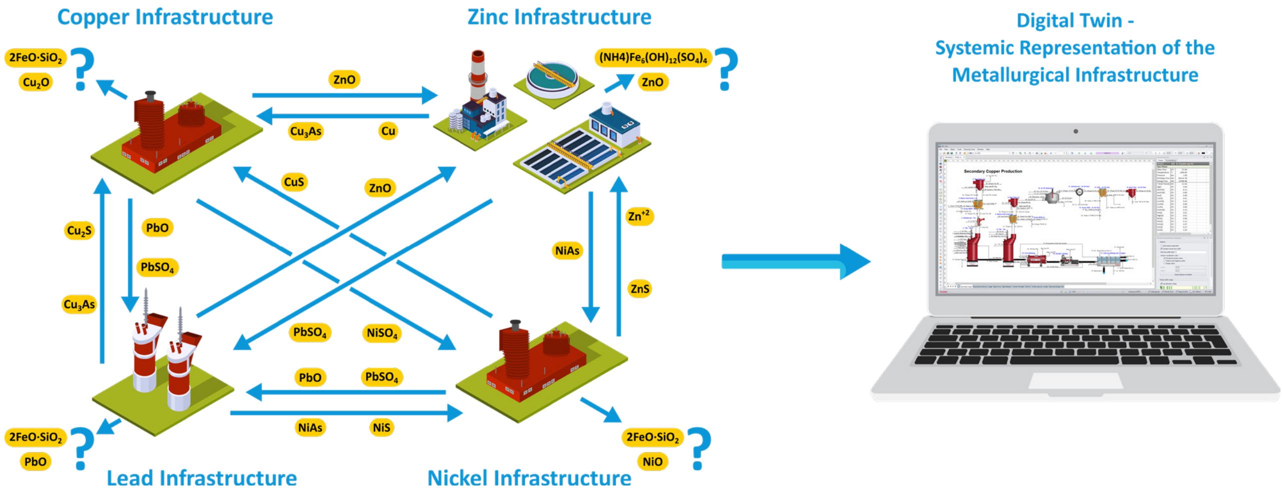

Figure 3. Metallurgical infrastructure (left) and the associated digitial twin (right)

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[4] *Abadías Llamas A, Bartie N J, Heibeck M, Stelter M, Reuter M A, (2020), Simulation-Based Exergy Analysis of Large Circular Economy Systems: Zinc Production Coupled to CdTe Photovoltaic Module Life Cycle, Journal of Sustainable Metallurgy, 6(1):34–67.*

SOCRATES case: Valorization of slags as a construction material

The EU zinc and copper infrastructure produces a considerable quantity of intermediate products such as slags and precipitates (**Figure 1**).

ETN-SOCRATES has developed and evaluated new innovative methods to valorize copper slags and hydrometallurgical zinc precipitates. They are processed to create construction materials such as cement or inorganic polymers. ETN-SOCRATES created a digital twin to quantify its benefits in resource consumption and environmental impacts (**Figure 4**). Different options have been benchmarked to the current situation to select the best one: the residues are converted into construction materials by recovering the contained metals.

If the copper slag and zinc precipitates generated in the EU are converted and used as construction material, 5,730,000 tonnes of CO_2 emissions are avoided during cement production. Also, 7,750,000 tonnes of limestone and 760,000 tonnes of sand would be saved every year (compared with a typical cement). Base and technology metals are recovered from the intermediate products. Moreover, the landfilling of 5,000,000 tonnes of slag in copper production and 900,000 tonnes of hydrometallurgical precipitates in the zinc industry would be avoided, freeing up land.

The detailed, physics-based information included in the digital twin has been used by the stakeholders to precisely identify potential issues, as well as the role of every stakeholder to overcome them (**Figure 5**). Here, detailed information from the digital twin is used by R&D and industry to find technical solutions to: (i) produce a stable cement where the elements contained do not leach during its use, (ii) design a new cement with strength and durability properties equivalent to those of the cement it substitutes and (iii) do this in a resource-efficient, eco-friendly and sustainable manner. The digital twin, and the information contained, is used to engage society in the dialogue and decision-making process to create the Social License to Operate (SLO). It can also quantify the impacts of policy decisions, new legislation and technology, enabling a fact-based dialogue between stakeholders.

