POSITION OF THE RESOURCE COMMISSION AT THE GERMAN ENVIRONMENT AGENCY (KRU)

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Opportunities and limits of recycling in the context of the circular economy:

Framework conditions, requirements, and recommendations for action

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The Resource Commission is a panel of independent experts. The Commission advises the German Environment Agency with concrete recommendations towards more sustainable resource use.

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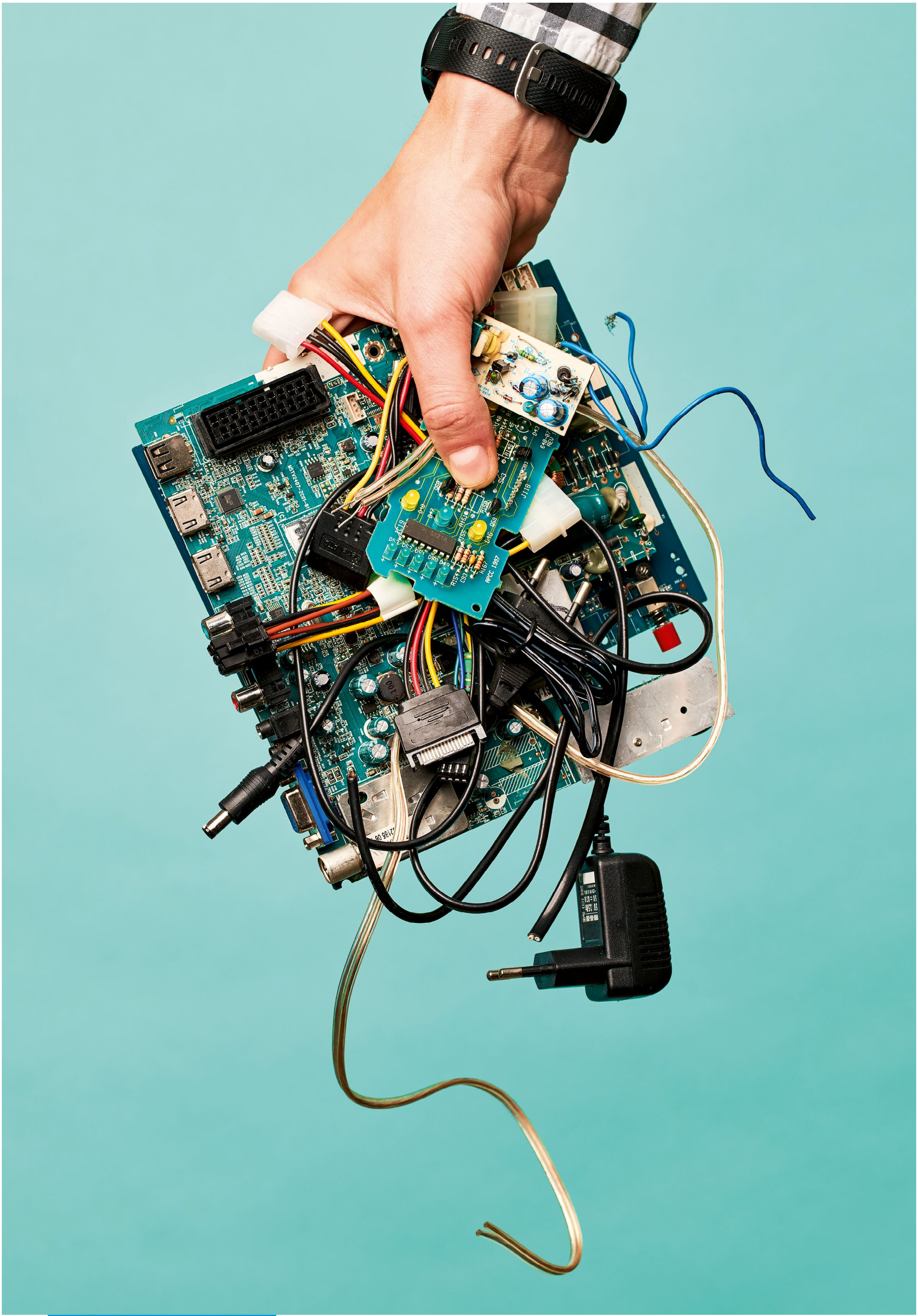


Summary

Circular economy (CE) has become an important topic with regard to environmental and climate policy, and is important for industrial policy and economic strategies in order to strengthen the security of supply and overall sustainability. Recycling, i.e., the continued loop-closing by using recycled materials within the economy, is one of the leverage points together with other CE strategies such as longevity, intensity of use, and a sharing economy. In order to evaluate the contribution of recycling to sustainable resource use and climate protection, it is necessary to clearly define the system under investigation including the system boundaries, and to derive target-compliant definitions, calculation approaches, and indicators to verify the real or potential contribution of recycling to such overarching targets. Furthermore, an understanding of the opportunities and limitations of recycling and CE to achieve environmental, economic, and socio-economic goals such as the UN Sustainable Development Goals (SDGs) and the European Green Deal is required.

This paper focuses in particular on the **recycling of metals**, which play a key role for the energy transition and for climate protection. Recycling as part of an overarching CE concept is crucial for the physical closure of material cycles and thus for reducing the use of primary raw materials and to improve the security of supply. CE and recycling are not an end in itself, but an approach to achieve environmental and climate protection, raw material availability, social standards, product standards, product service benefits, and resource conservation – because sustainable resource use is a prerequisite for the prosperity and economic viability of Europe and Germany. In order to measure the degree of target achievement, the selection of suitable indicators is necessary. The key objectives can be associated with specific action fields, for which operational indicators can be selected to reflect the efficiency or effectiveness of individual measures.

In contrast to classic recycling or waste management, CE aims at more than just minimizing the amount of waste generation. So that through recycling a real contribution to the supply of raw materials and thus to our well-being can be achieved, materials must actually be recycled with high quality at end-of-life and find their way into new products, i.e., recycling must physically close the material cycles. In this paper, we highlight possible recycling indicators, discuss their advantages and disadvantages and outline the necessary requirements for system boundaries, definitions, and calculation methods.

1 Introduction

The careful and efficient use of natural resources[1] is more important than ever. On the one hand, the extraction, processing, and use of raw materials have an impact on the environment and the climate, and in some cases also negative social consequences in the supplier countries. On the other hand, supply shortages are increasingly occurring in the economy due to increased demand, for example as a result of new technologies and applications, but also due to supply bottlenecks and geopolitical conflicts. The so-called Circular Economy (CE) can partially alleviate this situation. This approach, as also advocated by the EU, goes far beyond the previous *"German circular economy (Kreislaufwirtschaft)"*. At the political level, the goal of the CE is stated as *"maintaining the value of products, materials and resources in the economy for as long as possible, and minimizing the generation of waste, thereby making an important contribution to the development of a sustainable, low-carbon, resource-efficient and competitive economy in the EU"* (EC, 2015). Whereas the conventional circular economy focused on the reduction and safe disposal of waste, CE is now concerned with preserving the value of the (raw) materials used. These materials are to be made available continuously with the highest functionality possible in order to create benefits in products and services. The so-called "disposal economy" ("Entsorgung") thus becomes part of the "supplying raw materials economy" ("Versorgung"), in that as many raw materials as possible are made available for products and services, thus reducing the need for primary raw materials. This can reduce energy and associated greenhouse gas emissions, as well as other environmental and social impacts caused by the extraction and processing of raw materials.

Against this background, CE encompasses much more than recycling. CE is an overarching conceptual approach to the way products are developed, designed, distributed, used, repaired, reused and finally recycled so that the materials can be kept within a (raw) material cycle and resources, environmental impacts, and supply shortages can be avoided. In this sense, two views of a CE can be distinguished:

1. The above-mentioned overarching approach involves the entire economic system and can be referred to as CE in the broader sense.

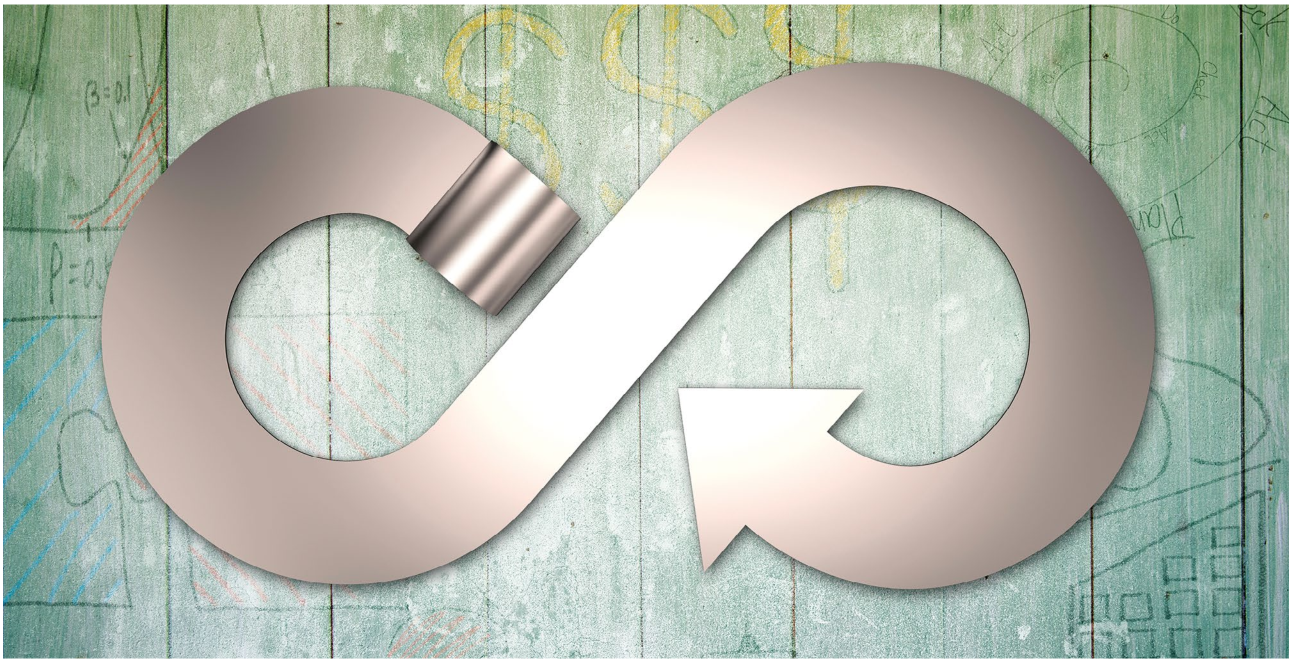
2. Recycling, i.e. the closing of material cycles in the economy, can be referred to as CE in the narrower sense, and accordingly represents an important and indispensable part of the broad CE approach.

