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ORIGINAL PAPER

Recycling and circular economy—towards a closed loop for metals in emerging clean technologies

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Abstract

Resource efficiency, energy, and mobility transition are crucial strategies to mitigate climate change. The focus is on reducing the consumption of resources, especially energy and raw materials. While raw materials are the basis of our material world, their excessive consumption over the last decades has also contributed significantly to climate change. However, raw materials, and here especially metals, play a key enabling role as well for climate protection technologies, such as electro mobility, the hydrogen economy, and solar and wind power plants, and also for digitalization. Accordingly, it is necessary to make the use of raw materials much more resource-efficient than before and to use them as purposefully as possible instead of consuming them. Advanced circular economy systems and sophisticated recycling technologies build the backbone for the development of a resource efficient and sustainable society. Closed metal cycles contribute for a paramount share to this by securing relevant parts of the raw material supply for high-tech products and by reducing CO_2 emissions in their production at the same time. Interacting steps in multistage treatment processes by mechanical, chemical, and thermal unit operations are challenging but will give a competitive advantage for networks of industry and science that are able to handle that.

Keywords Recycling · Circular economy · Metals · Li Ion batteries · Automotive catalysts · WEEE

Introduction—significance of recycling and the circular economy

Resource efficiency, energy, and mobility transition are crucial strategies to mitigate climate change. The focus is on reducing the consumption of resources, especially energy and raw materials. While raw materials are the basis of our material world, their excessive consumption over the last decades has also contributed significantly to climate change. However, raw materials, and here especially metals, play a key enabling role as well for climate protection technologies, such as electro mobility, the hydrogen economy, and solar and wind power plants, and also for digitalization.

Accordingly, it is necessary to make the use of raw materials much more resource-efficient than before and to *use* them as purposefully as possible instead of *consuming* them. A key approach to this is the circular economy, because metals can basically be reused "infinitely," mostly without any loss of quality.[1] If modern recycling technologies are applied consistently, pure metals are available again at the end of the processes that are identical in their chemical and physical properties to those from mining. But how can metals such as cobalt (Co), nickel (Ni), and lithium (Li) in electric car batteries; platinum group metals (PGM) in catalysts; or precious metals, copper (Cu), and tin (Sn); and other technology metals in electronic components be used and recycled as resource-efficiently as possible?

We will look at this question in more detail in the following chapter, with a focus on metals in consumer products. After pointing out the significance and policy approach of recycling and the circular economy, we will briefly explain the technical and economic fundamentals of metal recycling. We will then look into concrete examples: Where do we

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[1] Nevertheless, some dissipative metal losses along the lifecycle cannot be completely avoided. Hence a 100% cycle is never possible and the in-use metal stock of a certain application slightly decreases with every additional cycle, see also Sect. "Current status of metals recycling". Some quality losses can occur for less noble metals such as aluminum (Al) or magnesium (Mg) and in case of alloy recycling but compared to non-metallic resources the principal recyclability of metals is excellent.

stand today with regard to circularity and recycling with established products such as cars, catalysts, or electronics? What can we learn from this for new emerging products such as batteries for electric vehicles (EV)? Taking these in-praxis insights as basis, the general opportunities and challenges of metal recycling will be identified. As will be shown, many of these challenges are beyond technology—legal framework conditions, business models, and stakeholder collaboration are of key importance as well. EV batteries are considered here on purpose in an own sub-chapter, as they have a high relevance for (critical) metals. They are an example of an emerging, highly dynamic market (also on the technology side) where circularity strategies and recycling will become a "policy must." Although currently only small volumes of end-of-life EV batteries are available, it is now the right time to develop technologies and set up appropriate framework conditions and business models. It offers a chance to overcome recycling deficits we have experienced in established products such as cars or electronics. In this context, electromobility could become a role model to establish a circular economy.

The final part of this chapter will look into new developments and requirements in collection, mechanical processing and extractive metallurgy, including slag engineering and slag processing. It will emphasis the importance of systemic approaches which make use of various complementing technologies, considering interdependencies and interface optimization.

Rational—on the significance of recycling in modern societies

The benefits of metal recycling go far beyond proper waste management. While responsible sourcing of raw materials, specifically metals, rightfully has drawn more attention over the last years, also effective and responsible recycling needs to be understood as a cornerstone for a more sustainable and competitive economy (Goldmann 2010a, b). In this context, responsible metal recycling:

- Contributes to the conservation of raw materials, complementing the primary supply of important and partially critical metals for our society.
- Can significantly improve supply security, especially for many technology metals which currently are imported from outside Europe. Many metal imports derive from regions with higher geopolitical risks, hence making the European economy vulnerable to supply disruptions. Exploiting the European "urban mine" built from our end-of-life (EoL) products, infrastructure, and other residue streams reduces import dependence, improves the resilience of crucial value chains, and hence supports economic activities and jobs in Europe. The need for more supply chain resilience has become even more obvious in the context of the Covid 19 pandemic and the Ukraine war.
- Contributes to cushion volatile metal prices as the additional supply of recycled metals can help to overcome demand–supply imbalances and increases the number of metal sources beyond the primary producers.
- Reduces the CO_2 footprint and overall environmental impact of raw materials supply. If taking place in state-of-the-art recycling facilities, in most cases the energy efficiency (per kg of metal) is better and the impact on water, air, soil, and biosphere is considerably lower than in mining operations. Main reason is that the metal concentration in most of our products is much higher than in geological deposits.
- Is one pillar of responsible sourcing by providing transparent and clean supply chains.
- Is important as well for the protection of the environment as non-recycling or landfilling of EoL products such as electronics, batteries, or vehicles bears the risk of emitting hazardous and harmful substances.

This does not mean to strive for 100% recycling of all metals, as technical and economical limits need to be considered. As discussed in Wellmer and Hagelüken (2015), an optimum mix of secondary and primary metal supply exists. Recovering the last bits of metals from low-grade and complex materials can become more energy intensive than supplying these from primary resources. However, as will be shown in this chapter, there is significant room to improve recycling, especially of precious and special metals from industrial residue streams and EoL consumer goods such as electronic devices, vehicles, or batteries.

Due to the permanent nature of metals and the long lifetime of some metal-bearing products and infrastructures (which can stay in stock for tens, e.g., vehicles, or hundreds, e.g., buildings, of years) or the huge sales volumes of consumer products such as electronic devices or batteries (with relatively short use times), we have been building up a significant anthropogenic stock, creating a potential future urban mine for technology metals. Setting up a circular economy means that at the end of these products' lives—whenever and wherever this will take place—they need to be responsibly and efficiently recycled (Hagelüken 2014), (Hagelüken et al. 2016).

Today's growing demand for metals, however, cannot be met by recycling alone. Primary (mining) and secondary (recycling) supply will remain complementary in the future. But with an increasing utilization of the recycling potential, and as mining conditions are expected to become more difficult (lower ore grades, more complexity, greater depths, etc.), the optimum supply mix will move towards an increasing share of secondary metals (Wellmer and Hagelüken 2015).

The circular economy policy approach as the overarching concept

With the Raw Materials Initiative started in 2008, the EU Commission has placed the significance of raw materials for the European Economy high on the European policy agenda. “Resource efficiency and supply of secondary raw materials through recycling” is one of three pillars of this initiative, in addition to a “Fair and sustainable supply of raw materials from global markets” and a “Sustainable supply of raw materials within the EU” (EU-COM 2008, 699). Linked to this, from 2010 onwards, the EU commission started the assessment of Critical Raw Materials (CRM) for the EU economy. The first list of 14 CRMs was published in 2011 (EU-COM 2011, 25). It is updated every 3 years; the most recent edition from 2020 comprises 30 raw materials, 21 out of which are metals (EU-COM 2020b, 474). A Commission report from January 2018 highlights the potential for a more circular usage of CRMs. “Reviewing important sectors for CRMs, it describes relevant EU policies, refers to key initiatives, presents and gives sources of data, identifies good practices and indicates possible further actions” (Gislev et al. 2018). Recycling is one of the factors addressed in these assessments and publications because it reduces the supply risk for raw materials. For a positioning of the European Union, studies on international developments can provide relevant benchmarks (Goldmann et al. 2014).

This work has been complemented by a number of further policy actions. In July 2014, the Commission published the communication “Towards a Circular Economy—A zero waste programme for Europe” (EU-COM 2014, 398), followed in Dec. 2015 by “Closing the Loop—An EU action plan for the Circular Economy” and a number of revised legislative proposals on waste (EU-COM 2015, 614). The essence of the approach in this “Circular Economy package” becomes clear in the following quote from the 2015 communication:

Circular Economy is defined as “an economy where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimized. … to *develop a low carbon, resource efficient and competitive economy*” (EU-COM 2015, 614).

This shows that circular economy is not a target in itself but is linked to carbon reduction, resource efficiency, as well as to industrial competitiveness. In this context, metals are the ideal candidate, because—in principle—they are “eternally” recyclable. They are not physically lost like fossil raw materials and—if recycling is taking place in state-of-the-art processes—down cycling or materials quality issues can mostly be avoided, as we will see later in this chapter. Their comprehensive recycling and reintroduction into new lifecycles enables a secured access to metals, a key building block for a competitive economy. Figure 1 shows the widely used circular economy loop from this communication.

A more recent important initiative is the “European Green Deal,” launched in December 2019. It lists 11 main action areas for transforming the EU’s economy for a sustainable future. Among these are four with a high relevance for materials and metals, either needed as enabler and/or becoming a key subject for circularity themselves. These are “Supplying clean, affordable and secure energy,” “Mobilizing industry for a clean and circular economy,” “Accelerating the shift to sustainable and smart mobility,” and “A zero-pollution ambition for toxic-free environment.” Linked to this is also “Mobilizing research and fostering innovation” (EU-COM 2019).

The “Circular Economy Action Plan” published in March 2020 builds on the Green Deal and the preceding circular economy actions and “provides a future-oriented agenda for achieving a cleaner and more competitive Europe in co-creation with economic actors, consumers, citizens and civil society organizations.” It “presents a set of interrelated initiatives to establish a strong and coherent product policy framework that will make sustainable products, services and business models the norm and transform consumption patterns so that no waste is produced in the first place. This product policy framework will be progressively rolled out, while key product value chains will be addressed as a matter of priority. Further measures will be put in place to reduce waste and ensure that the EU has a well-functioning internal market for high quality secondary raw materials.” This new Circular Economy Action Plan addresses specifically electronics and ICT as well as batteries and vehicles as key product value chains (EU-COM 2020a, 98).

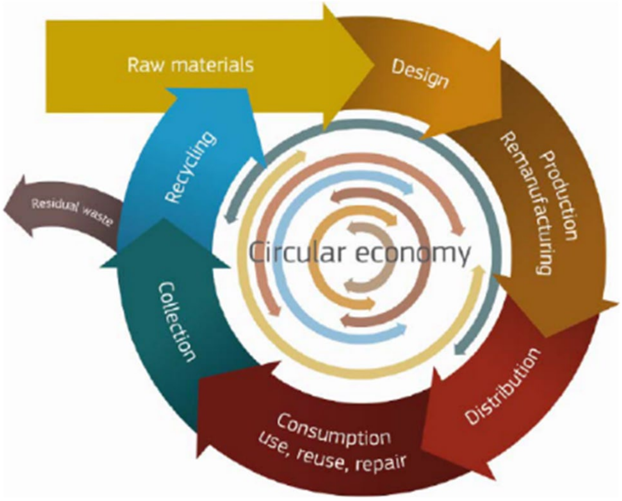


Fig. 1 The circular economy approach of the EU Commission (EU-COM 2014, 398), Towards a circular economy

From these communications, it becomes evident that the Circular Economy will play a key role to achieve the climate goals for 2050. This is also referred to in the "Fit for 55" communication from July 2021 (EU-COM 2021, 550).