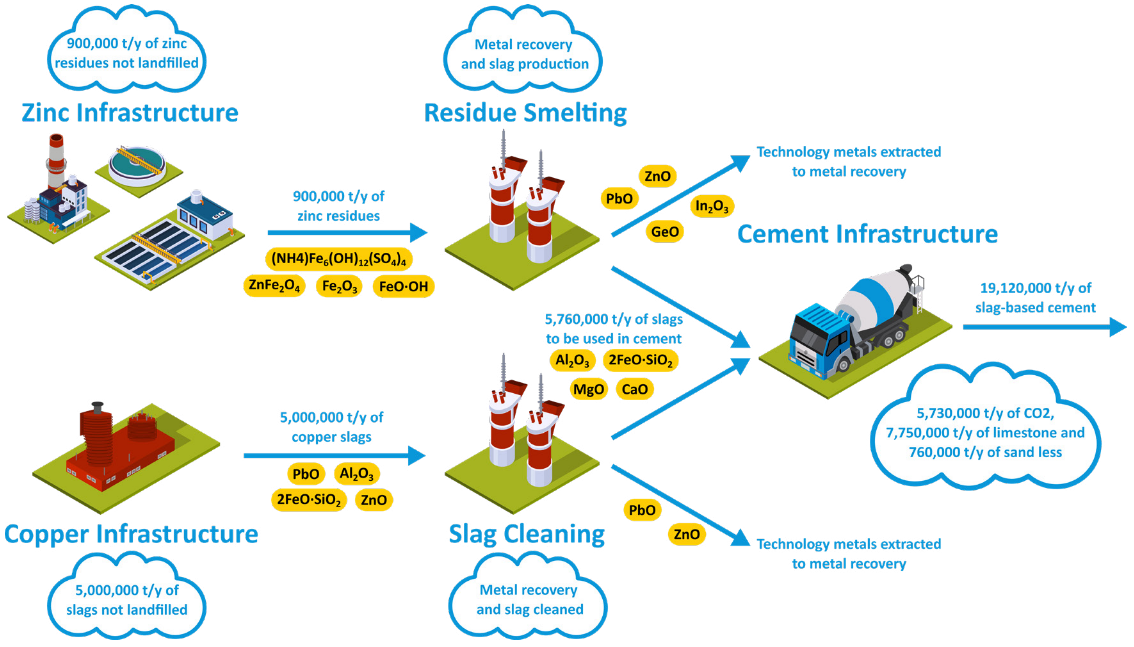


Figure 4. Digital twin to quantify benefits in resource consumption and environmental impacts

Industrial alliances engaging all the CE stakeholders

To find the opportunities for the inter- The reduction of intermediate product generation cannot be dealt with only by the metallurgical plants. Instead, industrial alliances must be established and engage all stakeholders in a dialogue so each can play their role in the CE.

The Metal Wheel suggests that this is essential to realize the EU Green Deal and the SDG expectations. Nevertheless, the creation of these alliances is not an easy task. There are many stakeholders, sometimes with conflicting objectives. However, the realization of the CE opportunities, the Green Deal and the SDGs requires these conflicts to be resolved.

Therefore, the systemic evaluation of CE with rigorous assessment tools such as process simulation to create digital twins is essential to identify the potential issues that may affect all the stakeholders. When it is performed, the synergies and trade-offs among different industrial partners can be pinpointed, and a balance between all stakeholders can be found to overcome these issues. Specifically, the R&D solutions for the technological challenges are evaluated on their actual economic and circularity potential using rigorous engineering tools; society is engaged since they have facts with a robust physics basis to understand the importance of metallurgy and decide on whether to grant SLO; Industry and government funding have a rigorous perspective to invest in technology and R&D to achieve economically viable technological solutions, and policymakers have a physics-based basis for formulating consistent policy frameworks to make industrial alliances among the EU industrial infrastructure easier and harmonious.