The optimization of raw material extraction and the entire production chain up to the product and beyond through use to the so-called end-of-life (EoL) of the products are part of the overarching CE approach. For this reason, the assessment is often referred to as life cycle approach. Social, environmental, industrial, and geopolitical aspects need to be assessed systemically across the entire life cycle in order to capture and compare advantages or disadvantages and select the best courses of action. Overall, there is optimization potential for enhanced resource efficiency both in the raw material cycles and supply chains as well as in the use phase.

Particularly in the current geopolitical environment, with sometimes drastic effects on supply chains and raw material supplies (e.g., COVID pandemic and war in Ukraine), the importance of a secure supply of raw materials is also becoming apparent to the wider public. These import dependencies exist not only for oil and gas, but also for many metallic raw materials. Measures to use these materials more efficiently and to keep them in the cycle better than before (i.e., to consistently use EoL products as a "domestic source of raw materials"[2], highlight that CE does not only address ecological aspects, but also industrial policy and economic strategy with the aim also of strengthening the security of supply (Kullik, 2022).

1 Resource that is a component of nature. This includes renewable and non-renewable primary raw materials, physical space (area), environmental media (water, soil, air), flow resources (e.g., geothermal, wind, tidal, solar), and biodiversity. This includes both resources that are used as sources for producing products or that act as sinks for the absorption of emissions (water, soil, air) (Source: (UBA, 2012)

2 However, specific aspects of raw material supply must also be taken into account when extracting raw materials domestically, including, e.g., land use requirements including issues of nature protection during the extraction of mineral raw materials, or the effects of the coal phase-out on the raw material gypsum.



Globally, the demand for biotic and abiotic raw materials is increasing and has more than doubled since 1990 to currently around 96 billion metric tons per year (latest available data for 2019), including around 10 billion tons of metals (UNEP, 2019). Globally, less than 10 percent of all raw materials used are recycled at the moment (Circle Economy, 2022). In addition to the resource-efficient production and -use of products, their effective recycling plays a central role. This is intended to reduce the use of primary raw materials by replacing them with secondary (recycled) raw materials. Since the extraction of primary raw materials is usually more energy- and resource-intensive than recycling, this would also reduce the burden on the climate and the environment.

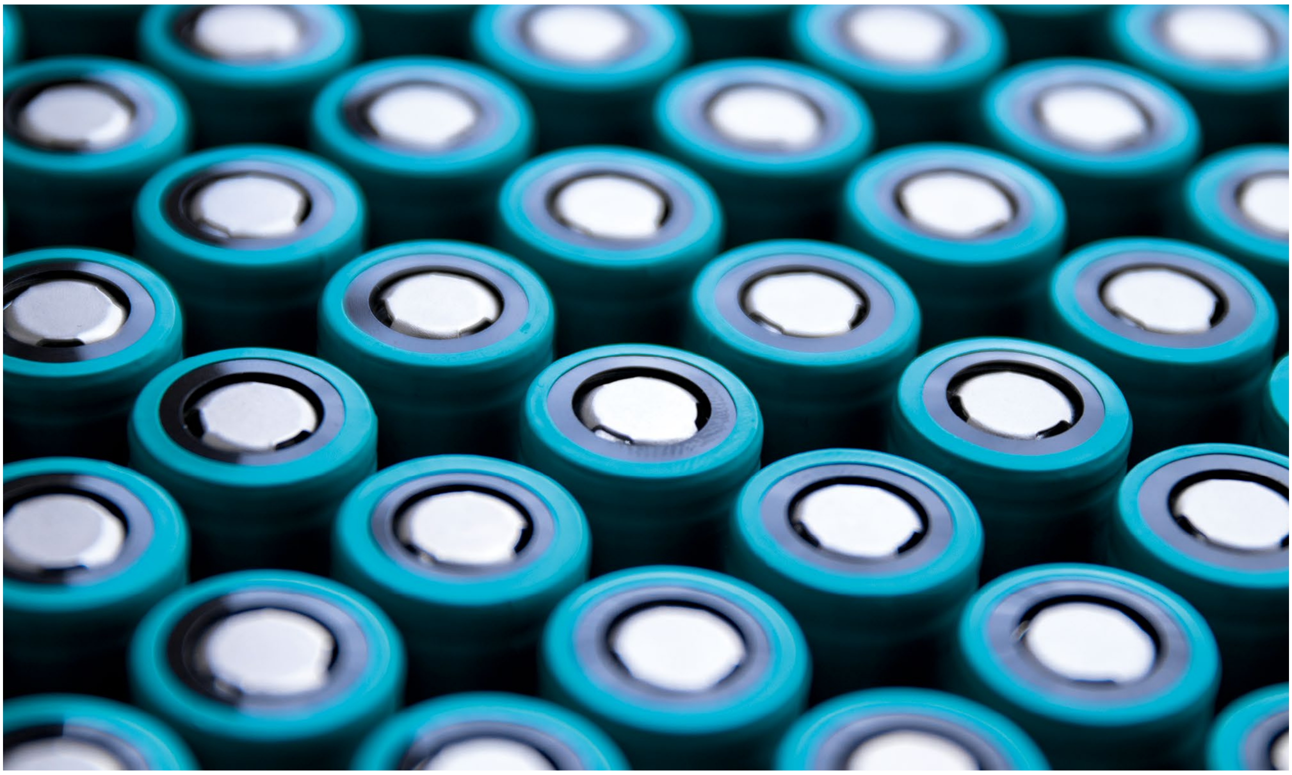
Metals play a special role within the resource category of raw materials. About 80 percent of all chemical elements are metals. Metals play a central role in modern technologies and high-tech products and are essential for the energy supply, mobility, electronics, and medical applications. Especially for the transformation to more climate-friendly energy supply and mobility, metals play a central role. As chemical elements, metals do not disappear after use[3] and can theoretically be continuously recovered. However, metals can be so highly diluted in products or waste ("dissipation") or be present in complex compounds, so that recycling in hindered increasingly inefficient, or even technically and practically impossible. Therefore, the recycling-friendly handling of metals along the entire value chain is of utmost importance.

3 This does not apply, e.g., to uranium as a nuclear fuel.

2 Goal and scope of this paper

While CE and recycling are gaining in popularity socially and politically, there is a lack of common definitions and the necessary overarching framework. In this context, it is important to clearly describe the scope and system boundaries as well as definitions, calculation approaches, and indicators to verify the real contribution of recycling to the goals of the CE. Furthermore, the setting of strategic priorities for the use of raw materials is necessary. For this purpose, concrete material systems must be considered and evaluated in terms of their development against the background of various influencing variables. For example, the transformation of the energy system is also a material transformation ("Materialwende"). Due to the expansion of renewable energies (solar and wind), storage systems (e.g. lithium-ion batteries), and other parts of the energy system, the demand for special raw materials is increasing rapidly. Because of the longevity of such parts of the energy system, such materials are kept in the anthropogenic material stock before they flow back into the recycling system during dismantling or upgrading. The example of the energy system, but also of other areas such as digitization, clearly shows that social and political objectives and the associated investments in research and development have a considerable steering effect on the material flows of the economy. This is also important for understanding the opportunities and limits of recycling, in order to be able to derive the right measures from it.

This paper focuses on the role of recycling in a CE with a focus on the recycling of **metals**. Other aspects of resource efficiency and sustainable resource use, such as the production of durable and reusable products, the development of resource-efficient business models and services (e.g., sharing economy), or resource-efficient consumption patterns, are of great importance for the aforementioned goals, but are only touched upon here (please also refer to the studies by (IRP, 2020) in that regard).



3 Target hierarchy in the Circular Economy

As explained in the introduction, the CE's policy objectives/targets are to maintain the value of products and to minimize waste in order to support sustainability, climate protection, and economic competitiveness. However, this line of reasoning does not always work: The long and intensive use of a classic car (diesel-powered and possibly without a catalytic converter and fine particulate filter), an old refrigerator (energy efficiency class E, with chlorofluorocarbons (CFCs)) or an old and poorly insulated house (dating from the 1950s) maintain their (utility) value and avoid waste, but due to the high resource consumption during use, they are not necessarily always the most "sustainable", most climate-friendly, or even the most competitive alternative. Therefore, the correct naming of the overall objectives/targets and the identification of the contribution of a measure to these goals are essential.