It is crucial to understand that circular economy means more than recycling, it is a conceptual approach on how to develop, design, distribute, use, repair, reuse, and finally recycle products (Ellen MacArthur Foundation, Sun, McKinsey 2015). While effective product recycling is a key measure to increase and secure the *supply* of raw materials, there are additional important measures which impact the *demand* side. These so-called "inner loops" of the circular economy comprise better utilization rates of products, reuse, repair, refurbishment, and remanufacturing; they all contribute to extend the lifetime and/or utilization of products and hence delay the demand for new raw materials. In this context, an appropriate product design (e.g., modular devices) is crucial to support repair, refurbishment, and remanufacturing. Such products usually can also be recycled (disassembled) easier. For example, if a battery in a tablet computer or smart phone is removable, this facilitates both the repair by exchanging a defect battery and the battery dismantling at end-of-life of the device as prerequisite for high-quality recycling (see below).

However, ultimately reuse must lead into-high quality recycling. Exporting old products to regions where a subsequent high-quality recycling is rather unlikely to happen creates the so-called "reuse paradox" as it in fact extends the product lifetime but decreases resource efficiency by failing to finally close the material loop. Hence, in this contribution, we will focus on the "outer loop," i.e., the recycling of metals as the final step in the circular economy, which in an ideal case has been delayed by lifetime extension via successful measures for the "inner loops."

Industry can make use of circular strategies and appropriate business models to mitigate supply risk for (critical) raw materials (Tercero Espinoza et al. 2020; Cimprich et al. 2022).

Current status of metal recycling and circularity

The level of recycling and circularity differs quite a lot, depending on products and metals taken into focus.

The UNEP report from 2011 on "Metal Recycling" (UNEP 2011) gives an overview on the share of secondary raw materials in the global metal production (so called "Recycling input rate") (Fig. 2). However, the numbers in this graphic just partly indicate the recycling effectiveness as also dynamic effects such as market growth have a big impact. In case of a rapid demand increase for a metal due to emerging product use even at 100% recycling, the secondary supply will not be able to meet the new demand (e.g., Co or Li in rechargeable batteries).

Especially in comparison with the recycling rates of metals from EoL products (Fig. 3), major differences get visible. Only these "EoL recycling rates" are a useful circularity indicator, i.e., how well specific metal loops are physically closed. They indicated which share of a metal originally placed on the market within certain products finally is recycled from these products.

While some production residues are recycled already effectively in some stages along the production chain, there is still a way to go for others. The higher the value of the constituents and the lower the complexity of a specific residue, the more of that material will be recirculated, preferably if this can be accomplished in a closed production loop.

Major avoidable problems appear, when different residual streams from different production steps within one plant are mixed. While producers care thoroughly for their precursors and products, they partly still do not pay sufficient attention to those side streams. Classical examples are downgrading of aluminum scrap by a common collection of different alloys, used in one product. A separation afterwards is possible but at higher efforts. Even more critical is the mixing of residues from different sputtering or galvanization processes. In some cases, mixing of specific material streams also can lead to a higher recycling potential if this improves the overall thermodynamic environment of the process.

An optimization can be reached by a better understanding of the overall chain and easily applicable information tools, supplying all essential information at one sight. Such developments are fostered by what is called digitized circular economy. New developments on "Recycling 4.0" offer opportunities to transfer "Industry 4.0" approaches onto the field of recycling (Lawrenz et al. 2021).

Certainly more complex are the challenges when dealing with EoL products. While recycling rates for some classical commodities are quite high (Fig. 3), many critical metals are lost almost completely yet. This is especially true for those elements, used as very low concentrated "spice metals" with respect to the overall composition of a product.

Typical examples would be tantalum in capacitors of electronic equipment or indium in LCD panels. While the value of precious metals like gold or platinum and the content in products compared to natural ores are very high, their recovery rates even from EoL products reach higher, though partly still not satisfying levels. Major attention has been put therefore over the last years on critical metals, essential for high-tech products but with limited markets. An efficient and economical viable recovery and recycling of these metals is a major technological challenge. This challenge can be met by complex treatment chains comprising modern pre-sorting and robotic-based dismantling steps followed by multistage mechanical, thermal/metallurgical, and chemical treatment steps in multimetal recovery processes.

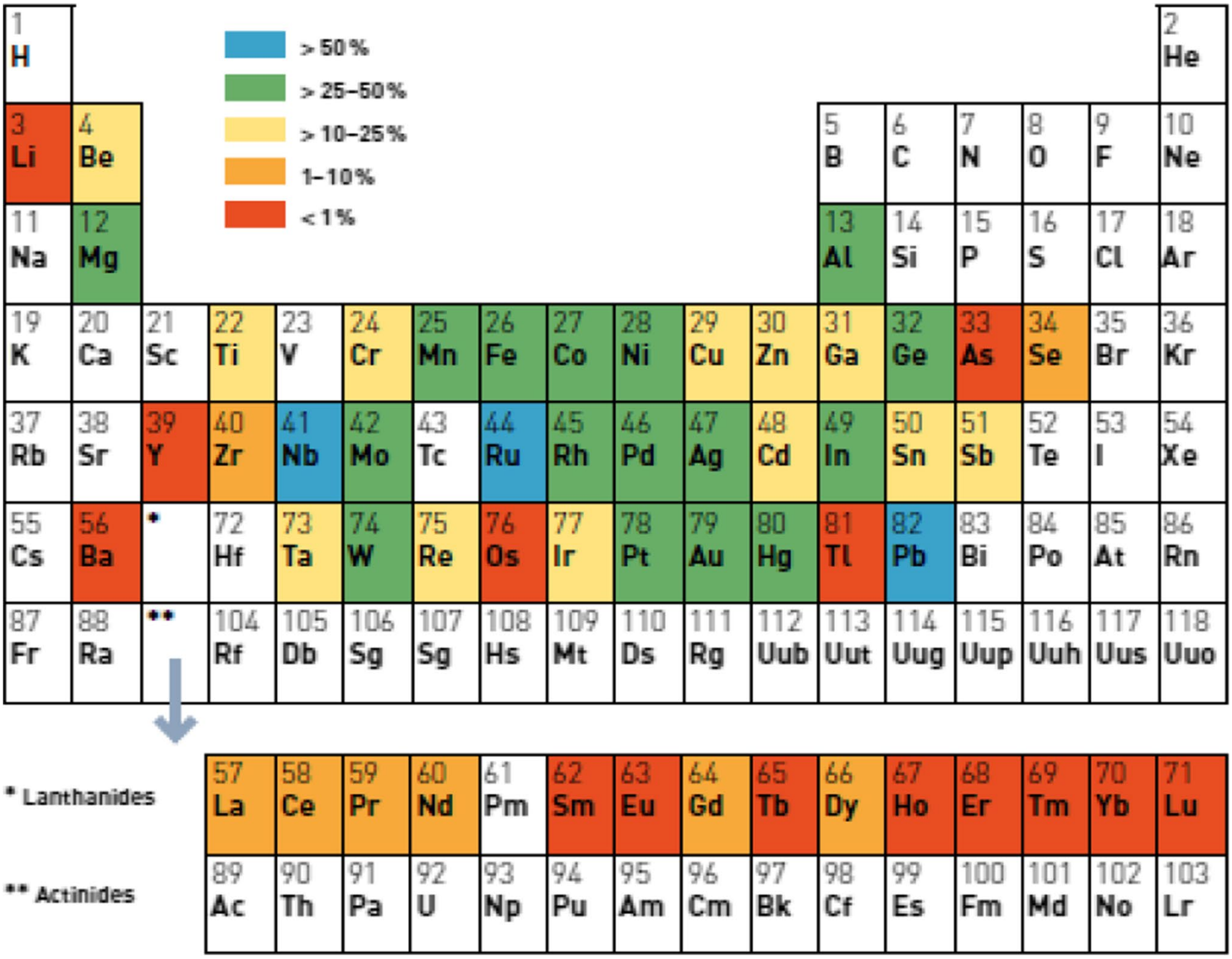


Fig. 2 Secondary raw materials in metal production (UNEP 2011)

To push that further, reliable research strategies and research funding, safeguarding of investments on new technologies by reliable political economic setting, and a strengthened societal understanding are necessary.

So where do we stand today? Let us have a closer look to Germany. A set of papers has been published between December 2020 and June 2021 dealing with the situation, the challenges, and necessary next steps. A very good overview and the state of the art is given in a paper, published by nine leading associations in the field of waste management and recycling in Germany in 2020 (Statusbericht Kreislaufwirtschaft 2020). It can be seen that approximately 45% of the feed for steel production is coming from scrap in German steel plants. Aluminum production is already based on scrap for about 57% and copper production for around 41% (data from 2015 to 2016). Focusing on future challenges and measures to be taken, the "CEID Circular Economy Initiative Deutschland" sketches out a Circular Economy Roadmap for Germany (CEID 2021). Specific parts have been dedicated to packaging and batteries. The latter ones are of superior importance for the recycling of several important metals like cobalt, nickel, and lithium. Beyond specific questions on process chains, major attention has to be paid on new business models for circularity. Finally GERRI, the German Research Platform on Raw Materials recently published a position paper on responsible raw materials supply, addressing effects on climate change as well (GERRI 2021).

Summing up, there is still significant potential to improve circularity and recycling of most metals. But it needs to be understood that "100%" recycling will not be possible. Some metal losses will be inevitable as there are limits of metal recycling due to a dissipative use in some applications and technical/thermodynamic constraints especially in the case of multi-metal mixes.

The following parts of this chapter will provide a closer view on opportunities and limits of metal recycling.

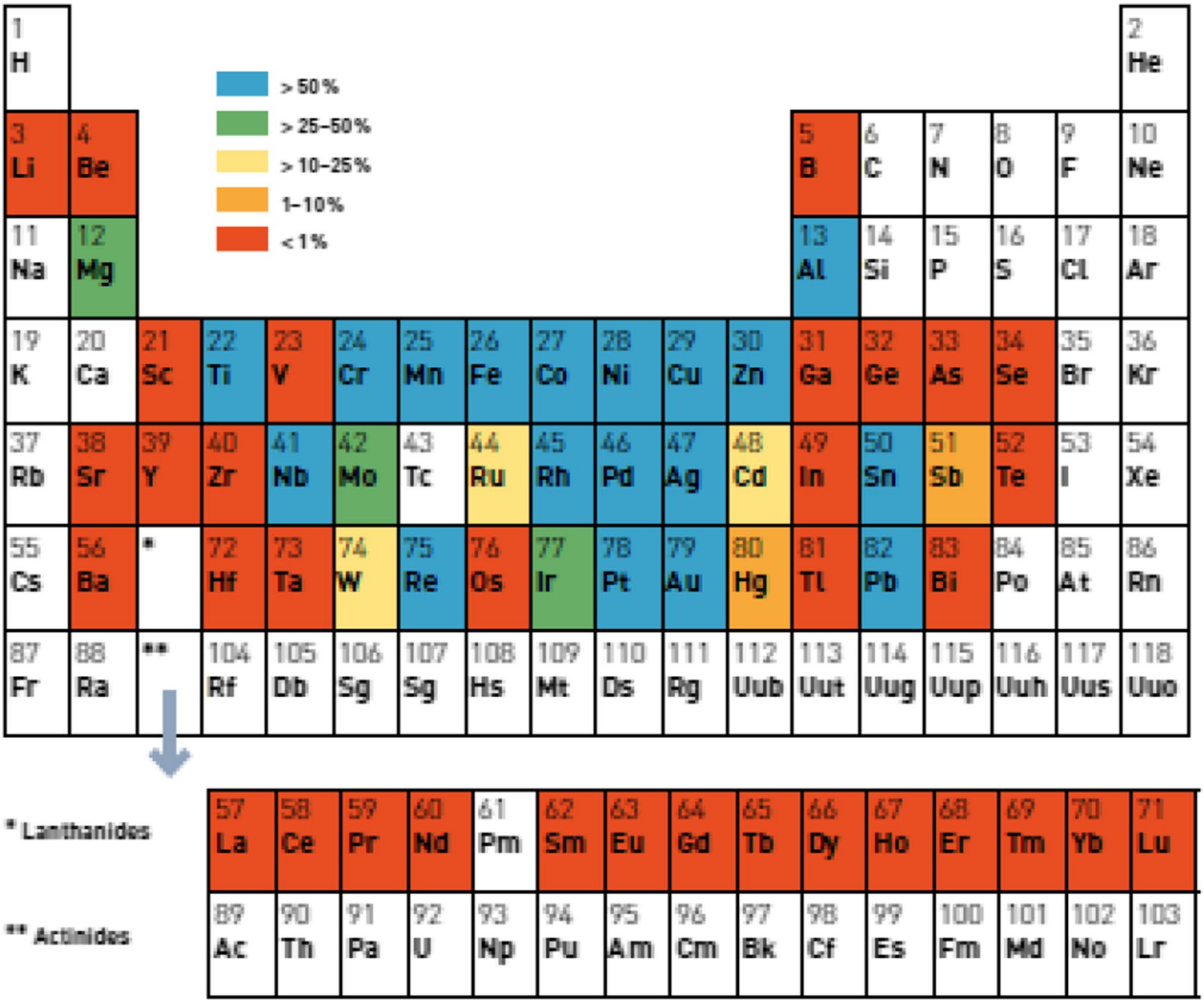


Fig. 3 Recycling rates of metals from End of Life products (UNEP 2011)