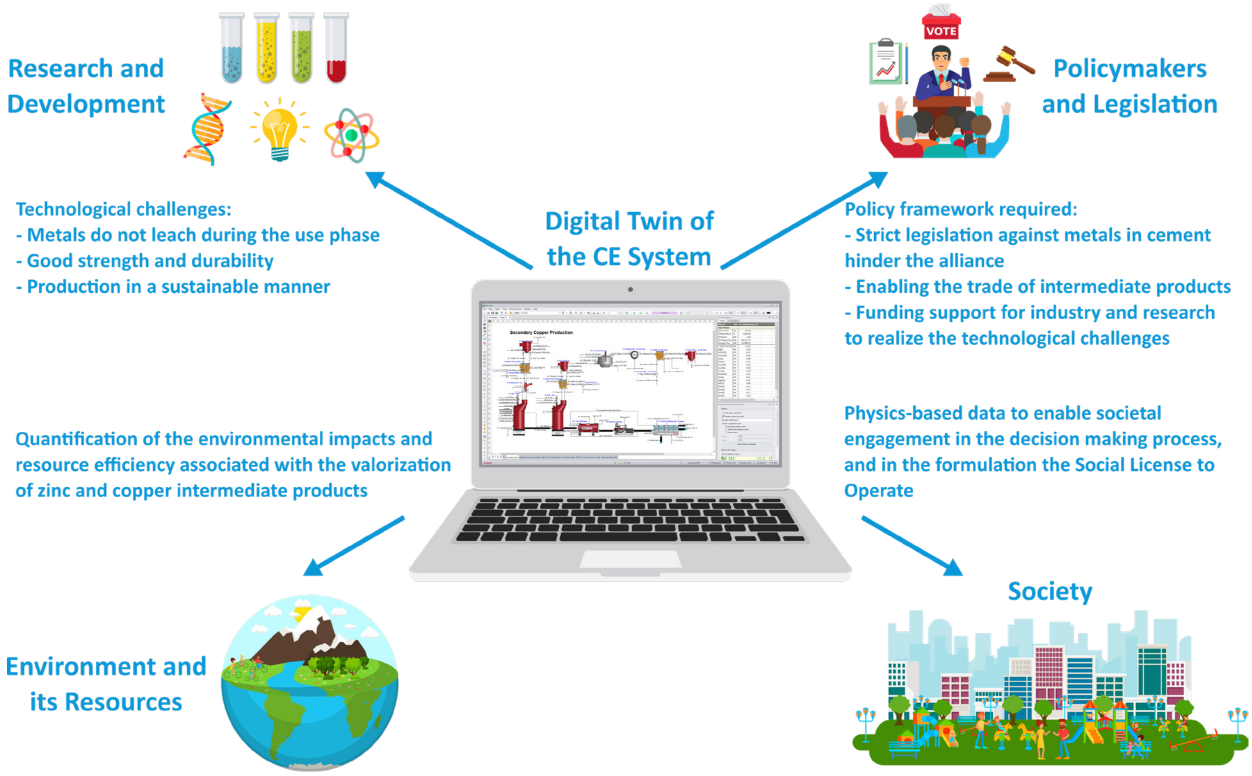
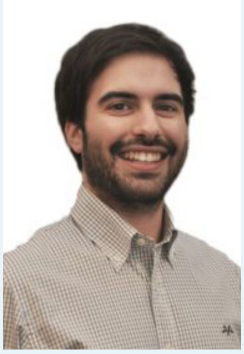


Figure 5. Details of the digital twin for the Circular-Economy system



Alejandro Abadías Llamas is originally from Spain. He is a graduate from the University of Zaragoza with a bachelor's degree in mechanical engineering and a master's degree in renewable energy and energy efficiency. After his studies, he worked as a research assistant for two years in the industrial ecology and resource efficiency group at the Research Centre for Energy Resources and Consumption (University of Zaragoza). Then, he joined the SOCRATES European Training Network as Marie Skłodowska-Curie fellow, being the Early Stage Researcher number 15. He undertook his doctoral studies at the Institute for Nonferrous Metallurgy and Purest Materials of the Technische Universität Bergakademie Freiberg. Now, he is a research associate at the Helmholtz Institute Freiberg for Resource Technology, working on the sustainability evaluation of circular economy systems using process simulation.

Christina Meskers graduated from Delft University of Technology with an M.Sc. (2004) in resource engineering and a Ph.D. (2008) in materials science and engineering, including stays at McGill University, the Norwegian University of Science and Technology, and the University of Melbourne. At UMICORE she was a Senior Manager Open Innovation and a Senior Manager Market Intelligence & Business Research. Through innovation and research, her aim was to ensure the product and materials value chain becomes more sustainable. The United Nations' International Resource Panel report, Metal Recycling-Opportunities, Limits, Infrastructure (2013) is a key publication that she co-authored. Meskers is co-recipient of the 2014 Ondernemers voor Ondernemers Award, and the 2013 Belgian Business Award for the Environment. She has a strong passion for innovation, strategy and partnerships coupled with a focus on connecting people and ideas across disciplines, industries, organisations and value chains. She accumulates over 15 years of experience in the (raw) materials sector and is currently a Senior Research Fellow at Helmholtz Institute Freiberg for Resource Technology.

Neill Bartie is originally from South Africa where he studied chemical engineering. After working as a researcher in pyrometallurgy at Mintek for 2 years, he studied extractive metallurgical engineering for which he conducted high temperature experimental research at CSIRO Minerals and Metals in Australia. After returning to South Africa and working at Lonmin Platinum as a process engineer for 8 years, he moved to Australia and worked in various process, design and project engineering roles at Worley and BHP Olympic Dam, and obtained an MBA. After 10 years in Australia, he moved to Germany and is currently a researcher and doctoral candidate at the Helmholtz Institute Freiberg for Resource Technology, focussing on sustainability assessment and optimization of large metal-containing product systems.