Here, a concrete distinction must be made as to what the final objective is and what the means are to achieve this objective. In the above-mentioned political objectives, the primary goals are global climate and environmental protection, national security of raw material supplies, and compliance with social standards in the supply chain. This also includes the conservation of other natural resources such as water and land or biodiversity. This list shows that CE and sustainable resource use[4] policy can encompass a large number of individual goals. This makes decision-making more difficult and therefore requires further structuring and prioritization. While the objective of climate protection is given the highest priority in current policy, there is a controversial debate as to whether the conservation of mineral resources is a goal in itself or rather a means to an end, e.g., to avoid adverse environmental and social implications of mining[5]. If resource conservation is seen also as a final objective, then CE would be a means to achieve the four objectives mentioned above, namely climate and environmental protection, availability of raw materials, compliance with social standards, and resource conservation.

In order to measure the achievement of a target, the appropriate indicators must be selected to quantify the target and be placed at the center of the evaluation. It should be noted that for a clear interpretation of an indicator, the procedure/method for its determination must also be defined. These target indicators are based for the most part on quantitative data and on correspondingly derived key figures (Figure 1):

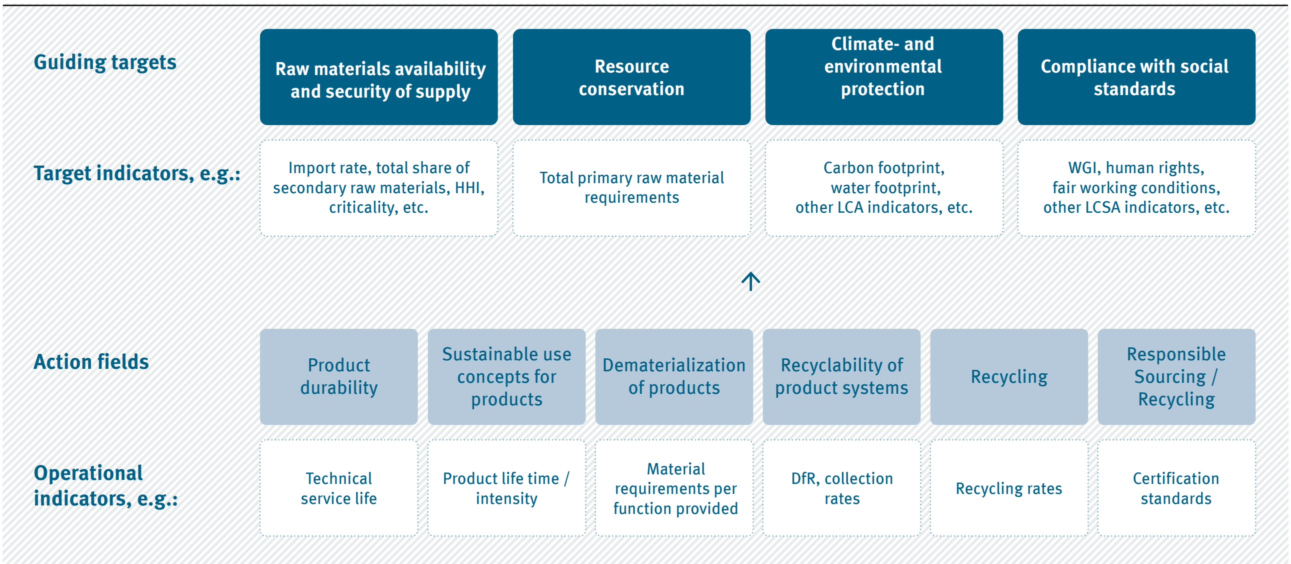
- For example, in the case of *supply security* the question arises as to how large the domestically produced share of primary and secondary raw materials in Germany or the EU is, how diverse the global supplier structure is, and what specific dependencies exist;
- *Resource conservation* is about the absolute reduction in the use of primary raw materials in order to preserve of raw materials for future generations;
- For *climate protection*, the goal is the global reduction of greenhouse gas emissions;
- *Compliance with social standards* in production and disposal can be measured; etc.

Figure 1 shows the guiding objectives (overarching targets) of a CE, their indicators as well as the objectives in the various fields of action and their operational indicators in relation to each other. The fields of action of a CE, such as the manufacture of durable products, improving the recyclability of products, the design of alternative use concepts (e.g., sharing economy), the dematerialization of products and services, and recycling, should ultimately contribute to the achievement of the overarching targets and can only be tracked using target indicators. This also allows the prioritization of measures across different action fields. Similarly, trade-offs between different fields of action or strategies can be described, e. g., between dematerialization in product use and recycling.

4 Sustainable resource use here refers to the "efficient and economical use of natural resources (raw materials, water, soil, air, flowing resources and biodiversity) with the aim of preserving their quantity and function" (UBA, 2012).
5 For a discussion of the geological scarcity of mineral resources, see e.g. (Schmidt, 2021) or (Meinert et al., 2016); on the social consequences of mining, see e.g. (Mancini and Sala, 2018).

Figure 1

Schematic figure of a target hierarchy in the Circular Economy (CE) with guiding targets and a selection of fields of action and indicators.



HHI: Herfindahl-Hirschman-Index; LC(S)A: Life Cycle (Sustainability) Assessment;
WF: Water Footprint; WGI: World Governance Indicator; DfR: Design for Recycling.

Source: own illustration by the UBA Resource Commission

Operational indicators such as product life times or recycling rates for different action fields and levels of action (system boundaries) can be interpreted as proxy indicators which can be used to measure the operational success in the respective areas. Such operational indicators are important, but in the target hierarchy they are found at a lower level and always have a limited context of application (e.g., for a specific action field). The operational indicators might not always be meaningful with regard to the achievement of the guiding targets. Only a life cycle wide evaluation of individual strategies allows to highlight possible trade-offs at the level of target indicators and the overarching guiding targets.

Furthermore, system boundaries need to be clearly defined when selecting targets and the corresponding indicators. Many overarching guiding targets, such as climate protection or resource conservation must be assessed at a global level. Measures that only result in a spatial shift (between countries or world regions) of greenhouse gas emissions, do not count towards global climate protection. However, when it comes to the fulfillment of intergovernmental agreements, indicators at a national or regional level can be useful. Raw material availability, on the other hand, is based on national or economic system boundaries.

However, for many action fields the system that can be influenced by the actors is relevant, e.g., the product system or the company. Many CE measures such as recycling, repair or reuse, are usually considered at the product level, since product development or the corresponding business models play a decisive role. However, such measures should also contribute to loop-closing at the national level and to climate protection at the global level. The appropriate consideration of these different system levels in the choice of indicators is crucial in order to avoid trade-offs and conflicting goals when designing policy measures.

4 Recycling in the Circular Economy

In the classical circular economy, one of the main goals was to minimize the total volume of waste in order to reduce the amount of waste going to landfill disposal, because landfill space is scarce and waste incineration controversial. For example, recycling rates are therefore based in the end-of-life vehicle directive on the total mass of the car. Waste materials that did not end up in waste disposal were, hence, regarded as a positive contribution. However, in a CE that aims at the physical preservation of the materials or their properties, maintaining their functions and quality in order to reuse them as raw materials, other indicators going beyond only waste quantities have to be used. Recycling rates must now be applied to individual materials or marketable metal alloys (see (Reuter et al, 2019)) and they must capture whether these elements or materials are actually kept within the material loop.

This means that after the end of the (preferably long) product life and increased intensity of use (see (IRP, 2020)), materials must actually find their way into new products, as plastic, metal, alloy, mineral (mixture) or as whole components. End-of-life products (EoL products) must not only be collected with high collection rates, but must also be fed into a subsequent efficient and high-quality recycling process chain. Against the background of physical material loop closing, only the final output of the recycling process chains should be counted for the CE success and only if the output materials are of a marketable quality that further reuse for (if possible similar) new products. Only then an actual conservation of resources takes place through substitution of primary raw materials and associated lower environmental burdens.

Recycling rates should therefore not be based solely on output figures or intermediate products in the recycling chain, but should capture the share is actually reused as a high-grade raw material. For example, is the important technology metal neodymium really reused as neodymium, or does it remain as impurities or slag in low-grade products? This requires, on the one hand, a differentiation into the various substances or elements (e.g., neodymium, cobalt, lithium) and, on the other hand, a system view that includes all collection and processing steps (e.g., by means of individual material flow analyses for process chains, countries and regions). Only by doing so can the quantitative material losses in the entire recycling chain be captured and the quality of the final recycled (raw) material be evaluated. This is because there is a connection between the quantity and the quality of the output. A purely quantitative view without sufficient consideration of quality can postulate a recycling success that does not lead to an actual substitution of primary raw materials. This is clearly illustrated by the term downcycling, which describes the emergence of low-quality products (e.g., flower pots made from recycled plastic mixtures). A circular economy in this sense requires the development of business models with material and metal logistics from which products can emerge and re-enter (i.e., business models that are designed in such a way that the functions provided by material and substance flows are at the center).

In the past, the focus was on relatively simple products (e.g., glass bottles or aluminum cans), for which it is easier to close loops than for complex multi-material products such as electronic devices or modern vehicles. Especially e-mobility and the digitization of entire sectors requires the use of a large number of strategically important raw materials and functional materials based on specific elements, the quality of which should be preserved as far as possible for further applications.

The current waste legislation with the specified general recycling rates (e.g. end-of-life vehicle (ELV), waste electrical and electronic equipment (WEEE)) does not yet adequately reflect this physical dimension of complex products. For individual materials/metals/alloys no specific recycling rates existed until recently.

An important step in the right direction is the draft EU Battery Regulation of Dec. 2020 (EC, 2020a)., which for the first time sets specific recycling rates for some key metals (Co, Ni, Cu. Li) in the waste legislation. The exact definitions of system boundaries and the basis for calculating for determining the rates are, however, still open.