Fundamentals of metal recycling

Complex products in the "urban mine"

The metal concentration in many products of our daily life is significantly higher than what can be found in most geological deposits. This principal advantage of "urban mining," so recycling of metals from EoL products, over the extraction of primary ores can be nicely illustrated on the example of gold (Au). In gold mining, the ore concentration is on global average well below 5 g of Au per ton of ore. In other words, a lot of rock has to be mined, hoisted, milled, etc. to get access to a tiny amount of gold, requiring substantial resources. From the magnitude, this is very similar for PGMs and also for base metals such as Cu, Ni, and Sn where big concentration differences do exist.

In comparison, our urban mine, e.g., of electronic products, is much richer: motherboards from a computer, tablet, etc. have Au contents of 100–150 g/t, with palladium (Pd), silver (Ag), Cu, Sn, antimony (Sb), and many other metals in addition. In a smartphone, the Au content even is at 150 g/t and more, again in addition with all the other metals. And an automotive catalyst contains between 2 and 3 kg of PGMs in a ton of automotive catalyst ceramic. These figures show that for a lot of precious metals containing products, there is a concentration advantage of factor 20 and more. So urban mining should be a no-brainer for such products, widely used in modern societies. But why in reality do we face so many challenges?

One of the reasons is that primary mining, although often at low grade, benefits from a large ore volume available at a fixed location. Once a mine is explored and started, it can be exploited over decades. On the other side, our urban mine made out of our EoL products can be of high grade but is dissipated over millions of units in private households and industry. So there is a huge global dissemination and one key question arises: how to accumulate millions of such discarded EoL products into an "urban mine" of a reasonable size which makes it economically viable to recover it? Only after such an accumulation of EoL products at a suitable location, the urban mine "orebody" is formed and the image really fits.

To achieve economic viability of recycling, an effective collection of EoL products is of high importance, as illustrated hereafter on the example of a smartphone. Although the purchasing price of such an item easily can exceed 300 €, its metal value at 2020 prices is just a little more than 1 €, and about 75% of this derives from Au (Bookhagen and Bastien 2020). So the economic incentive to recycle a single phone for recovering the metal value is rather low. On the other side, a company managing to collect about 50.000 mobile phones—which accounts for some 5 tons—and placing these at the gate of a state-of-the-art metallurgical recycling plant creates a net metal value of up to 50.000 € (already considering the recycling costs at the plant). From this, it becomes evident that accumulation of large quantities of devices is crucial for economic viability. Looking now at the global sales of mobile phones—about 1.8 Billion annually—their total metal value is close to 2 Billion €. This represents a very significant resource value that should not be wasted.

In addition to the accumulation and economic challenge, the material composition of products can differ fundamentally from mining ores. Taking again the example of electronic products, these contain a highly complex mix of materials: valuable ones like the precious metals but also base and special metals such as Cu, Ni, Al, Sn, Co; hazardous substances like mercury (Hg), beryllium (Be), lead (Pb); halogenated plastics with bromine (Br), chlorine (Cl), fluorine (F); and many other substances such as glass, ceramics, and organic materials. Recycling has to cope with this complex mix, aiming to recover a wide range of metals and substances with high yields while preventing hazardous emissions and environmental or health risks from material processing or landfilling of residues. A specific challenge in this context is the simultaneous presence of inorganic (metals) and organic materials as well as of certain metal mixes which as such do not occur in geological deposits. Recycling flowsheets have to address such differences, and although the final metallurgical processing often is based on flowsheets developed for primary ores, various adaptions are needed to treat recyclables (UNEP 2013).

Technological basics—the recycling chain for (complex) metal containing products

As illustrated in Fig. 4, product recycling never is just a single step but always a chain of subsequent processes. It starts with collection of EoL products, followed by pre-processing, which means a manual and/or mechanical disintegration of these products into certain fractions for further treatment and recovery. In the case of metal recycling, the final step is the chemical-metallurgical end-processing of these individual fractions to generate pure metals or metal salts (Hagelüken 2012).

The lower the quality standard of a recycling process, the higher are the metal losses. For an effective recycling chain, it is not sufficient to have highly efficient metallurgical processes as final step; efficiency in the sense of a high-maintained value is needed along the entire recycling chain. This total chain efficiency is mostly determined by the weakest link in this chain (usually collection) and derived by multiplying the efficiencies of the individual steps. This can be illustrated on the concrete example of gold recycling from electronics (see Fig. 4). In case of

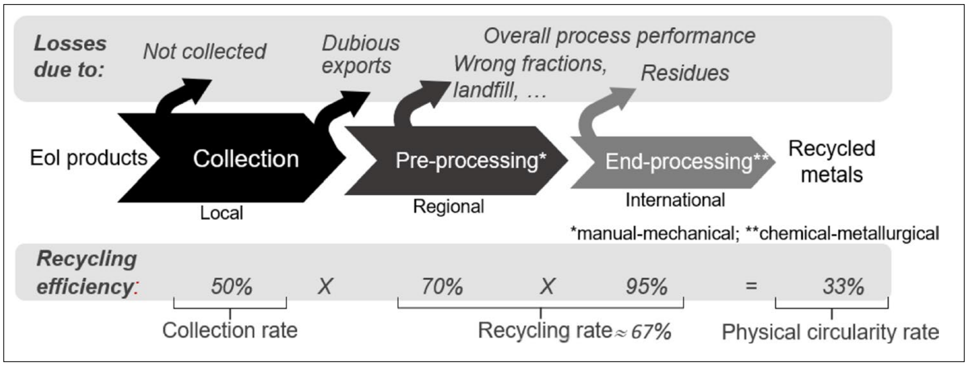


Fig. 4 Recycling chain and material losses for EoL consumer products (example calculation for Au yield from electronic scrap). Along this chain, metal value losses do occur, because (1) EoL products are not collected or—after collection—are leaving Europe as dubious or illegal exports and (2) in pre-processing metals can get lost into wrong fractions or to landfill and (3) also in end-processing certain metal losses occur into slags and other residues

a collection efficiency of 50% and a pre-processing efficiency for gold of 70%, then even with a very high end-processing efficiency of over 95%, the overall recycling efficiency for gold would only be at 33%. And this is quite close to today's recycling reality even in Europe.

Hence, in the case of most consumer goods such as electronics, vehicles, or batteries, improving the overall effectiveness of recycling mainly requires adequate measures to boost the collection of these products at their end-of-life—and to secure that after collection they are channeled into state-of-the-art recycling processes. Next important step is to make use of appropriate pre-processing facilities, capable of disintegrating complex products into fractions suitable for further end-processing respectively metallurgical processing in the case of metal recycling. Here, pre-sorting the collected items by main product groups, product design (accessibility of product components such as batteries or circuit boards) and operational excellence of the pre-processing facilities are crucial factors for cost effectiveness and to avoid that metals are lost into wrong fractions (e.g., Cu in steel fraction) from where they cannot be recovered.

In many cases, the subsequent metallurgical processes are already of high efficiency but they can only recover what reaches such facilities. For complex materials, such as electronic fractions or catalysts, usually a combination of pyrometallurgy ("smelting") and hydrometallurgy ("leaching and chemical separation/purification") is applied. Again, preparation and blending of feed for the metallurgical treatment, operational excellence and management of slags, effluents, and other residues are of high importance. Also, thermodynamic limits do exist; in a complex multi metal mix, not all materials/metals can be recovered (at high yields) and without trade-offs for the recovery of others; hence prioritization of target metals is often needed. Depending on the feed composition and operational parameters of the applied process, some elements will report to slags, flue dusts, or effluents. Although principally this can be used as a separation step as well and metals could be recovered from such streams, energy requirements and economics often result in constraints. This is more elaborated in UNEP (2013).

Basic economics of recycling

The economic viability of recycling is determined by a set of principal factors. We need to distinct here between the micro and the macro-economic level as shown in Fig. 5.

On a micro-economic level these factors are:

- Product type and composition: which recyclable materials are contained in which concentration?
- The current market prices of recyclable materials and metals.
- The performance of the recycling chain and of the applied processes (e.g., with regard to metal yields, energy efficiency, environmental and safety standards).
- Economies of scale: which quantities are where available, and when?

  However, it is not sufficient to look only at the micro-economic level. In addition, societal benefits and societal costs caused by inappropriate waste management have to be considered. These recycling benefits on the macro-economic level were already explained in the "Rational—on the significance of recycling in modern societies" section and comprise:

- Resource conservation, complementing the mine-supply of scarce raw materials
- An increased supply security by accessing metals from local waste sources instead of imports.
- A contribution to responsible sourcing by providing access to clean supply chains
- Reducing the CO_2 footprint and environmental impact of metal supply
- Avoiding damage and related societal costs from landfill or sub-standard treatment

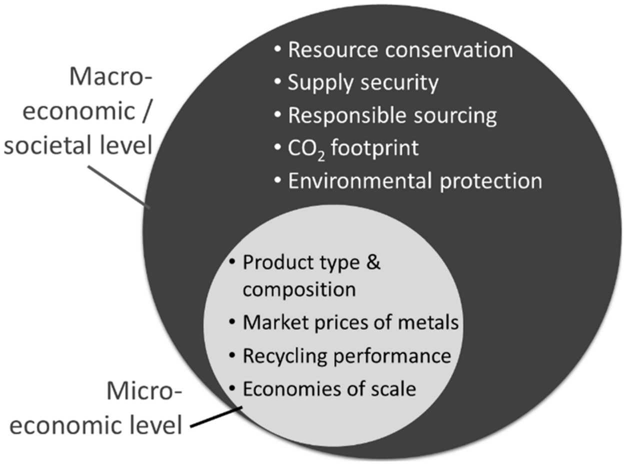


Fig. 5 Impact factors for the economic viability of recycling

Although these societal benefits are crucial, it is the micro economic level which foremost counts for companies. Hence an appropriate legal framework is needed to realize the societal benefits, making use of tools such as producer obligations, fees, collection and recycling targets, etc. An additional approach would be the internalization of external costs, e.g., by incorporating CO_2 pricing.