Markus Reuter is originally from Stellenbosch (South Africa) where he studied chemical and metallurgical engineering. After having worked for several years in Anglo American, he returned to academia and did his habilitation in Germany. After that he worked at Mintek South Africa leading the furnace process control group after which he had a tenured track professorship in process metallurgy and recycling at TU Delft in The Netherlands for 9 years. After this he returned to the metallurgical industry in Australia and Finland, working for the technology provider Outotec as the Chief Executive Technologist (Ausmelt-Outotec) and Director Technology Management at Outotec. His career combines various positions in industry and research, he holds various professorships globally to link to the young generation, and he has been awarded various prizes and 2 honorary doctorates. From 2015 to 2020 he was a director at the Helmholtz Institute Freiberg for Resource Technology (Germany), ongoing as advisor. Presently he is at SMS-Group in Düsseldorf (www.SMS-group.com) as senior expert. More information can be found at on his career, publications and patents via LinkedIn and Google Scholar.

SOCRATES

Zero Waste

EU MSCA-ETN

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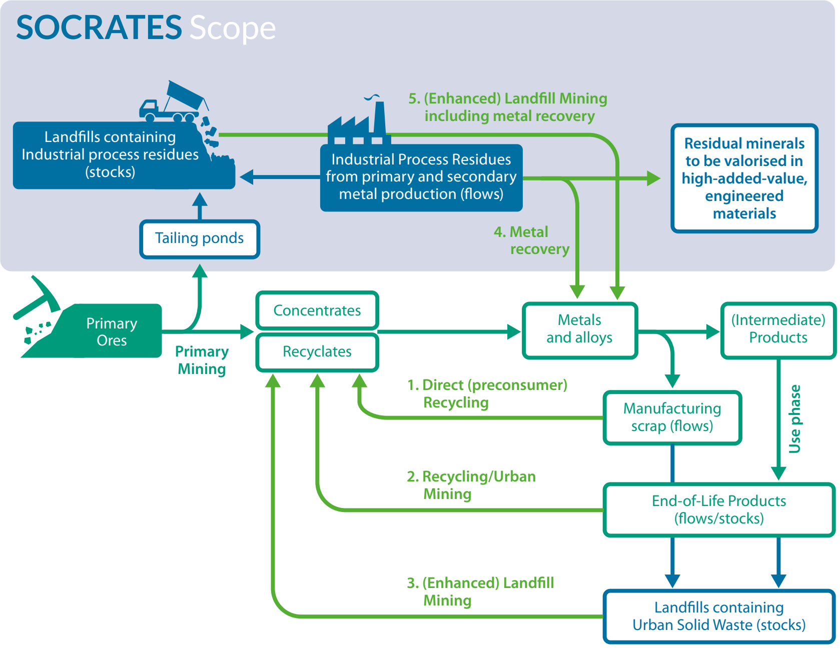
Website: http://etn-socrates.eu/
EU contribution: €3.86 m
Coordination: KU Leuven

The European Training Network for the Sustainable, zero-waste valorisation of critical-metal-containing industrial process residues (SOCRATES) targets ground-breaking metallurgical processes, incl. plasma-, bio-, solvo-, electro- and ionometallurgy, that can be integrated into environmentally friendly, (near-)zero-waste valorisation flow sheets. By unlocking the potential of these secondary raw materials, SOCRATES contributes to a more diversified and sustainable supply chain for critical metals (cf. Priority area 3 in EC Circular Economy Action Plan; COM(2015)614/2). The SOCRATES consortium brings together all the relevant stakeholders along the value chain, from metal extraction, to metal recovery, and to residual matrix valorisation in added-value applications, such as supplementary cementitious materials, inorganic polymers and catalysts. To maximise applicability, SOCRATES has selected four commonly available and chemically complementary residue families: (1) flotation tailings from primary Cu production, (2) Fe-rich sludges from Zn production, (3) fayalitic slags from non-ferrous metallurgy, and (4) bottom ashes from incineration plants. As a basis for a concerted effort to strengthen the EU's critical-metal supply chain for Ge, In, Ga and Sb, SOCRATES trains 15 early-stage researchers (ESRs) in technological innovation: metal extraction (WP1), metal recovery (WP2), residual matrix valorisation (WP3) and integrated assessment (WP4). By training the ESRs in scientific, technical and soft skills, they are the next generation of highly employable scientists and engineers in the raw-materials sector.



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