In summary, it can be stated that the recycling rates related to waste types in the current waste legislation are not sufficient to achieve the far-reaching goals of a circular economy. This would require recycling rates also related to individual materials and metals as well as other indicators. In addition, system boundaries, indicators including various definitions for recycling rates, and calculation methods should be comprehensively defined. Attempts in this direction, for example in the context of the ongoing international work on an ISO standard in the 59000 series on Circular Economy, are proving difficult.

5 Limits of recycling – about avoidable and unavoidable losses

Special challenges exist with complex and multiple metal-containing consumer goods produced in large quantities such as vehicles or electronic devices. Even with optimal product design and framework conditions, it is not possible to recycle 100% of the materials contained in such products at the same time.

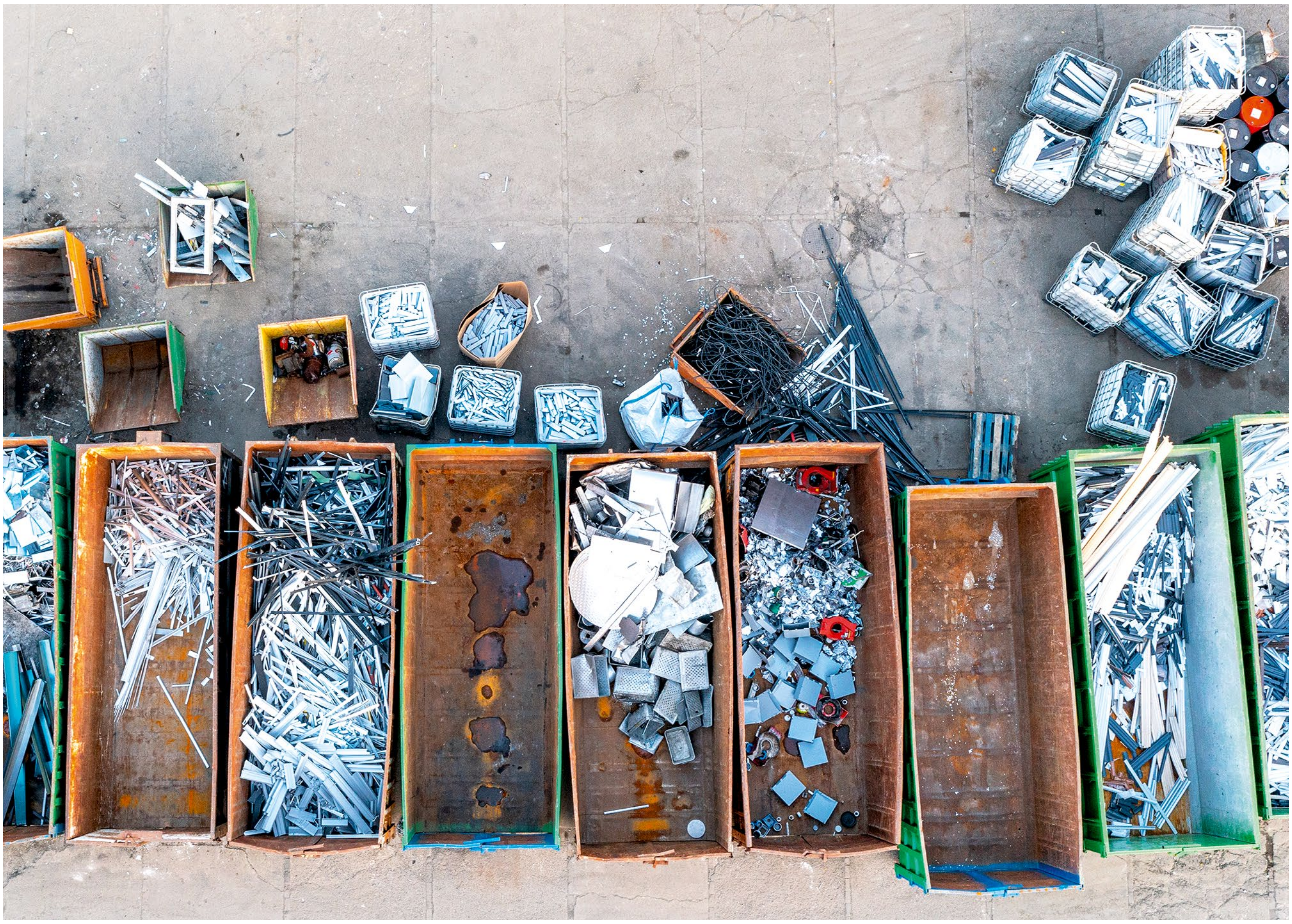
To some extent, material losses occur due to:

- **Incomplete collection** and the **application of low-quality recycling processes** (see Figure 3 in Chapter 7)
- **Cross-border losses:** Through the export of EoL products or EoL fractions, an economy may be missing out on important secondary raw materials, which are no longer available for recycling within the same economy. Recovery and treatment might take place under significantly worse ecological and social conditions in the economy to which EoL products/fraction were exported.
- **Dissipative processes:** In many product applications, material losses are unavoidable (e. g., due to corrosion or abrasion). The use of materials in small quantities or concentrations (e.g., in LED[6] lamps, color pigments, RFID[7] chips, etc.) not only complicates collection, but also technical recovery. The required accumulation of the materials and substances at higher concentrations is always associated with a high energy input, which in turn leads to climate and other environmental impacts. Thermodynamic limits exist beyond which recycling is not environmentally feasible anymore.
- **Technical limits:** Complex, highly interconnected mixtures, e.g., of chemically noble (precious metals, Cu, Ni, Pb, ...) and ignoble metals (Ge, Ga, rare earth elements (REE), Ta, ...) of which the latter are often only present in traces (coatings) or in micro-components (e.g., printed circuits)), can no longer be separated into all individual parts with a justifiable effort, but a residue always remains in a slag or similar.

The latter can be vividly explained by the fact, that while it is easy to pour milk into a coffee, it is practically impossible to separate the milk from the coffee and turn it back into pure milk. There are limits to a Circular Economy.

A distinction must also be made in the discussion between avoidable and unavoidable material losses. While appropriate measures can increase collection rates and recycling quality, and reduce cross-border losses, there is less room for maneuver when it comes to dissipation and the technical limits of recycling, as these are often unavoidable losses. But even these can at least be reduced in a systemic approach, e.g., by taking recycling and material choice into account already during product design, by substitution of critical raw materials (in dissipative applications used at large scales), and via the strict use of high-quality recycling processes along the full recycling chain (UNEP, 2013; Schoch et al., 2021; Reuter et al., 2019).

6 Light-emitting diode (LED)
7 Radio-frequency identification (RFID)



Finally, it must be noted that recycling, including collection logistics, also involves technical processes that always require a certain amount of energy and material input, and thus inevitably also cause environmental implications. In most cases, the environmental implications associated with recovered materials are significantly lower compared to extraction of an equivalent amount of raw material from nature (e.g., from mining). However, this is not always the case and there are instances where primary extraction can actually be better than recycling.

This is especially true when the quantities and concentrations of the materials and substances to be recovered become very small (dissipation) and eventually even below the concentrations found in natural raw material deposits. In that case and from an environmental standpoint, primary raw material recovery would then be preferable to recycling.

6 Defining indicators for recycling

The UNEP International Resource Panel (IRP) already made suggestions in 2011 on how to classify recycling targets in a meaningful way (UNEP, 2011). In addition, the IRP wrote in 2013: *"Defining the system boundaries for which targets are set is critical. In addition, weight-based targets hinder rather than promote recycling of the many critical elements in complex products, which are typically present in very low concentrations. In addition, priorities must be set between different metals, such as base metals, specialty metals, metals for critical technologies, etc. This highlights the dilemma in setting recycling targets for metals that are present in small quantities in products."* (UNEP, 2013). The focus of this review is on the product-specific ("product centric") perspective, i.e., the extent to which raw materials put on the market by certain products can be recovered at the end of their life (irrespective of the place and time of being put on the market).

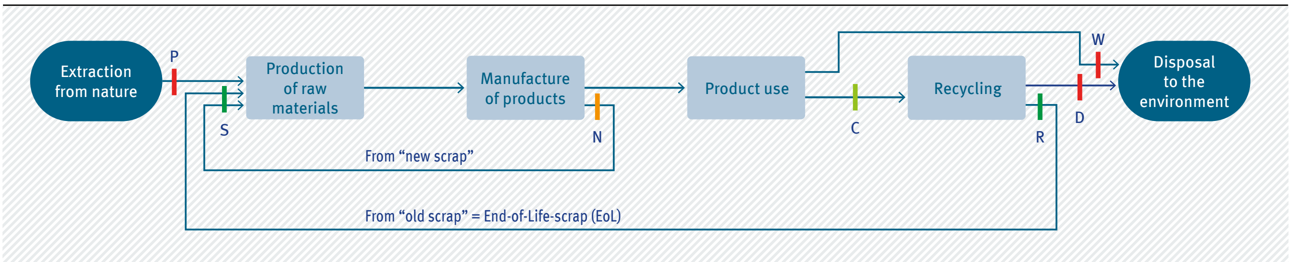
What is required is a systemic view and the selection of a suitable indicator or set of indicators that robustly indicate the impact on the corresponding targets. If waste generation is to be reduced, then the chosen indicator – e.g. a recycling rate – should also be a good proxy for this. If the extraction of primary raw materials from the environment is to be minimized, then the recycling rate should also indicate this. However, in practice, the choice of system boundaries and indicators can vary widely and may not always be compatible with the overarching goals or may obscure the actual success or failure.

The following is a simplified illustration (Figure 2) which highlights how recycling can be described by operational indicators and which different views are expressed in them.