In order to assess whether recycling of a certain waste category is economically viable on a company level, the formula outlined in Fig. 6 can be applied: calculating the recoverable material value, deducting from this the total recycling chain costs, and eventually adding a recycling fee. Such a fee can be imposed by business models (e.g., leasing, deposits) and/or legislation to cover externalized costs. Waste recycling will not take place in case for a longer period the total recycling costs are higher than the recoverable value and the gap cannot be bridged by a recycling fee or other legislative measures.

The recoverable material value is the sum of the individual material contents, their achievable recycling yields and their respective market prices.

The recycling chain costs depend on the technical performance, the process chain efficiency, and also on the factor costs, which are labor, energy, and capital. They can be directly impacted by the recycling industry. But there are additional costs which are beyond the direct control of a recycler. These are:

- Available volumes (determining economies of scale)
- Environmental, social, and governance performance (ESG) of the recycler
- Shipping costs, including taxes and customs
- Administrative costs and time requirements for transboundary shipments

These latter factors are impacted by legislation and its enforcement as well as by trade legislation. As pointed out earlier, complex wastes are a mix of valuable and hazardous materials. "Externalisation" of ESG costs by non-compliant recyclers within or outside the region where the waste is generated—e.g., by avoiding depollution of hazardous components and reporting to authorities and/or by not caring about process emissions and work safety—enables them to pay a higher price for waste (Magalini and Huisman 2018). In many cases, the significant cost-saving achieved by non-compliant, low-quality processes often outweigh their lower recycling yields and the shipping costs to such activities. Hence, there is an unlevelled playing field for compliant, high-quality recyclers. The reason for "bad" recycling, unfortunately still quite common today, is pretty simple—it is much cheaper than good recycling.

Basic definitions, system boundaries, and calculation of recycling rates

The term "recycling" is not always used uniformly and is often interpreted differently. When does recycling begin and end? Is it a matter of a rather abstract waste-legal dimension of the term or a description of the concrete physical processes? It is important to have a clear designation of the system framework as well as definitions, calculation approaches, and indicators to verify the degree of target achievement that are in line with the objectives.

In the sense of the circular economy's goal of preserving the value of products, materials, and resources in the economic cycle, we focus here on the physical definition of recycling. For this, the cycle must actually be closed in a materialistic sense, i.e., recycled materials or metals must find their way into new products. In this context the following definitions apply, which are based on (CEID 2020):

- Recycling: the entire process from the introduction of end-of-life products into the recycling chain to the completed extraction of marketable raw materials (recyclates) for the manufacture of new products of comparable quality to the primary material. It comprises both pre- and end-processing steps. In the case of metal recycling, the process ends with the generation of pure metals, marketable metal alloys or metal salts.
- Return or collection rate: Proportion of EoL products compared to the products of this category originally placed on the market that were demonstrably collected for recycling. It is important to take the system boundary into account (e.g., a country, Europe, …). Collection of

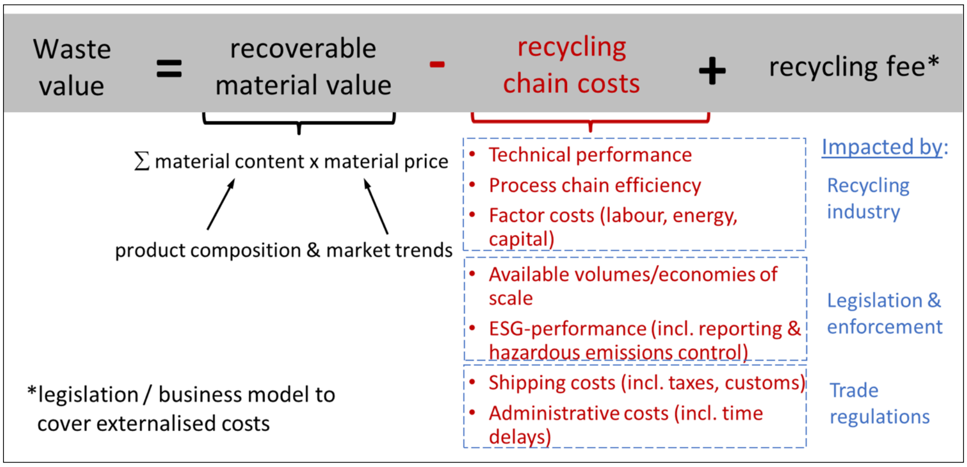


Fig. 6 Principal calculation of recycling value from waste

products for repair and reuse should be accounted separately to avoid double counting.

- Recyclate: Secondary raw material recovered through recycling, of comparable quality to primary raw materials, can be used as an input for the production of new products and thus replace primary raw materials. It is important to emphasize the quality aspect of recyclates: intermediates which require further processing (e.g., metal concentrates) are not a (final) recyclate in the sense of this definition.
- Recovery/recycling rate (RR): Yield related to the overall recycling process. It describes the quotient of the mass of physically reusable recyclates and the recycling input mass, considering the entire recycling process of a product. Since material losses can occur in all individual steps of the recycling process chain (dismantling, mechanical pre-treatment, chemical-metallurgical recycling), the recovery rate (total yield) results from multiplying the yields of all process steps used.

  A distinction must be made between an overall RR related to the product (the masses of all final output streams are considered) and differentiated, material-specific RR for the most relevant materials and substances in these products (e.g., x % Co; y % Ni, etc.). Material-specific rates are important if products contain relevant quantities of “critical” and economically important and/or particularly CO_2-intensive metals and substances (example draft EU Battery Regulation (EU-COM 2020c, 798)).

  The RR can be determined as the average over a financial year for an operational unit (recycling site, business unit or recycling process) and needs to be verifiable by appropriate audits or certification.
- Circularity rate/CE indicator: Only the physical circularity rate (or EoL RR), taking into account the collection rate *and* the recycling rate of the overall process, can be used as a success factor for the degree of circularity of a specific product group or material/substance, i.e., what proportion of a product/material that was placed on the market x years ago is recovered at the end of life of this product and physically used again for production. The EoL recycling rates assessed by the UNEP Resource Panel (UNEP 2011) and displaced in Fig. 3 are based on this approach.

The current waste legislation, e.g., for Waste Electric and Electronic Equipment (WEEE) or End of Life Vehicles (ELV), had been developed with another intention. The historic focus there is still on waste avoidance and pollutant management instead of a comprehensive raw material recovery from waste. The recycling rates in these legislations do not sufficiently reflect this physical dimension in complex products. Accordingly, the input rather than the output of the final process is usually used to calculate recycling rates, and the losses in the final process itself are not taken into account. There are also hardly any specific recycling rates for individual materials/metals. This now has been introduced for the first time in the draft of the new EU battery regulation (EU-COM 2020c, 798) which can be a promising blue print to transfer the traditional waste legislation towards a legislation to improve resource recovery.

- Recycled content/recycling input rate: The share of recycled material in new products is an important indicator, e.g., for raw material import dependency. However, it says little about the degree of circularity, because:

  o For products with longer lifetimes and growing markets, even 100% recycling of old products would not be sufficient to cover the current demand for raw materials.

  p If recyclates from the recycling of other material streams are used for a specific product, they increase its recycled content but reduce the available recyclate quantities in the original application (e.g., use of Al from beverage can recycling for mobile phone housings; use of recycled jewelry Au in electronics).

  q A high recycling content in a product alone does not indicate whether this product will be collected and recycled to a high standard at the end of its life (in extreme cases, it could end up in landfill completely).

Recycling experience from established products with high relevance for metals

To develop effective recycling technologies and process chains for emerging products such as traction batteries for electric vehicles (EV), it is helpful to draw on the experience of past technology launches. It is not unusual for new technologies to trigger a significant increase in the demand for specific metals. In the following, the experiences from the introduction of the automotive catalytic converter and from the recycling of electronic devices are considered. This provides useful hints on whether, e.g., the rapid increase in demand for battery metals can be ensured, whether effective recycling cycles can be established, what measures need to be taken for an effective resource management of such emerging products, and what (legislative) framework conditions need to be established.

Raw material requirements and recycling of automotive catalytic converters

The automotive catalytic converter was introduced at the beginning of the 1980s, driven by new exhaust emission legislation in California which then gradually spread worldwide. As a result, cars and increasingly commercial vehicles are now equipped with catalytic converters and particulate filters in all major global automotive markets. The platinum group metals (PGMs) platinum (Pt), palladium (Pd), and rhodium (Rh), which are used in various combinations, are decisive for the function of automotive catalytic converters and active particulate filters. The introduction of the auto catalyst has increased the demand for these three PGMs by a factor of 4–5 within 20–25 years. Today, the auto catalyst is responsible for some 40% of the global demand for Pt, and for Pd and Rh, it is even more than 80%. Although innovative catalytic converter technology has reduced the specific PGM use required to achieve a given limit value, ever stricter emission limits (e.g., from Euro 1 to Euro 6) have led to a net increase in the PGM load per vehicle.

Similar to cobalt and lithium which are essential for EV-battery materials, the primary supply of PGMs is also concentrated in a few countries. More than 80% of PGM mine production comes from South Africa and Russia, with South Africa clearly dominating in platinum and rhodium. Around 50% of the palladium is a by-product of Russian nickel production. Like cobalt, PGMs are also classified as critical raw materials in the EU and other regions. Although PGMs have occasionally experienced temporary supply bottlenecks and considerable price volatility, supply has never had a negative impact on the market penetration of auto catalysts. Technical innovations for the efficient extraction and use of PGMs, substitution efforts from Pt to Pd and vice versa, as well as a significant expansion of mine production have enabled the demand for PGMs to be satisfied at all times.

The recycling of auto catalysts has also increasingly contributed to the supply of PGM. Figure 7 shows that the recycling share of the PGM supply for auto catalysts has risen continuously. In 2018, 44% of Pt, 39% of Rh, and 30% of Pd demand came from auto catalyst recycling; this static value is referred to as the “recycling input rate.” Similar to batteries, catalytic converters are long-lived products which usually last the lifetime of a car. So it was not until a good 10 years after their market launch that larger quantities of spent catalytic converters were available for recycling. The time lag between placing on the market and PGM availability from catalyst recycling is on average about 15 years, including also the time needed for car dismantling, catalyst collection, and PGM recovery. From the magnitude this can be similar for EV batteries (not considering potential 2nd life applications). As can be seen from Fig. 7, in a growing market, even if 100% of all PGMs from auto catalysts were recycled, this would not be enough to cover current demand. If this dynamic is taken into account and the current quantity of recycled PGMs from auto catalysts is compared with the quantity originally used, this results in the so-called “EoL recycling rate,” which is 50–60%. This means that from 100% of PGMs originally used in a given year to produce catalysts at the end of these catalysts’ life 50–60% have been recovered (while 40–50% was lost). Although this is a high value compared to many other metals, it is significantly below the PGM yield of over 95% that can be technically achieved with modern catalyst recycling processes (Hagelüken 2019, Hagelüken 2020a).