Figure 2 shows the system of a simple production chain over the entire life cycle ("cradle-to-grave") from the extraction of the primary raw material (P) to the disposal of the product waste (W). It is assumed that recycling produces a secondary raw material (S) of the same quality, otherwise the presentation would be more complex. But even in this simple case of equal material quality there are many misunderstandings about terminology. This starts with the fact that on the output side (see Figure 2 on the right), the losses during recycling described by the rate D (disposal) are often neglected. These material quantities can be significant due to inefficiencies in the recycling system. Thus, the collection rate (C) at the end of the product's use is always greater than the recycling rate (R), which describes the proportion that can be physically reused in new products. **A recycling rate, as also defined by (UNEP, 2013) as C/(W+C) on the output side, therefore conveys a too positive picture, since it only refers to the collected and not to the final product output of the recycling process, R**. This rate should therefore be more correctly referred to as the capture or collection rate.

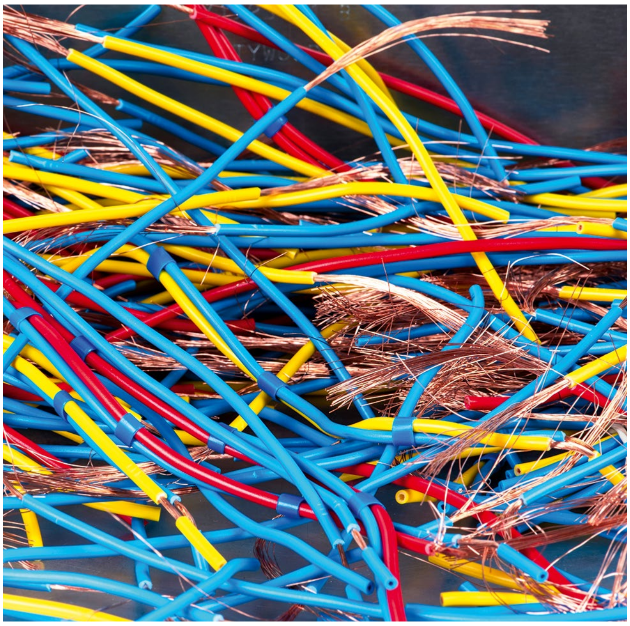
Figure 2

Simplified schematic diagram of a product system including recycling



The abbreviations are explained in the text.
Reference points P,S, N, etc. refer to the bars.

Source: Own illustration by the UBA Resource Commission based on (UNEP, 2013).



For measuring the "success" of recycling, the more correct definition would be the definition R/(W+C)=R/(W+R+D). This quantity shows what is actually recycled from EoL products and can be returned to the cycle by means of material recycling and, thus, replaces primary raw materials (P) or minimizes waste (W+D). If the **EoL recycling rate** were R/(W+C) =1, then no waste would be generated and the material would be fully returned to the cycle. This value "1" is hypothetical, however, and can hardly be achieved for natural and practical reasons. The EoL recycling rate, is a good indicator of the degree of circularity of a given raw material (in a given application) as it shows what proportion of the raw material contained in the original product is returned to the cycle at its EoL.

On the **input side** (see Figure 2 on the left), the recycled content in the raw material P is often given by the ratio S/(P+S) (with S = R+N). This value would then, however, also include the processing losses N ("new scrap") from the industry, such as offcuts, punching residues, or chips. These are material inefficiencies within the manufacturing system. Of course, it makes sense to recycle these residual materials using high-quality recycling, but it would be even more important to avoid or minimize these inefficiencies[8]. Because they lead in any case to an increased ecological and economic costs in the production system (e.g., due to required energy input). The **recycled content** in a CE that has product recycling in mind should therefore focus on secondary raw materials at the end-of-life (R) of a product, i.e., on the quantity R/(P+R). If the Recycled Content were R/(P+R)=1, then no extraction of primary raw materials from the environment would be required, which is, however, hypothetical for the reasons mentioned so far.

At the macroeconomic level and for the four raw material categories: biomass, metal ores, non-metallic minerals, and fossil energy carriers Eurostat reports in the monitoring framework for a circular economy on the "**Circular Material Use Rate (CMUR)**[9]. The CMUR represents the proportion of material recycled and reintroduced into the national economy as a share of total material input. For individual raw materials Eurostat reports the "Contribution of recycled materials to raw materials demand – **End-of-Life Recycling Input Rate (EOL-RIR)**"[10] based on EU Material System Analyses (MSA) studies.

A fundamental challenge is the development in the demand for raw materials for products over time. In most cases, this demand rises due to increases in consumption and new developments such as the energy transition desired by society. However, in some cases the demand for a (raw) material may also decrease, for example, if the dematerialization of products happens, a change in technology occurs, or if materials are banned for environmental reasons. If the demand increases, the recycled content R/(P+R) will always be significantly smaller than the EoL recycling rate R/(W+C). This means that in a growth market the recycled content can never be very large, because the material has to be made available in the anthropogenic stock in the first place before it can be (later) recycled. This applies to many of the technology-relevant metals, especially in the energy sector, which have only

8 Since significant quantities of such production residuals are often generated initially, particularly when new technologies and production processes are being developed (e.g., production of battery cells), these also represent an important source of secondary raw materials that must be recycled to a high standard within the EU. Accordingly, an outflow of these quantities from the EU must be avoided at all costs, especially during the critical ramp-up phase of newly invested recycling facilities. Therefore, both flows should be quantified and clearly communicated

9 https://ec.europa.eu/eurostat/de/web/products-datasets/product?code=cei_srm030

10 https://ec.europa.eu/eurostat/de/web/products-datasets/product?code=cei_srm010

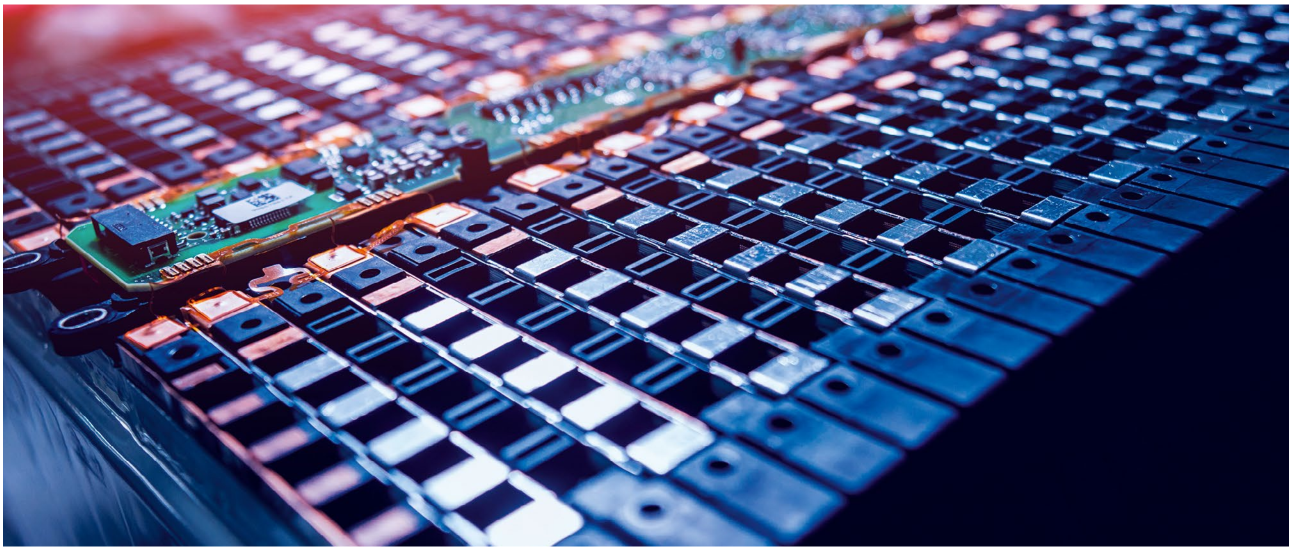
been in use for a relatively short period of time in applications with strong growth rates and long service lifetimes (e.g., Co, Ni, Li, etc. for lithium-ion batteries). The recycled content is therefore only suitable to a limited extent as a CE indicator for individual raw materials and this should be considered in specifications and evaluations. We also note that the fast circulations of specific alloys with low concentrations may be necessary in order to maintain economic functions in the event of supply shortages and to keep pace with innovation cycles.

In the present case, the material cycle was illustrated on the basis of a product system. This means that a kind of **"closed loop"** takes place: The material is used again for the same product. If the quality of the secondary raw material corresponds to that of the primary raw material (it has "inherently" the same material properties), then it can of course also be used to replace the corresponding demand for other product systems.

From this point of view, metal recycling has fundamental advantages over, for example, the recycling of plastics, textiles, or paper. This is because metals, which are recycled in modern metallurgical plants, are generally of the same quality as primary metals, i.e., they have identical purity, chemical and physical properties, and are also traded internationally at the same prices[11].

In the event that the secondary raw material is of lower quality than the primary raw material and **downcycling** takes place (i.e., the secondary raw material can only be used for other or lower-quality products), a closed loop is not possible. **Cascading** into other product systems then occurs. The meaning of downcycling (Helbig et al., 2022) and the effect this has on the extraction of primary raw materials or on the generation of waste should be considered in much greater detail for the specific application under investigation.

Products or product components can also be directly reused or reused further. Ultimately, this leads to an extended service life and increased intensity of use, but the necessary closed loop through recycling is merely postponed.



11 Many smelter sites process both primary and secondary raw materials in the same flowsheet, and the fine metals in the process output can only be differentiated on a mass balance basis. For this reason, there is no need for incentives to use recycled (rather than primary) metals in products; if they are present as fine metal, then marketability is automatically given. However, incentives can be important to ensure comprehensive collection of end-of-life products and to steer them into high-quality recycling processes.