In summary, the following experiences with auto catalysts may also be relevant for lithium-ion batteries:

- Mining production can usually respond to a strong increase in demand for raw materials if appropriate price signals are available. There are many examples where—triggered by new technologies—mining pro-

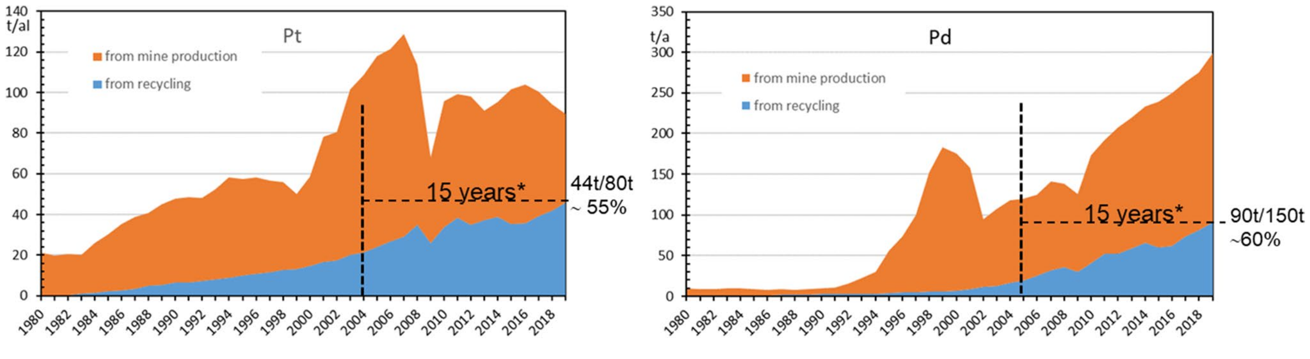


Fig. 7 Raw material supply 1980–2019 Platinum and palladium for auto catalysts from mine production and catalyst recycling, worldwide (Hagelüken 2019). As new demand fluctuates heavily between years, the denominator numbers for 2004 are approximated by a best-fit line, i.e., considering the adjacent years

duction has increased significantly and then remained at this higher level (Wellmer and Hagelüken 2015).

- The expansion of primary production takes time, especially when new mines come on stream. As a result of this and geopolitical factors in the producing countries (e.g., strikes, political influence, export restrictions), temporary supply bottlenecks can occur, especially during demand surges, which can have considerable price effects.
- A (partial) substitution of key metals (e.g., Pd vs Pt) can reduce supply deficits and price spikes and drive technological innovation (and vice versa).
- Recycling can increasingly contribute to security of supply (consider product lifetime).
- New technologies and material compositions may require new recycling processes. Early exchange between product developers and recyclers can prevent “design flaws.”
- With the appropriate lead time, adequate recycling processes can also be developed for such new products.
- Deficits in collection and the recycling process chain used usually prevent the full utilization of the recycling potential. Especially in the case of less valuable EoL products, this can lead to considerable recycling losses.
- Economic incentives alone are usually not sufficient for comprehensive and high-quality recycling. Especially in the case of consumer goods, accompanying legislation and long-term strategic cooperation between industrial market participants are important!

Unused potential in the recycling of electronic devices

Portable lithium-ion batteries have been used for more than two decades in laptops, tablets, and mobile phones and increasingly in power tools and household appliances. The use in these devices still accounts for a major share of cobalt demand in batteries today. In recent years, about 30,000 t/a of cobalt has been used worldwide for such portable batteries, some 25% of 2019 cobalt mine production. Recycling technology and industrial capacities are available to recover cobalt and other battery metals with high yields. However, only a small proportion of spent portable batteries actually reach these state-of-the-art facilities at present. This means that globally, a quantity of cobalt is lost annually sufficient to equip 2–3 million fully electric cars with batteries. As pointed out before, in addition many precious, special, and base metals that are also needed for the control electronics in new technologies can be recycled from old electrical appliances, but this suffers as well from low collection rates and low qualities of many applied recycling processes (Hagelüken 2014).

Comparison of recycling rates of precious metals in different applications

Metals are ideally suited for closed-loop recycling due to their permanent nature. Although recycling rates for steel, many base, and precious metals in jewelry and industrial process catalysts are high, there is still considerable potential for optimization, especially for precious and special metals in consumer goods such as electronics or vehicles. Precious metals are valuable by definition, and their 2021 prices are close to record levels. Moreover, gold and silver have been used since ancient times, while platinum group metals are found in various applications since decades. Accordingly, recycling technologies are very mature, and effective recycling processes have been developed to recover these metals with high yields from numerous products. So both economic and technical prerequisites for successful recycling are principally excellent. But while for some precious metal-containing products indeed recycling works very effectively, for others this is not the case.

Despite sufficient capacity of technically advanced recycling facilities, collection rates are insufficient in many cases and even many collected EoL products are not treated in high-quality recycling processes. As Fig. 8 shows, in applications such as consumer electronics or automobiles, the real recycling rates over the entire product life cycle (EoL recycling rate) are significantly below the technical yields achievable with modern processes (> 95% for precious metals), even for the valuable precious metals. Most of these material cycles are only partially closed in practice, despite existing laws such as the WEEE, ELV, or battery directives, because there are other important influencing factors in addition to technology.

The material value and the underlying business model have a significant impact on the real EoL recycling rates. In a business-to-business (B2B) environment, it is usually easier to close the loop even for lower-value materials than in a business-to-consumer (B2C) environment. Beyond the logistical and technical capabilities of the recycling industry, a major challenge for consumer goods is to create collection and recovery incentives that trigger comprehensive and effective metal recycling and also make it economically attractive.

Requirements for closing the metals loop

It can thus be seen that, in spite of existing waste legislation and circular economy approaches, in the case of consumer goods, we are still relatively far away from a “circular economy.” The following sections deal with the basic requirements and success factors for a true circular economy.

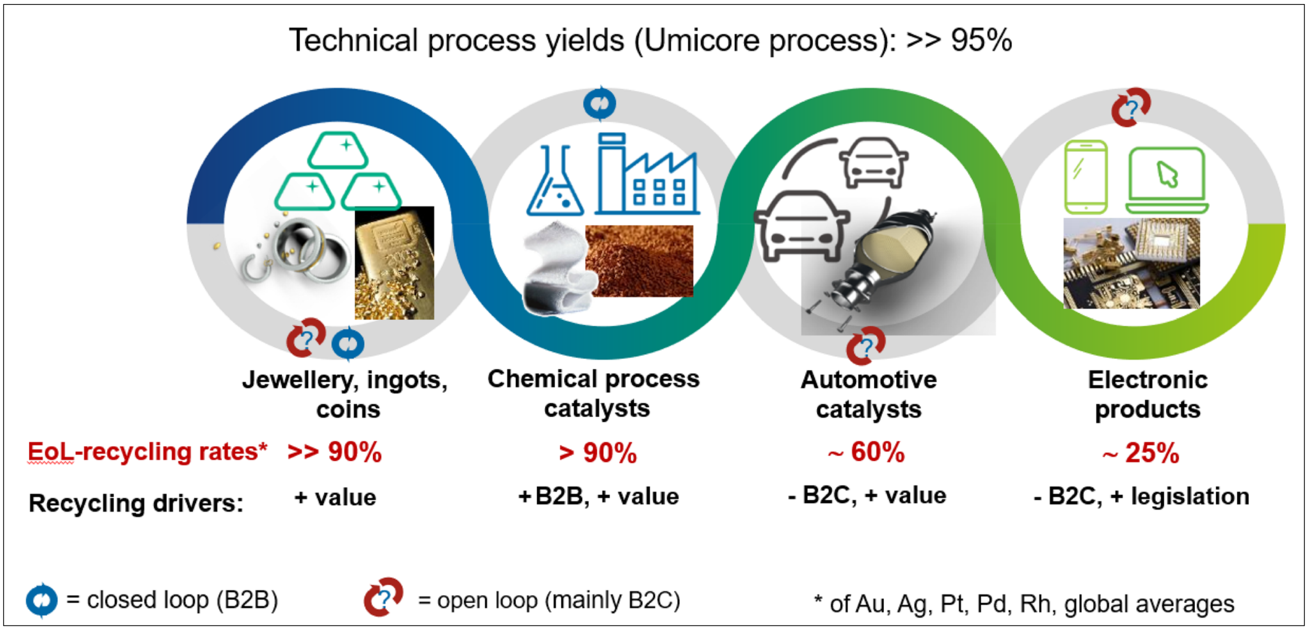


Fig. 8 Comparison of real EoL recycling rates for products containing precious metals. (B2B = Business to Business; B2C = Business to Consumer; ± positive/negative influence on EoL recycling rate)

The physical and the economic dimensions of the circular economy

The term 'circular economy' semantically encompasses two basic requirements—the physical and the economic dimension. The physical dimension requires that materials actually find their way into new products after the end of product life, as metal, alloy, or component. EoL products must therefore not only be comprehensively collected but also subsequently fed into an efficient and high-quality recycling process chain. Only in this way can a wide range of materials and metals be recovered with high yields, in high quality (replacing primary materials), and under high environmental and labor standards. The physical cycle is in principle easier to close for simple products (e.g., glass bottles or aluminum cans) than for complex, multi-material products such as electronic devices or cars. A clear focus on the quality and performance of the applied processes along the recycling chain is therefore crucial. The recycling industry has developed efficient processes for mechanical pre-treatment and chemical-metallurgical end-processing even for complex products. In many cases, however, less costly but also far less efficient processes are preferred.

The economic dimension of the circular economy considers the cost efficiency of this process chain. If the total costs of the recycling chain (including collection) are higher than the achievable revenues, no recycling will take place, unless the revenue gap can be closed in some other way. The more complex a product is, the more technically demanding and cost-intensive its recycling is in terms of a physical circular economy. Since many products contain a mixture of valuable and hazardous materials, it is important to close the loop for a wide range of materials without compromising environmental and occupational safety. This requires treatment in specialized, high-tech recycling facilities equipped with appropriate environmental technologies, which usually cost more than recycling with poor performance and without sufficient standards (often outside Europe). Products such as precious metal jewelry or automotive catalytic converters offer an attractive value proposition for recycling. By contrast, this incentive is lacking in the case of EoL electronics, which is also due to the high costs of the first collection stages. If consumers were better motivated to hand in their old products at central collection points, e.g., through a deposit or leasing system, the logistics costs would drop significantly. A corresponding adaptation of business models can make the decisive difference here and create strong incentives to hand in old appliances.

However, collected EoL products do not automatically end up in efficient, state-of-the-art recycling processes. If the recycling price alone is the decisive criterion, without taking into account the recycling service quality actually provided, cheaper, less efficient processes will get their way. It is therefore important to have a binding requirement to use only recycling plants that demonstrably meet minimum recycling standards, such as those defined in the CEN 50625 series for waste electrical and electronic equipment (EU-WEEE Directive 2013).

Many EoL vehicles—often filled with electronic waste—are exported from Europe to West Africa, for example, through dubious export channels (Adie et al. 2018). Even if some of these products are still in use, there is no high-quality recycling at the end of their life due to a lack of infrastructure and framework conditions. The economic driver for exports is not only the reuse value of some products or components but also the "externalization" of the environmental and social costs of recycling. The focus is solely on recovering a few valuable metals such as gold or copper while pollutants are emitted. Even the most modern recycling plants that recover more materials and achieve higher yields cannot compete economically here. Therefore, legislation and its enforcement are extremely important for creating a level playing field for responsible recycling. Only through this can a physical cycle for a greater variety of metals and materials actually be established.

For product manufacturers, the responsible sourcing of raw materials has gained in importance. Driven also by public pressure from NGOs, it must increasingly be proven that the raw materials in supplier parts are sourced "cleanly." In terms of the circular economy, however, it is just as important to demonstrate "responsible recycling" along the entire recycling chain at the end of a product's life.

Success factors for a circular economy

The extent to which product loops are closed in practice depends on various intrinsic and external factors. *Intrinsic factors* are the material value (e.g., metal content and prices), product complexity and design (e.g., accessibility of batteries, ease of disassembly), applied business models especially B2C vs. B2B (e.g., leasing/product service systems), as well as the product attractiveness for a second use or transferability between users.

External factors include, for example, collection infrastructure and logistics solutions, external incentives for collection and recycling (deposits, fees, producer responsibility schemes, public procurement policies….), available recycling infrastructure as well as quality and cost-effectiveness of the recycling processes used (technical, environmental and social performance; available quantities/economies of scale), legislation, monitoring and enforcement, and cooperation between stakeholders (manufacturers, retailers, users, take-back systems, logistics, recyclers). The following are some examples of external factors that can be considered as external incentives for collection and recycling (Hagelüken 2017).