7 Specific aspects of recycling rates of metal recycling

The complexity described in the previous section of indicators for the recycling chain can be highlighted well with an example for metals (Figure 3). The recycling process itself consists of several steps and starts with the collection of EoL products, followed by a manual and/or automated disassembly and/or mechanical pre-treatment (pre-processing) of these products to produce suitable fractions for further (final) recycling. In the case of metal recycling the last step is the chemical-metallurgical processing of these individual fractions in order to produce fine metals or metal salts.

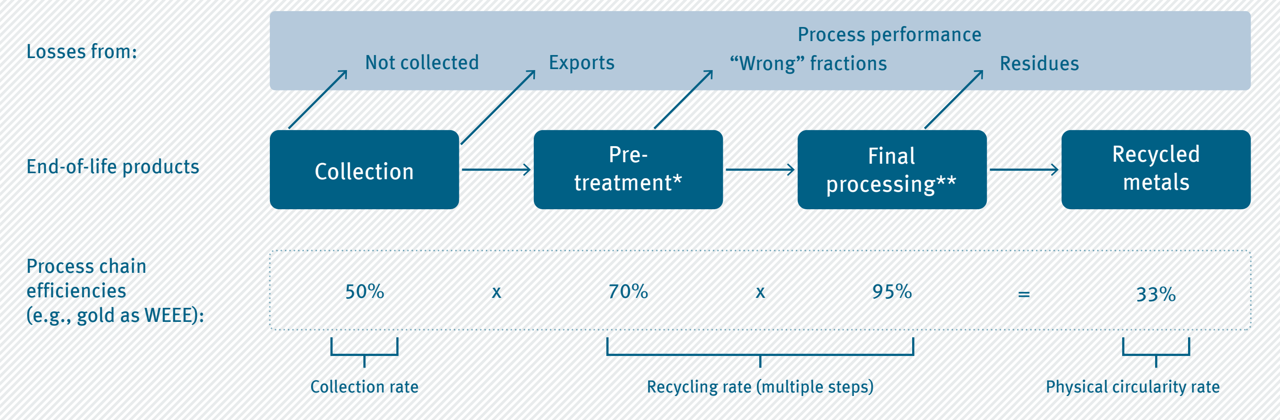
The lower the quality of an individual process in the chain, the higher the overall (metal) losses. It is therefore important to achieve high efficiency across all stages of the process chain. This overall efficiency of the chain is decisively determined by the weakest link in the chain (mostly the collection) and results from multiplying the efficiencies of the individual steps. This example of the recycling of gold (Au) from electronic equipment (Figure 3). With a collection rate of 50%, a gold recovery rate in pre-treatment of 70%, and an assumed metallurgical recovery yield of over 95%, the total gold recovery would be only 33%. This is quite close to the current recycling reality for gold recovery from WEEE in Europe. Gold is only one example for a raw material contained in complex products such as electrical and electronic equipment and should be recovered from them if possible.

Accordingly, high-quality recycling requires the economically viable recovery of many relevant containing materials with high yields, in marketable quality, and in compliance with high environmental and social standards (taking into account energy efficiency and CO_2-balance). Along the recycling chain, numerous metal losses may occur because:

1. EoL products are not collected or leave the system (e.g. Europe) after collection as (often dubious or illegal) exports,
2. Metals during dismantling and pre-treatment end up in fractions from which they cannot be recovered or end up in landfills and are lost,
3. During the final metallurgical processing metal losses in slags and other residues arise.

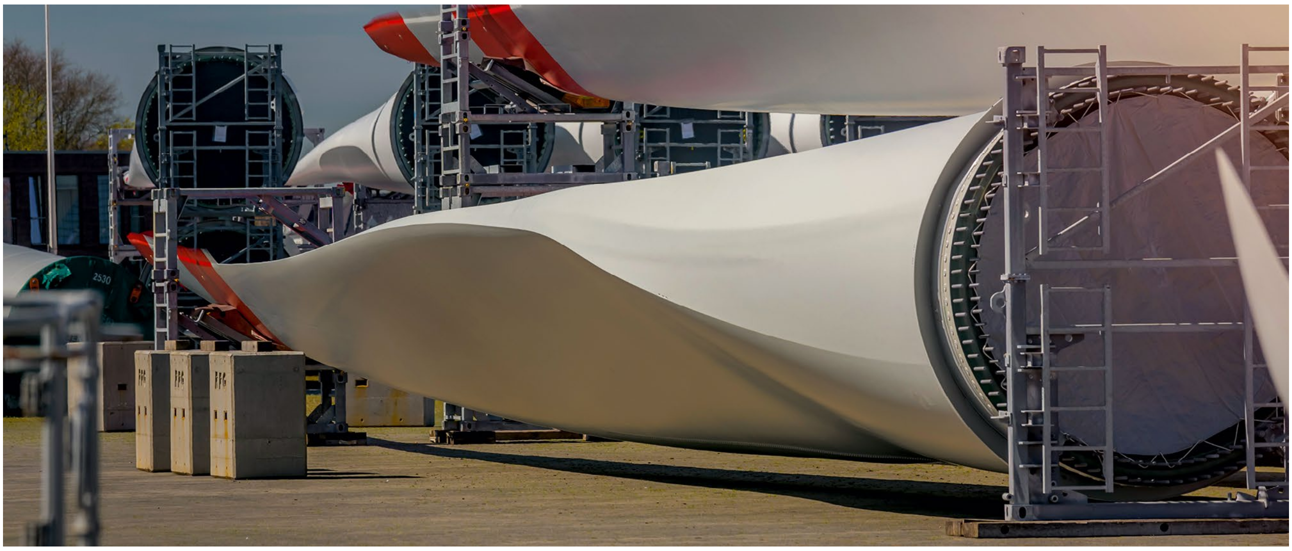
Figure 3

Basic recycling chain of (complex) products incl. an example for gold from WEEE



* manual-mechanical
** chemical-metallurgical

Source: own figure by the UBA Resource Commission based on Figure 4 in (Hagelüken and Goldmann, 2022)



For most consumer products such as electronics, vehicles or batteries, improving the overall recycling therefore requires, first and foremost, appropriate measures to **ensure the effective collection of these products at the end of their life cycle**. It must be ensured that after collection, waste materials are actually fed into high-quality recycling paths. The use of suitable pre-treatment facilities is then required, where fractions are generated from complex products that are suitable for further metallurgical processing. Decisive factors here are the **product design** (e.g. accessibility of product components such as batteries or printed circuit boards, design for circularity (Schoch et al., 2021)), the pre-sorting according to main product groups, and operational excellence of the pre-treatment plant to minimize metal losses (e.g. in wrong fractions from which they cannot be recovered. e.g., copper is a relevant impurity in the steel fraction).

For many types of materials, efficient metallurgical processes already exist, but they can only recover what actually enters these plants. For complex materials (e.g. printed circuit boards, catalysts), a combination of pyrometallurgy ("smelting") and hydrometallurgy ("chemical dissolution and separation/refining") is usually used. Here, too, preparation and blending of the feedstock for metallurgical processing, operational performance, and the management of slags, wastewater and other residues are of great importance. In addition, there are **thermodynamic limits**, because from complex multi-metal mixture, not all metals can be recovered (with high yields). Depending on the composition of the feedstock and the operating parameters of the processes used, certain elements are lost in slags, flue dust or wastewater, from which they cannot be recovered with justifiable energetical and economic effort (for more details see (UNEP, 2013)).

For this reason, even in an "optimal" CE the use of primary raw materials will still be required, as unavoidable losses (dissipation, thermodynamic limits), and new demands through market growth and new technologies (e.g. battery metals) have to be compensated. Recycling and mining thus remain complementary systems, with the share of recycled raw materials continuously growing and primary raw materials increasingly having to be produced in a more climate-friendly, environmentally safe, and socially just manner[12].

12 Of crucial importance for a CE in Europe is the maintenance or expansion of an efficient metallurgical infrastructure. In many cases, primary and secondary raw materials are processed together at modern EU smelter sites. Base metals such as copper, nickel and also lead are important as so-called "collector metals", especially for the extraction of precious and special metals from end-of-life products. The loss of metallurgical processing capacities for these base metals would reduce the extraction possibilities of the other associated metals.

8 Proposals for the further development of recycling indicators of complex products using the example of battery recycling

After the general introduction and classification of the terms used to describe recycling rates in previous chapter this section presents more detailed ideas using the recycling of battery materials as an example.