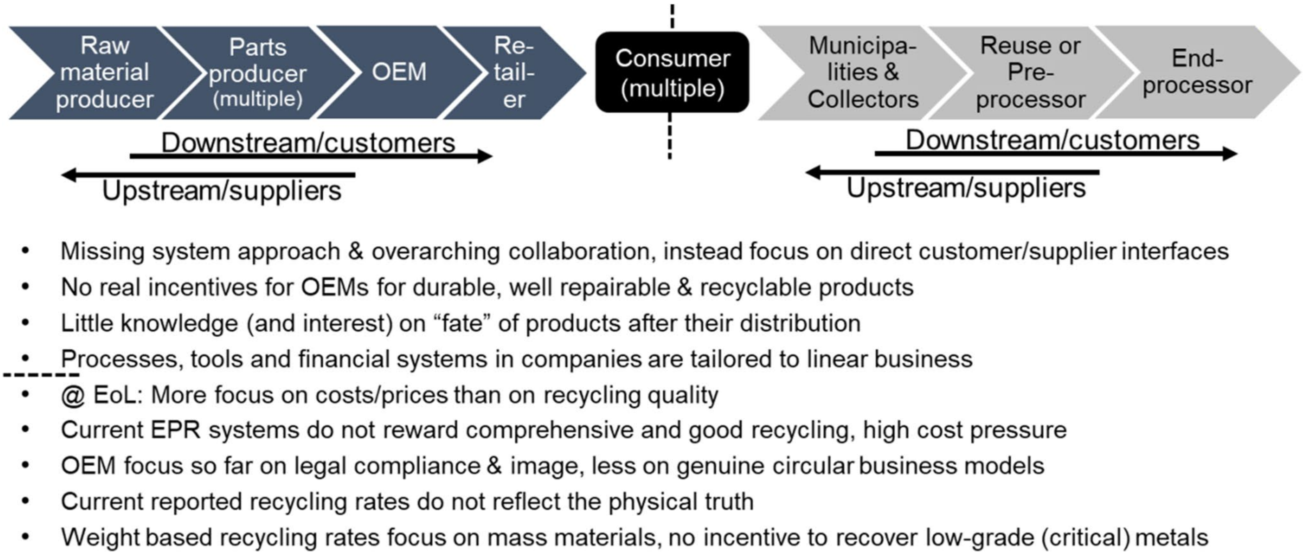
In most cases, positive framework conditions for comprehensive recycling go hand in hand with those for improving repair and reuse: for example, a product that is designed for repair (e.g., replaceable battery) facilitates also the recycling by enabling the removal of single components (e.g., battery) and channeling these into the most suitable final treatment processes. Transparency about the actual product and material flows of EoL products as well as a focus on the performance of the applied processes are also important for repair/reuse and recycling. A business model based on a product service approach ("using instead of owning"; leasing) creates an inherent economic interest in making products durable, repairable, and recyclable. In addition, it generates a critical mass of EoL products for recycling. This reduces logistics costs and allows the lessor (manufacturer or specialised product service provider) to contract recycling services directly to certified, high-quality recyclers.

In current practice, especially for consumer goods, the interface to the consumer is the main obstacle to a circular economy. There is currently no real link between the value chain of product manufacture—left part of the diagram (Fig. 9) from raw material producer to retailer—and the chain at the end of product life, from the collection point to the final recycling process. For the transition from a linear to a circular economy, suitable approaches to overcoming the broken cycle must start at the consumer interface. The pursuit of a physical circular economy will only be achievable through "business as unusual." It requires new forms of cooperation between actors in the product life cycle, taking into account the different influencing factors. Ultimately, it is about developing innovative circular business models that involve fundamental changes in the design, production, distribution, use, and recycling of products.

One key element in this context will be the creation of more transparency on the real physical flows of products and the materials contained in those, especially at product end-of-life. It needs the implementation of tools and framework conditions for tracing and tracking of resource relevant products along the product lifecycles. In a well-functioning circular economy, so called "unallocated outflows" of products like old vehicles, electronic devices, or batteries cannot be tolerated any more. Product passports which cover both static data (product composition, responsible origin of materials, dismantling manuals, etc.) and dynamic data (use cycles, physical crossing of borders, certificate of authorized recycling, etc.), as it is the case for our personal passports, will play an important role for this.

Recycling of lithium-ion batteries

The sustainable supply of the battery metals cobalt, nickel, lithium, manganese, and copper is a decisive factor for the success of electro mobility. The clear goal must be that recycling and reuse of batteries increasingly represent an important component of the raw material supply in the future. As mentioned, an effective circular economy for batteries can only be achieved if—in contrast to the current situation with many consumer goods—spent batteries can be collected comprehensively and fed into technically high-quality recycling processes. Various conclusions



- Missing system approach & overarching collaboration, instead focus on direct customer/supplier interfaces
- No real incentives for OEMs for durable, well repairable & recyclable products
- Little knowledge (and interest) on "fate" of products after their distribution
- Processes, tools and financial systems in companies are tailored to linear business
- @ EoL: More focus on costs/prices than on recycling quality
- Current EPR systems do not reward comprehensive and good recycling, high cost pressure
- OEM focus so far on legal compliance & image, less on genuine circular business models
- Current reported recycling rates do not reflect the physical truth
- Weight based recycling rates focus on mass materials, no incentive to recover low-grade (critical) metals

Fig. 9 Current barriers to a physical circular economy for consumer goods (Hagelüken 2020a, b)

from this discussed case on battery recycling can be transferred as well to other products.

Requirements for the recycling of lithium-ion batteries

Decisive for this is legislation with ambitious recycling rates based on clear, target-compliant definitions and system boundaries, as well as their consistent enforcement. The EU Commission's draft Battery Regulation of December 2020 (EU-COM 2020c, 798) is an important step in this direction. The following criteria are crucial for the development and use of the recycling processes themselves:

Basic technical requirements

- High effective recycling rates of the functional metals cobalt, nickel, lithium, and copper in relation to the entire recycling chain (dismantling, mechanical pre-treatment, metallurgical recycling): The goal must be to obtain a marketable, reusable raw material of high quality, because only then is the cycle actually physically closed.
- Exclusive use of environmentally sound and energy-efficient recycling processes along the entire recycling chain.
- High safety standards when handling battery systems and recycling materials, especially with regard to fire hazards, residual electrical charges and the handling of toxic components such as electrolytes.

Economic requirements

- Cost efficiency of the process chain: as a rule, high process stability and high throughput rates ("economies of scale") are decisive for this.
- Handling large volume flows on an industrial scale. This applies both to the pre-treatment/disassembly of battery systems and to the metallurgical recycling of battery cells or cathode material.
- Flexibility in dealing with different battery types and chemical compositions. If processes are not able to process the different types of lithium-ion batteries (NMC, NCA, LCO, …) and metal ratios (e.g., NMC 111, 622, 811) at the same time, this requires a cost-intensive pre-sorting process and leads to several parallel metallurgical recycling processes with correspondingly lower throughputs and higher fixed costs.

Considerations on second life and recycling approaches

Recycling and circular economy for batteries from electric vehicles (EVs) are often discussed controversially and sometimes almost dogmatically, sometimes with too little fact-based analysis and evidence-based empirical research. Therefore, two of these controversial topics will be examined in more detail below.

The focus here is on the recycling of EoL batteries, because—unlike the currently still quite high proportion of production rejects and batteries from test vehicles—the former will offer by far the greatest potential for recycling in the future. It can be assumed that these spent batteries will only be available after a period of about 10 years or even later from initial use.

Reuse and 2nd life versus recycling

Assumptions about the proportion of EV batteries that can be used for a second use ("2nd life") after the initial use vary widely. The range is 10–75%. In order to estimate what is ultimately realistically feasible in practice, it is necessary to take a closer look at the various influencing parameters. Consideration must be given to significant differences in the type of secondary use, i.e., whether this takes place in the same or in other applications.

- Batteries or battery modules that are used as spare parts for (older) EVs have a comparable technical requirement profile; if necessary, a reduced battery capacity is also tolerated for cost reasons. They compete with more expensive new EV batteries of the current generation.
- The greatest potential for secondary use is generally seen in stationary applications (e.g., home storage, energy storage, load balancing,…). For all these stationary applications, the requirement profile, e.g., in terms of dynamics or energy density, is different from that in electric vehicles. They compete with stationary storage batteries specially designed for this application, which in many cases also manage with less expensive battery chemistries, e.g., LFP (lithium-iron phosphate). It is questionable how sensible it is, for example, to use a first-generation battery with a high cobalt content for many more years in a stationary application, instead of directly recycling it to a high quality after initial use, making the battery metals it contains available for new batteries and instead using LFP types that are not critical for stationary applications.
- In all 2nd life approaches for old batteries, batteries that are about 10 years old compete with the latest generation of batteries.

2nd life is an extension of battery use. This can reduce specific costs and the ecological footprint of the battery, which is a decisive advantage of second use. However, this only applies if the batteries are completely collected after the second use phase and fed into high-quality recycling processes. This requires integrated concepts and transparent material flows across all use and after-use phases.

What does all this mean for recycling structures and business models?

On the supplier side for 2nd life batteries (refurbishment/repair), highly professional, specialised structures are required. This is linked to a number of requirements:

- Refurbishers for 2nd life batteries need secure access to used batteries. Their input must be reliable and plannable. Today, the largest quantities of (conventional) EoL vehicles accumulate at car recyclers, with an extremely heterogeneous volume in terms of vehicle type, year of manufacture and condition. Provided that no sorting takes place in advance, e.g., through measures by car manufacturers or other specialised players, this will also apply to EoL EVs in the future. The variety of types and age structure of the batteries contained in them will be correspondingly large. For refurbishers, this means a high degree of complexity in order to cost-effectively refurbish old batteries and make them available for the various requirement profiles.
- In order to assess whether a used battery is still suitable for economic secondary use, the refurbisher must determine the remaining battery capacity. In addition, the refurbisher needs access to relevant battery use data such as the number of charging cycles, deep discharges/defects, or "state of health." These and other data are normally stored in the battery management system but are not accessible to third parties without the corresponding interfaces and activation by the OEM.
- For testing, repair, and marketing, a profound battery know-how is required, including knowledge of electrochemistry. Without this, neither safe repair can be guaranteed nor can the purchaser of the 2nd life battery be assured of long-term stable and hazard-free use.
- In addition to the aforementioned safe input of used batteries, the refurbisher also needs access to user markets for automotive and stationary secondary applications (output). The prerequisites for this are good market knowledge and reliable, long-term customer relationships.
- Finally, sufficient legal certainty is of crucial importance for all players involved. This includes questions of warranty and liability (who is liable, for example, in the event of a building fire caused by a 2nd life battery?), but also the transfer of the recycling obligation from the OEM via the refurbisher to the end user in the second life.

Even if under these requirements a large proportion of old EV batteries could be remanufactured for second life in the future, a profitable business model in the long term only could be established if demand for (stationary) 2nd life batteries develops accordingly. This is possible in the market ramp-up phase of electro mobility. However, it will become less likely when large quantities of old EV batteries start accumulating in the mid-2030s.

Although 2nd life is an important topic, it will probably only be feasible for a part of the future old batteries. In current 2nd life projects, there is usually direct cooperation between car manufacturers and 2nd life users, the batteries for which come from the OEMs' own fleets. Availability, data access, and legal security can be well regulated bilaterally here. In future, however, the large quantities will come from EoL vehicles, to which OEMs will not have direct access without changes to the business models. The current structures for recycling are also unsuitable in the context of future market requirements for 2nd life. New business models and cooperative ventures involving OEMs, battery manufacturers, and/or battery asset management specialists will be required.

Composite recycling versus metal recycling

It is also discussed whether recycling processes should focus on the recovery of individual battery metals such as cobalt, nickel, lithium, copper, aluminum, and manganese or on the recovery of battery composite materials such as cathode, anode material or electrolyte. At first glance, composite material recovery appears to be advantageous, as in this case the cycle would be closed at a higher value-added stage. However, various conditions apply to the recyclates:

- The added value can only be realized if there is actually a market for recycled materials as an input into current battery production or comparable applications.
- The sales opportunities for recycled materials are limited by high-quality requirements, a prerequisite for the production of new batteries with good performance.

Realistically, with these preconditions, composite material recycling is conceivable for production scrap but not very likely for old EV batteries. Because:

> Due to years of operation and chemical-physical ageing processes, it is difficult (expensive) to recover, e.g., cathode material, in a quality comparable to new material.
> The variety of types described above for the collection of old EV batteries would require a very large (pre-) sorting effort to enable sufficient material purity. Only if separate material recycling campaigns were run for each battery type could mixing and contamination be avoided. This leads to considerable additional costs for collection/presorting and recycling (reduced process throughput).
> Even if high quality is achieved, the recycled materials, which would then be approx. 10 years old, are hardly suitable for the current generation of batteries. The pace of innovation in battery chemistry is high and is likely to remain so.

In contrast, metal recycling has the following advantages when high-quality metallurgical processes are used:

- Metals such as Co, Ni, Cu, or Li can be recovered elementally or as metal salts with comparable qualities to primary metals and traded at the same prices. They are "universally" marketable for new battery materials, but in principle also for all other applications of the metal.
- In recent years, there has been an increasing substitution of Co by Ni in the cathode material; in the widespread NMC (nickel-manganese-cobalt) cathode, after an initial equal distribution, there is now up to 8 times more Ni than Co (NMC 111 → 532 → 622 → 811). Accordingly, the recycling of high-Co batteries of the early generations can disproportionately cover the Co demand for new generations.

In summary, metal recycling is likely to be the dominant solution for EV batteries at the end of life, while composite material recycling can develop as a (sensible) niche business for production scrap and replacement components for battery repair. By analogy, a comparison can be made with the recycling of electronic products. Even if it were possible to dismantle circuit boards from early-generation smartphones intact and in large quantities, they would not be of interest to a smartphone manufacturer today. There is no sales market for the product "old circuit board." However, there is a demand to extract the metals gold, silver, palladium, copper, tin, etc. from it. The principle applies that recyclates without a market are,worthless both economically and ecologically.

Working group traction batteries of the Circular Economy Initiative Germany

Although larger quantities of used EV batteries will only be available towards the end of the decade, it is important to start developing business models and setting up the corresponding take-back, repair, and recycling structures today. Within the Circular Economy Initiative Germany (CEID) launched by acatech (National Academy of Science and Engineering) in 2019, the working group "Traction Batteries," in which scientists, OEMs, component manufacturers, recyclers, logistics, and service companies work together, is dealing with this topic. In October 2020, the final report "Resource-efficient battery cycles" was published (CEID 2020). The entire battery life cycle (without raw material extraction and residual waste disposal) was considered (Fig. 10).

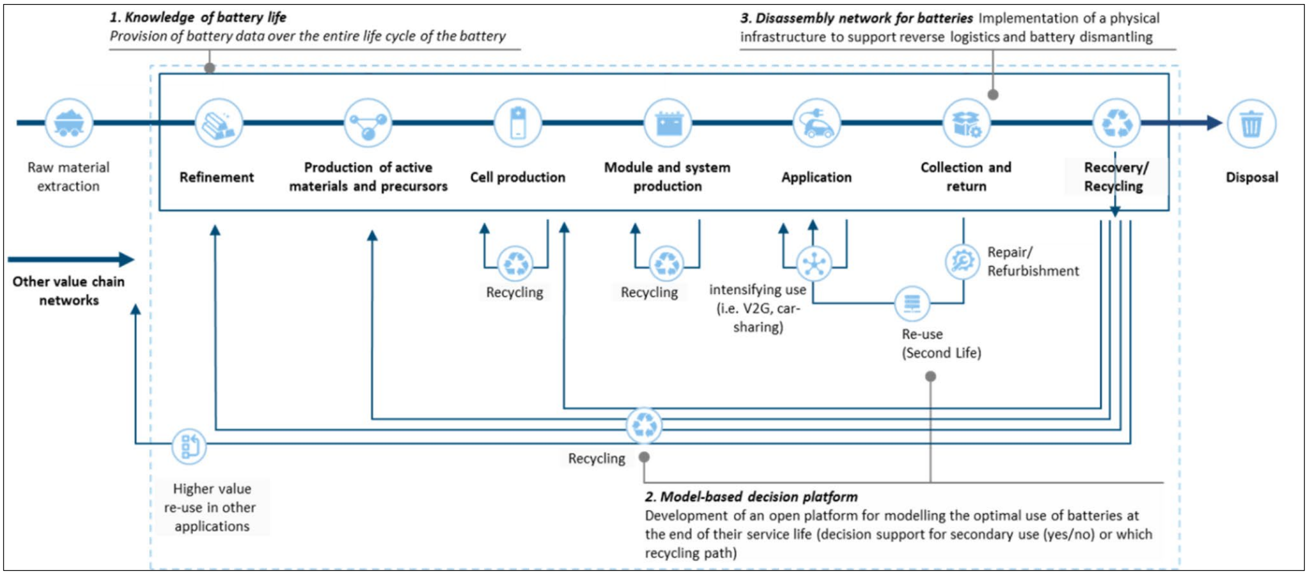


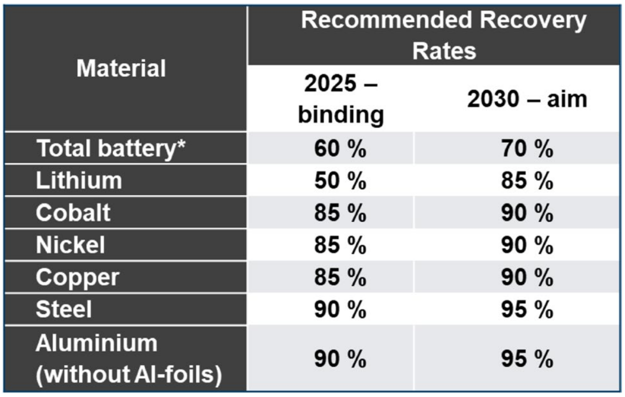
Fig. 10 Scope and pilot projects of the CEID working group on traction batteries (CEID 2020)

A common vision for 2030 was developed, three pilot profiles to support implementation (knowledge of battery life; model-based decision platform; disassembly network), recommendations for action for politics, industry and science, and a roadmap for short-, medium-, and long-term implementation. In addition, key topics are explored in depth in excurses (Covid 19, 2nd Life, Quantified Material Flow Analysis, Definitions and Recycling Targets, Financial Incentives/Deposit Systems).

Clear definitions of key terms and the unambiguous definition of system boundaries are important, as this is the only way to achieve ambitious recycling rates in practice (cf. Sect. Basic definitions, system boundaries, and calculation of recycling rates). As in the draft EU Battery Regulation, the report also calls for specific recycling rates for important battery metals (Fig. 11).

When comparing the CEID recommendations with the recovery rates in the draft battery regulation, some differences appear:

- The regulation proposes recovery rates 2026/2030 for Co, Ni, and Co of 90%/95% (so 5% higher) while for Li they are with 35%/70% somewhat lower. However, the recovery rates proposed by the CEID working group are based on the clear definitions and calculation method as described in the "Basic economics of recycling" section, while in the draft regulation the calculation method is not yet defined. We regard it as more important to call for recovery rates which really cover the entire recycling chain (pre- and end-processing) and are physically achievable in industrial praxis than to aim for seemingly higher legal recovery rates which might require "creative" calculation methods to fulfil these. One key factor here is the quality of recyclates and the interplay between quantity and quality. In many cases the achievement of higher quantities when recycling a specific product causes lower qualities of the recyclate—and hence can be counter-productive to the physical requirements of the circular economy.
- The CEID working group also proposed recovery rates for aluminum and steel, addressing the importance to have sound recycling solutions for these metals used in battery and module casings.
- Neither the battery regulation nor CEID is proposing recovery rates for manganese or graphite. The reason is that there are no mature industrial recycling processes known which are capable of economically recovering



Material	Recommended Recovery Rates	
	2025 – binding	2030 – aim
Total battery*	60 %	70 %
Lithium	50 %	85 %
Cobalt	85 %	90 %
Nickel	85 %	90 %
Copper	85 %	90 %
Steel	90 %	95 %
Aluminium (without Al-foils)	90 %	95 %

Fig. 11 Proposed metal specific recycling rates of CEID working group traction batteries, based on clear definitions and calculation methods (CEID 2020)

these materials in a battery grade quality and *without* having a detrimental impact on the recovery rates for Ni, Co, and Li. As described in the "Technological basics—the recycling chain for (complex) metal containing products" section, complex material mixes often require some prioritization of the target materials to recycle.

Out of the various recommendations to policy, industry, and science the following 9 central ones were identified in the CEID working group:

- Provision of battery data over the entire battery lifecycle (battery passport; linked to pilot topic "knowledge of battery life")
- Strengthening trans-/interdisciplinary education, training, and research for the circular economy
- Design for circularity, including modularity, better recyclability, and reuse
- Set-up of a physical infrastructure for revers logistics and dismantling of batteries (linked to pilot topic "disassembly network for batteries")
- Setting ambitious, binding recycling rates and further definitions and standards in the context of a harmonized national and transnational regulatory framework
- Development of digital tools to support optimal EoL applications of batteries (linked to pilot topic "model-based decision platform")
- Embedding in renewable energy systems and multiple use (sharing concepts)
- Development of effective incentive systems to ensure transformation
- Development of relevant metrics, measurement methods, and tools for the systemic assessment of optimal circular economy

Electro mobility—the ideal test case for a circular economy

The rapid development of the market for electric vehicles will have a significant impact on the demand for raw materials. The most important political driver for electro mobility and other green technologies is the fight against climate change. While this is intended to reduce the consumption of fossil raw materials, the implementation of climate protection strategies requires an increasing use of metals for the production of wind turbines, photovoltaic cells, electric motors, batteries, hydrogen electrolysis, fuel cells, etc. Since the extraction and refining of the required metals can themselves be resource and energy intensive, it is important to ensure that a clean utilization phase of these new technologies is not countered by a "dirty" and energy-intensive production chain or post-utilization phase. Therefore, along the global value chain of a product, resource efficiency in terms of energy, and raw material use is of central importance (Wellmer et al. 2018).

Raw material sourcing, product design, business models for product distribution and use, as well as repair, reuse, transparent waste streams and recycling all play a key role and are interlinked. The circular economy can address these complex interrelationships from an overarching system perspective, where the system boundaries encompass the entire product life cycle. Without new forms of interaction between the actors along the product value chain, it will not be possible to optimize the overall system towards greater total resource efficiency. Previous attempts of optimization have mostly been limited to the interface between "supplier and customer." However, since in most cases the sum of the individual optima is not that of the overall system, this approach will no longer be sufficient in the future. In a circular economy in the sense of the word, all actors in the product life cycle are simultaneously supplier and customer. There can no longer be simple "upstream" or "downstream" perspectives; all economic actors will need to develop a "roundstream" strategy. Longer-term strategic cooperation between manufacturers and recyclers with a strong service component will thus gain in importance.