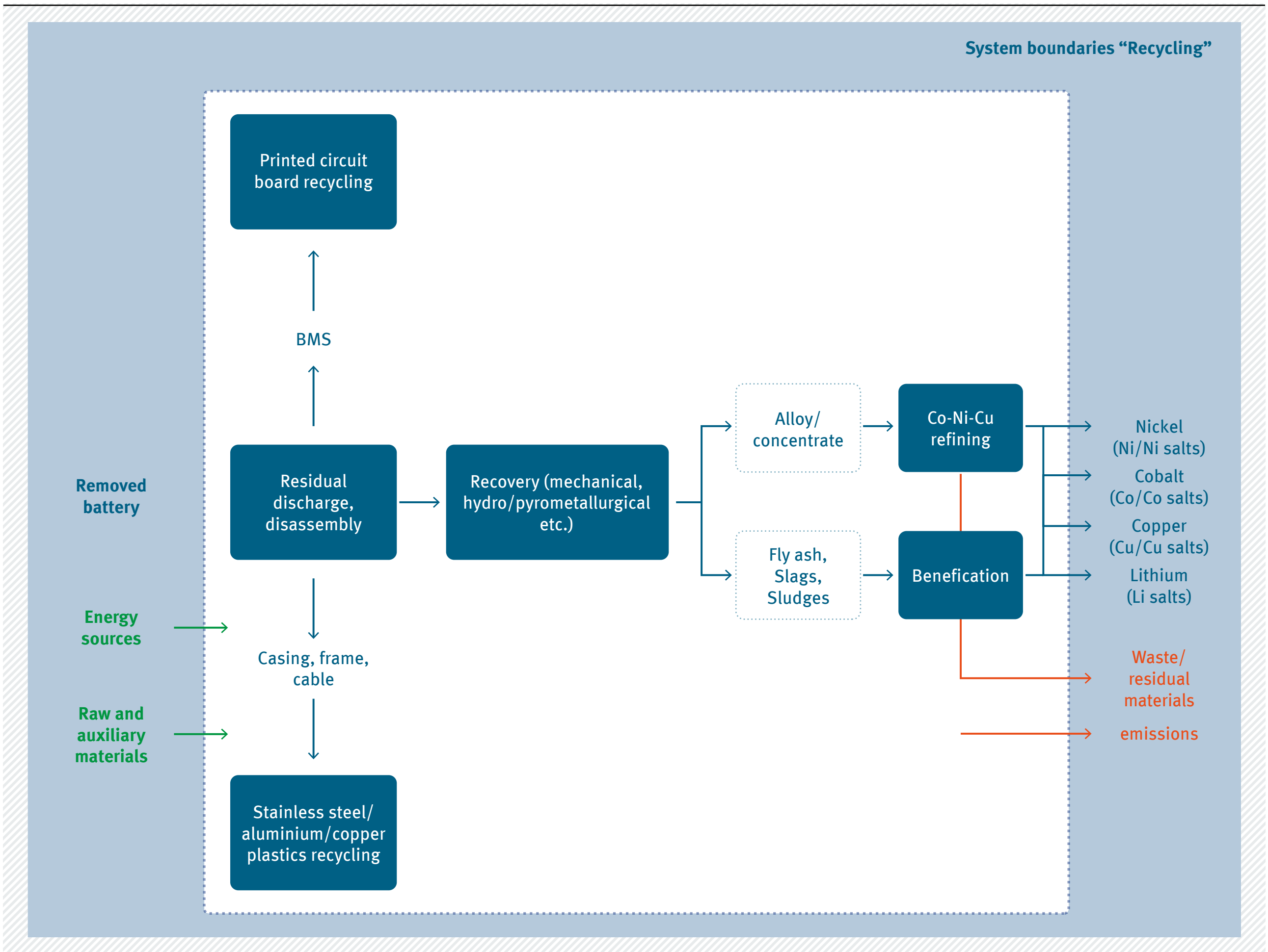
In the working group on traction batteries, the Circular Economy Initiative Germany (CEID) has worked intensively with target-compliant system boundaries and definitions for battery recycling with regard to the CE and has developed the following proposals (Figure 4).

Both the system framework shown in Figure 4 as well as the selected definitions can be applied exemplary to other complex product groups:

Recycling (system): the entire process starting from the entry of EoL products into the recycling chain until the final recovery of materials ready for sale (recyclates in a comparable quality to the material from primary raw materials)) for the manufacture of new products.

Figure 4

System boundaries for the determination of process-oriented recovery rates using the example of battery recycling



Source: CEID, 2020

Collection rate: EoL products as a share of all products of this category placed on the market in a year/ specified time period that were prepared for reuse or proper recycling. It is important to consider the system boundary. The collection of used products for repair and further- reuse (inner cycle) should be quantified separately, as this is outside the waste regime. In practice, the determination of this collection rate is demanding and can often only be an approximation. This is because in addition to monitoring the economic area under investigation, exports and imports as well as the time lag between the time when products are placed on the market and the end-of-life of the products must be taken into account appropriately. Against this background, the development of a data base and modeling approach for the individual material flows is first necessary, while also prioritizing strategic raw materials and alloys.

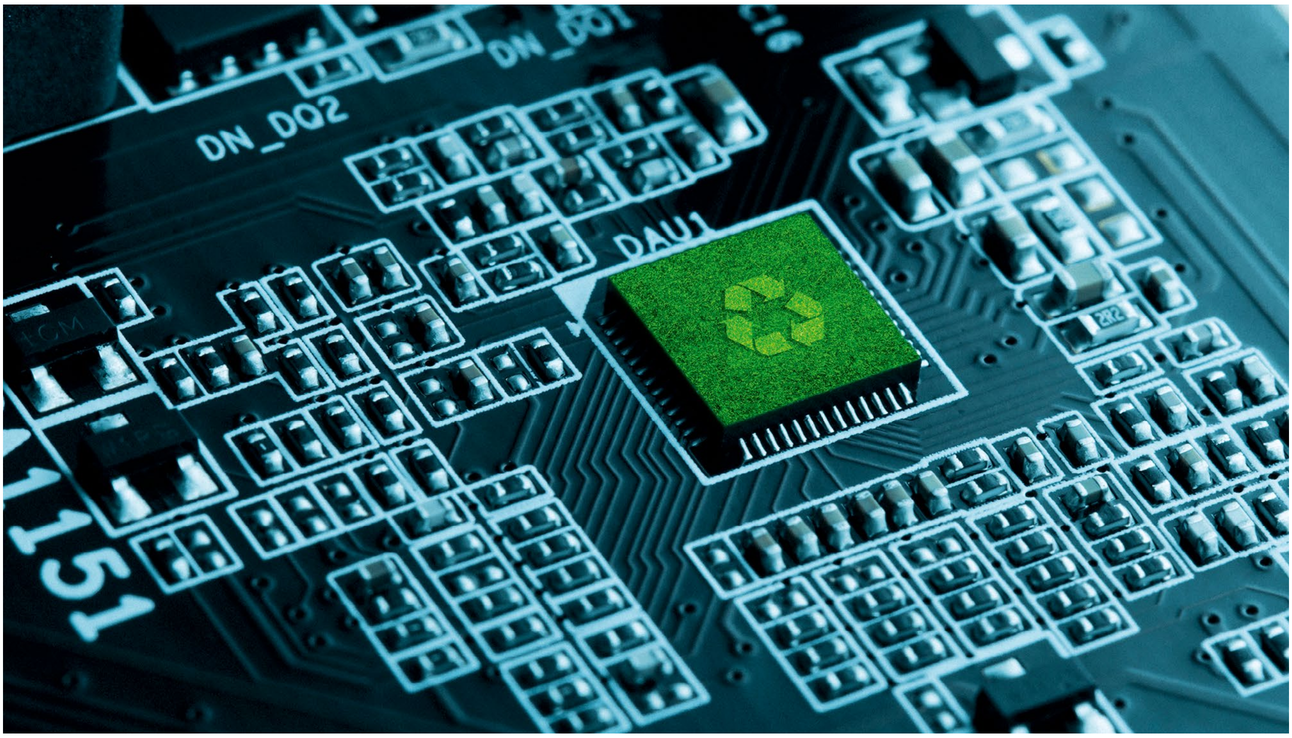
Recycled material (recyclate): raw material of comparable quality to primary raw materials which is obtained by recycling from secondary raw materials. It can be used as an input for the manufacture of new products and thereby replace primary raw materials. The high quality of the recycled material must be emphasized: Thus, recycled materials are of no substantial value if the quality is poor (downcycling). The lack of requirements for recycled material qualities allows for (and may economically foster) low-value recycling, which is not desirable from the perspective of a circular economy.

Recycling rate (RR): yield for individual substances (metals) related to the overall recycling process. It describes the quotient of the mass of physically recovered *recycled materials* to the total input into the recycling process (usually related to individual substances). Since material losses can occur in all individual steps of the recycling process chain (dismantling, mechanical pretreatment, chemical-metallurgical recycling), the recycling rate (overall success in recovering materials) results from the multiplication of the yields of all process steps used (see Figure 3). The *collection rate* of the corresponding materials in the EoL products to be treated is not part of the of the calculation of the RR.

The RR is to be determined as the average over a fiscal year for an operational unit (recycling site, business unit or recycling process) and must be determined and verified by appropriate audits or certification according to quantity, quality and energy, and/or environmental (incl. CO_2) footprint.

Circularity rate or EoL recycling rate (EoL-RR): Takes into account both the recycling rate (RR) as well as the collection rate of the corresponding materials in the EoL products to be recycled and is crucial for the success of the circular economy. As a success factor for the degree of circularity of a particular product group or material/substance, only the physical circularity rate (EoL-RR) taking into account the collection rate and RR of the overall process can be used.

A distinction must be made between the product-related recycling rates (the masses of all final output streams) and individual material-specific RR/rates for individual materials and substances in these products. Material-specific rates are important if products contain relevant quantities of “critical” materials



(according to EU definition (EC, 2020b)) as well as economically important and/or carbon-intensive (or environmentally damaging) metals and substances (see, for example, the draft EU Battery Regulation (EC, 2020a)).

Recycled Content (RC): The recycled content in new products can be an important parameter that ideally indicates the success of a CE in an economic area (e.g., if the absolute primary raw material input or greenhouse gas emissions are reduced (see Figure 1)). However, it must be ensured that no shifting between different product groups (leading to a lower RC in other products) takes place or that downcycling increases (i.e., the use of the recycled materials at lower-quality which ultimately leads to disposal in the second or later product life). In addition, the RC is significantly less than 100% in growing markets. Hence, it but could be an important summary indicator for larger economic or material systems (e.g., if the indicator can provide information about the percentage of recycled raw materials inputs into the German economy). This would correspond also to the substitution rate proposed by the UBA Resources Commission (UBA-Ressourcenkommission, 2019). The indicator would overall also be a suitable indicator for security of supply.