Electro mobility is an ideal test case for the circular economy and to develop solutions for practical use:

- Safe and responsible sourcing of essential battery raw materials such as cobalt, nickel, lithium, manganese and copper as well as graphite is key to the success of electro mobility.
- Without closing the loop for most of these functional battery metals, the sustainable supply of raw materials and the environmental benefits of electro mobility are at risk.
- Efficient processes for recycling the most important metals from batteries are already under development.
- Without the creation of suitable incentives and framework conditions, the comprehensive collection of EoL electric vehicles and batteries and their high-quality recycling cannot be guaranteed.
- "Business as usual" will not be sufficient to meet the challenges of sustainable electro mobility. New business models are needed to overcome systemic inefficiencies, for the competitiveness of industrial actors, for changes in user behavior, and, above all, for the reduction of the climate impact of mobility as a whole. This also includes car/mobility sharing and leasing concepts.
- Such mobility service platforms open up diverse synergies and offer advantages over traditional, individual car ownership. This is also particularly true with regard to a circular economy, as they transform a B2C environment, which is difficult for circularity, into an advan-

tageous B2B environment. There are also interactions with new technologies such as autonomous driving and vehicle to grid integration (load management of the electricity grid). Digitalization and thus all kinds of electronic devices are becoming increasingly important in this context. Consequently, these two areas of application for technology metals will increasingly grow together.

Although it will take several years before larger quantities of old electric vehicles and used batteries will be available, it is important to start developing the business models and setting up the corresponding take-back, reuse and recycling structures already today.

New and potential technical developments in collection, dismantling, mechanical processing, and extractive metallurgy

To get access to the resources from production residues and EoL products and to optimize the overall system several parts along the chain or rather the aimed circle have to and will be developed further on.

The major points to be addressed are collection, dismantling, mechanical processing, and methods of extractive metallurgy.

Collection and dedication to best valorization channels

Collection rates especially for EoL products and separation of residual streams from production processes still are not where they should be.

Dealing with residual streams especially from complex production processes closed loop supply chain management has to be pushed. Losses very often are due to missing or insufficient information. IT-based data flows easy to access and handle have to accompany product and material flows.

This system gets even more complex, if EoL products are introduced as well. Product passes and open market places for information are under discussion. Especially with respect to the latter new tools are under development which shall lead to a coordinated planning in closed loop supply chains. A development of such a “Recycling 4.0” system (Blömeke et al. 2020) has been started, taking lithium-ion batteries as a show case (Scheller et al. 2021).

In the end material and product streams have to be followed considering stock and flow resources. Over several years, predictive models have been developed, based on system dynamics approaches, e.g., for product and material stocks and flows for copper in different regions of the world (Soulier et al. 2018).

Complexity rises when taking all potential levels of valorization from products after “end of first use” into account. In fact “end of life” may no longer be the right description if the new approach of “re think” is rolled out. This will comprise “reuse” by others, repair under regional and social aspects (repair cafés), refurbish, remanufacture and, still a bit of a vision, “refit” (meaning an upgrade of products to new functionalities mainly when software updates can´t be run on older hardware components). In addition cascade use, leading to second life usage (e.g., LFP batteries from vehicles for stationary applications) may follow. All of these measures will influence the stock and flow system and therefore the availability of material streams for recycling and other measures of recovery. With respect to metals mostly recycling will be the goal but not in all cases. For example, using chips and fine particles of magnesium as desulfurization agent in steel refining is necessary and meaningful though magnesium will then not be recirculated into metal.

Optimization potential within single production plants is still given, if, e.g., different aluminum or steel alloys are used for different parts of the product and if a chance exists, to collect these waste streams separately. This will not always be possible so additional efforts for a differentiated collection scheme have to be contrasted to higher efforts for a more complex separation processes, e.g., Laser Induced Breakdown System (LIBS) based sensor-based sorting technologies. This is even more a question when looking on post-consumer waste streams in different parts of the world. How about the necessary space to store different waste streams? How do public and private collections look like?

New collection systems need to come up, partly setting on changes in behavior of consumers. In the last years, several studies have been carried out in interdisciplinary teams. To raise collection and recycling rates, it is unavoidable that consumers will play a more active part (Menges et al. 2020). Social and behavioral costing, not monetary costs will be strong drivers and of course environmental motivation on the long run.

New potentials from old mining and processing waste sources

Besides actually evolving waste streams old ones, deposited in former times will contribute to the future supply of raw materials. Anthropogenic “ore deposits” could be found in mining residues, slags, and ashes dumps from smelters and incineration plants and in landfills.

A big issue is already the handling of mine tailings, mainly dumped residues from ore dressing. Several reasons will come together to remine those tippings. Due to climate change longer dry phases, followed by heavy rain falls may threaten the stability of dams from tailing ponds, thus putting some pressure of either additional costly stabilization or remining them. Rising raw material prices combined with emerging new dressing technologies, which will allow the recovery of valuable material, lost in former times add interesting options. Finally constituents get into focus that have not been recovered in earlier times but now are of central interest. Research is done on domestic deposits, e.g,. the tailing ponds of the Rammelsberg mine where the contents of some critical metals like cobalt or indium together with the need for specific alumosilicate phases from gangue minerals are main drivers (Römer and Goldmann 2019). Another example are huge tailing ponds in Brazil as residues from mining and processing on niobium that show very interesting concentration of REE. Combined processing by mechanical dressing steps, mostly flotation and bioleaching as well as chemical leaching seam to deliver solutions for a larger range of tailings.

Slags and ashes from metallurgical processes as well as from incineration of municipal solid waste, sewage sludge or other materials also become more and more interesting for the recovery of metals, phosphate and calcium carrying phases where carbon dioxide already has been removed (oxides, silicates, sulfates). Due to technical or legal potential problems or restrictions when using slags and ashes as construction material and decreasing space for landfilling, those materials have to be processed in future anyway, thus raising the recovery rates of metals. A very obvious example is the rising content of copper in the fine grained ash and slag fraction from municipal solid waste incineration plants. Even when separate collection of copper bearing waste streams like WEEE is increasing, the amount of copper, ending up in the residual waste and thus in waste incineration slags and ashes is rising. This is due to miniaturization of appliances or their components. A wide spread dissemination of half of the periodic table of elements can be observed. Since fine fractions of waste incineration <2 mm, making up for more than 60% by weight of the overall mass, show copper contents above those of many ores mined today this is a relevant resource (Keber et al. 2020).

New opportunities by flexible IT-based dismantling technologies

Dismantling as a measure of pretreatment for removal of hazardous substances or parts for reuse is unavoidable but until recently deeper going steps for an optimized further processing have not been implemented yet on a broader range for EoL products. Manual dismantling is fairly expensive in highly industrialized countries. Dismantling by robotics was pretty tricky since it is simply not possible to run a reverse production line since every EoL part has individual properties due to different grades of wear and pollution, changes by individual repair, and other facts.

Due to new options on robot cognition processors (Poschmann et al. 2021) and future developments based on artificial intelligence new opportunities evolve. Specifically for highly complex and valuable products, these technologies will be applied. Especially if safety aspects during dismantling play a major role robot-based dismantling exhibits big advantages. An actual show case is the disassembly of Lithium-ion batteries from E-mobility since batteries have to be disassembled down to cell or cell pack level. To facilitate robot dismantling also product design needs to be adapted. This is specifically valid for a certain standardization of joints used, e.g., for a battery casing. Another approach is the development of a glue that can be disbonded on demand with a trigger agent, which would facilitate, e.g., the removal of glued in batteries from a tablet computer or the opening of a glued EV-battery casing. A close collaboration between product designers and dismantlers/recyclers is advisable in this context. With further differentiation within the "re-" processing lines, including more refurbishment, remanufacturing and refit several other components will be subject to robot based disassembly (Poschmann et al. 2020).

There are however boundaries for the application of this kind of technology. More and more highly integrated constructions and smaller components as, e.g., seen in the production of electronic equipment will restrict dismantling. Approaches for specific removal of tantalum capacitors by dismantling from PCB may come to its technical and economic limits. To avoid losses of valuable metals from complex assemblies, combined mechanical, thermal, and chemical approaches are necessary.

Intensified combined mechanical, thermal, and chemical processes

The higher the complexity of waste streams and the larger the number of constituents, which shall be recovered and recycled, the bigger is the challenge for efficient treatment processes. For more and more of these waste streams, it becomes obvious that only a multistage processing combining mechanical (mineral processing technologies), thermal (pyro-metallurgy, pyrolysis and incineration) and chemical (in case of metals hydrometallurgy) steps will lead to success. This of course includes a well-balanced procedure on separation and pre-concentration by mechanical means ahead of and after pyro-metallurgical treatment.

One of the most challenging recent topics is the engineering of artificial minerals, aiming to recover critical elements from waste streams. A pyro-metallurgical treatment offers the chance, to direct specific elements into three directions, either in a metal alloy melt, in a slag phase, or in a gas-dust-phase. While the path into the metal alloy melt with a subsequent split in hydro metallurgical processes is state of the art for the recovery of many metals, the recovery of chemical rather ignoble elements from the slag is not yet highly developed in specific cases, e.g., the recovery of lithium. Research has been carried out to concentrate specific valuable elements in such a slag in specific artificial minerals with slight changes of the melts composition (e.g., Haas et al. 2018). It has been shown that this will work out for, e.g., lithium (Elwert et al. 2012a), REE (Elwert et al. 2012b), or tantalum when spiking the molten slag with the right additives. Controlled cooling of the slag may then lead to the crystallization of sufficient large grains that can be liberated by subsequent comminution and afterwards separated by means of classical sorting technologies. This is specifically relevant if the valuable components in focus make up just a few percent or even less of the slag. This approach supposedly will not work out, if the concentration is too low and it does not make sense for very high percentages. In the first case, the constituent is too diluted to be recovered that way. Here only a pre-concentration before pyro metallurgical processing would help or if applicable a transfer into the gas-dust phase. At very high percentages of the desired element, direct leaching may be the best approach as it is as well for the mechanically pre-concentrated fractions or the dust.

In every case, it is important to pay attention not only to the recovery of metals but also on the quality of the residual slag phase after processing. In future, production of substitutes for cement or cement raw materials out of slags resulting from artificial mineral creation processes will be an important goal as it is already happening for some other industrial slags.

For the pre-concentrated metal containing fractions in most cases hydro-metallurgical processing will be the final step for concentration and refining partly in combination with electro-metallurgical processes. With respect to the recovery of metals from solutions solvent extraction for intermediate concentrations and resin-based ion exchange for low concentrations, partly in combination may lead to a recovery of the aimed element.

All in all the big challenge for any kind of metallurgical process is a combined one, aiming for a multi metal recovery, the production of slags as byproducts rather than waste streams and at the same time minimizing emission of carbon dioxide. Decarbonization of pyrometallurgical processes as approached by Salzgitter AG for example with their new SALCOS process will be a game changer not only for the metal production itself but also with respect to scrap qualities which can be processed as well as the resulting slags and dusts, which will be modified and may be processed in a new way.

Summary and perspective

Advanced circular economy systems and sophisticated recycling technologies build the backbone for the development of a resource efficient and sustainable society. Closed metal cycles contribute for a paramount share to this by securing relevant parts of the raw material supply for high-tech products and by reducing CO_2-emissions in their production at the same time.

Interacting steps in multistage treatment processes by mechanical, chemical, and thermal unit operations are challenging but will give a competitive advantage for networks of industry and science that are able to handle that. The growing urban mine, shaped by increasingly complex products, disseminating more than half of the periodical table of elements over the market, generates a growing need for experts on waste management and logistics as well as recycling engineers. Finally, growing complexity of the whole system demands a digitization of products and their use in a circular economy.

In combination with the preceding cascade of reuse, repair, remanufacture, and refit which generate findings for a design for circularity, an overall system can be established. If changes in mentality with respect to shared economy or longevity up to changes in mind set to products as a service will add to that, the road to a circular society is paved. Therefore communication and interaction between science, industry, policy, and the public have to be intensified, since nothing can be recycled that has not been collected before.

Declarations

Competing interests The authors declare no competing interests.

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