9 Indicators from a product perspective and from a macroeconomic perspective

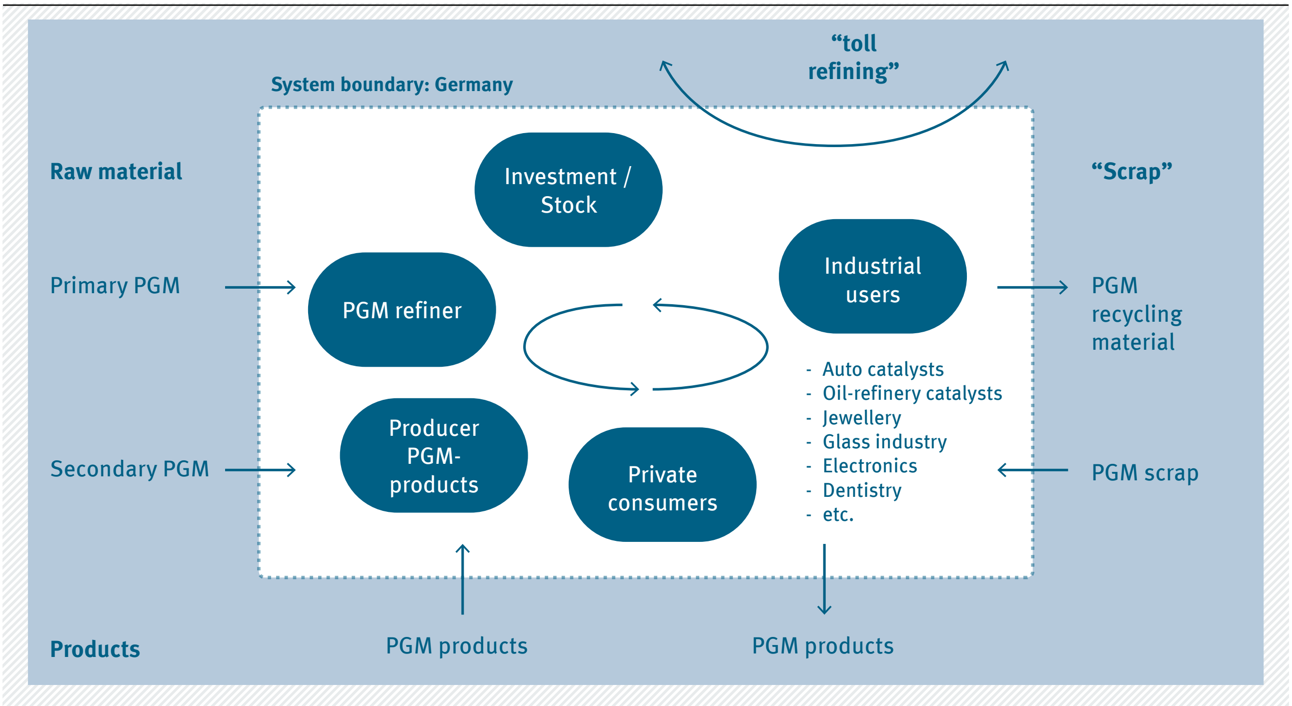
In the discussions above, the focus was on the product and process perspective in the foreground, i.e. what happened to a product and the raw materials it contains along its life cycle? The temporal (when was recycling carried out?) and spatial effect of recycling and loop closing (where did it take place?) is less relevant in this view.

However, from a macroeconomic point of view, these aspects should still be considered. The system boundary is then not product-centric (see Figure 4), but concerns an economic area (e.g., Germany or the EU) for which the material flows for individual raw materials are then considered. An example of this is shown in Figure. 5 for the platinum group metals (PGM).

Both perspectives (product perspective and macroeconomic perspective) are important and should be considered together when deriving measures. The **product and process perspectives** provides information, for example, on how recycling-friendly the products are designed, how effective and efficient the recycling processes are, and how many of the raw materials used are recovered at the end of the product's life - wherever and whenever this takes place. This can refer to a defined economic area (e.g. Germany or Europe), but it can also extend beyond this. In practice, the recycling of complex products often involves transnational material flows. This applies above all to the smelter sites, which for technical and economic reasons require operation at large capacities and using diverse input streams. For example, at the Umicore site in Hoboken near Antwerp, Umicore recycles printed circuit boards, catalysts and other metal-bearing fractions from globally sourced input materials and recovers 17 different metals from them (Hagelüken, 2006; UNEP, 2013). Since the recovered fine metals can also be traded and used worldwide, the global demand for primary metals is reduced by such recycling systems.

Figure 5

Systemic view of the material flows of the platinum group metals for the German economic area



PGM: Platinum Group Metals

Source: Hagelüken et al., 2005

In the macroeconomic perspective, the focus is on security of supply and the contributions of the circular economy toward resource efficiency and climate protection. Hence, important are, In addition to the aspects mentioned above, the magnitude of the anthropogenic (in-use) material stock[13] and the absolute contribution made by recycling to the supply of raw materials for an economy (or the possible access to the recycled raw materials)[14]. Important factors from this perspective are the exports of EoL products or relevant waste fractions and the imports of such for recycling within the economy.

13 Mass of raw materials bound within an economic area in infrastructure and products; this can be regarded as manufactured capital with the potential of recycling at the end of life.
14 In many cases, metal recycling is carried out as a “toll refining” service. The recycled metals can also be made available to suppliers of recycling materials across borders.

10 Recommendations of the Resource Commission

I. The Circular Economy (CE) Framework

1. The national circular economy strategy must be committed to an **absolute reduction in resource consumption** in line with the concept of the CE, i.e., the strategy must contribute to an absolute reduction in raw material consumption and environmental impacts, and at the same time help to secure well-being at national and international level. Beyond the circular economy in the narrower sense, this includes above all a fundamental discussion about existing product and service models of the economy as a whole.

2. For the target orientation of the CE, all measures shall be evaluated with **suitable indicators against the guiding targets**. Operational indicators for practice must be checked for their relevance against applicable guiding target indicators. For this, suitable system boundaries, definitions, and calculation methods for the indicators to be used are required.

3. Recycling in particular must suppport the **physical loop closing** of raw materials, materials, and components in order to substitute primary raw materials and obtain economic and societal benefits, ensure sustainability, and reduce import dependencies.

II. Indicators (systems) for recycling

4. In the current waste legislation, the operational indicators for recycling refer to the recycling rates of certain wastes at the level of product categories (e.g., waste electrical equipment, end-of-life vehicles, batteries). These indicators are inadequate, as they are only related to mass and only consider the waste management collection and initial processing stages. Instead, additional **operational indicators for priority materials** should be formulated which include the entire process chain up to reuse as a secondary raw material (enhanced system boundary). Indicators defined in this way can help to ensure that marketable output materials are available in a sufficient quality for reuse in the production/manufacture of equivalent new products. The draft *EU Battery Regulation* can serve as a positive example for appropriate system boundaries, indicators, definitions, and calculation methods for recycling rates.

5. The product-specific **EoL recycling rate** is a good indicator of the degree of circularity of a particular raw material in a particular application. Similarly, the indicator **Recycled Content** (content of recycled material in the raw material) is an important indicator for larger economic systems, e.g., for indicating what proportion of recycled raw materials used in a particular economy or a product group is used. However, when using this indicator it should be considered that it is not relevant for growing markets (e.g. lithium-ion batteries for electromobility) for individual raw materials because EoL products must first be created before they can be recycled. Therefore, in such strongly growing markets, the recycled content is usually significantly lower than the EoL recycling rate. The example of growing markets also shows that operational recycling indicators need to be considered in a long-term strategic view of resource consumption across different economic sectors, taking into account socially desired transformations such as the energy transition.

III. Improvement of recycling within the Circular Economy (CE)

The following recommendations were not explicitly discussed in this paper, but are implicitly derived from the objectives and approaches described above. They are therefore only mentioned here in the form of brief bullet points.

6. It is important to take appropriate measures to **comprehensively track and collect resource-intensive EoL products** (electrical and electronic products, vehicles, batteries). After passing through the R strategies to EoL, it must be ensured that, after collection, these products are in fact fed into high-quality recycling paths.

7. In this context, the introduction of **mandatory standards** for the high-quality recycling of such complex and resource-intensive product groups is necessary. Providing waste inputs to treatment facilities certified to these standards can ensure fair competition against non-compliant processes which might be loss costly but at the expense of low environmental and labor standards as well as recycling rates.

8. Measures are needed to **increase the transparency** about the real material flows at EoL, e.g., through product passports, efficient tracking and tracing systems, or also via improved linking of various statistics[15]. This would enable better control of waste flows in combination with a strengthening of the enforcement bodies, and also support restricting illegal and dubious exports of such of EoL products out of the EU to "recycling plants" which do not meet the defined standards.

IV. Creating conditions

9. **Standardization and design specifications** for circularity are important that ensure improved accessibility of raw material-relevant components (e.g., batteries), thereby enabling both repairs to extend use and improved material and metal recycling.

10. Improve the **framework conditions for circular business models** (e.g., leasing and sharing models) and adaptation of extended producer responsibility (EPR) in the EU context.

V. Enabling implementation

11. Strengthen **educational programs on CE and recycling at universities** also as part of traditional curriculums such as chemistry, materials science, engineering, or economics.

12. **Funding programs** for systemic CE approaches, more combination/integration of technical, ecological and economic approaches (incl. development of framework conditions for circular business models).

15 e.g. for vehicles considering the deregistration of inventory data of the Federal Motor Transport Authority and the information on end-of-life vehicle recycling and exports.

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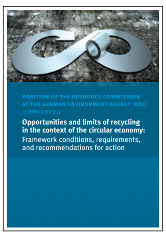

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