

Data requirements for a successful circular economy

Metal cycles and data gaps in recycling – An analysis of the current data situation

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Abstract

The circular economy plays a key role in both the European Green Deal and the European Union's new Clean Industrial Deal. The aim is to create a more sustainable economy characterised by growth, resource efficiency, climate neutrality, competitive advantages and a reduction in raw material dependencies, as well as more sustainable products. In 2024, the German government adopted a National Circular Economy Strategy (NKWS), which aims to consolidate all of the government's circular economy goals and measures across all functional areas of the value creation cycle. These goals are set out in European and national strategies and laws and are supported by measures and indicators. Notably, the EU's Critical Raw Materials Act (CRMA) establishes a series of benchmarks and reporting obligations for member states to fulfil in the coming years. These include the goal of achieving a 25% recycling capacity for strategic raw materials within the EU. In order to map the current and target states of material cycles, new information and data along the respective value chains are required, which are not yet available. Regarding the NKWS, the impact of measures on the material balance and specific material flows cannot yet be assessed adequately.

In this paper, experts from the German Environment Agency (UBA) and the German Raw Materials Agency (DERA) at the Federal Institute for Geosciences and Natural Resources (BGR), systematically evaluate the data available for metals.

The focus is particularly on the collection and accounting of secondary raw materials, the effectiveness of recycling in terms of quantities and qualities produced, and their reuse. To this end, the new requirements for circular economy are presented and explained (Chapter 1). Furthermore, a reference scheme for discussing the necessary complexity of a metallic material flow system is presented and data sources are qualitatively evaluated by category (Chapter 2). Using the two representative raw materials aluminium (base metal) and cobalt (technology metal) as examples, case studies show how the material cycle can be mapped using known data sources and quality criteria. Based on the results and the authors' expertise, conclusions are drawn about the general data situation for describing metal cycles and a conclusion is drawn about the data situation (Chapter 3). Finally, solutions are described that appear promising for improving the data situation and data availability in consultation with the relevant interest groups (Chapter 4).

The circular economy brings with it new requirements for data that must meet a variety of expectations: enabling forward-looking investments in plant capacity, reducing environmental impacts, increasing security of supply, and contributing to social services for current and future generations. This requires sufficiently differentiated and valid data on material flows and material stocks. The available database for metals does not currently meet these requirements in some cases. The challenges lie, on the one hand, in the lack of relevant data or its unavailability, and thus in the inability to measure and compare. On the other hand, the definitions required for the metrics are sometimes contradictory. However, some relevant data is available and is already being collected in the course of legal obligations such as Sustainability Reporting or the Carbon Border Adjustment Mechanism (CBAM). This data has not yet, however, been evaluated for circular economy purposes. This could be achieved by taking a smart bundling approach. In line with the once-only principle and the omnibus packages planned by the EU in its work programme until 2029, it will be possible to ensure that data is collected with minimal bureaucracy and without redundancy. This will enable the development of strategic measures in line with the NKWS to promote the circular economy, strengthen the secondary raw materials industry and measure the resulting successes, all without imposing further bureaucratic obligations on the economy.

Based on the structure of the metallic material flow systems outlined in this paper and the evaluation of the available data sources, it should be possible to expand and improve the database in a targeted manner.

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1 New requirements for the circular economy database

With the European Green Deal, the European Union is pursuing a sustainable growth strategy that aims to achieve a climate-neutral economy by 2050 while preserving biodiversity and the natural environment[1]. This is to be achieved primarily by establishing a circular economy in which the value of products, materials and resources is preserved for as long as possible. To facilitate the implementation of the Green Deal, the European Commission has presented a Clean Industrial Deal, which focuses in particular on the role of an internationally competitive industry by 2029. Decarbonisation and the circular economy are the fundamental orientations here [2]. One of the most important building blocks for the circular economy is the 2nd EU Circular Economy Action Plan of 2020[3]. As part of the Clean Industrial Deal, a European Steel and Metals Action Plan[4] has already been presented, which is specifically dedicated to increasing the supply and demand for recycled materials. A far-reaching European Circular Economy Act has been announced for 2026.

The operationalisation of the circular economy¹ is reflected in multi-layered hierarchies [5] across entire product and material life cycles. Recycling plays a special role at the end of these sequences as the desired material recovery option[6]. This is because recycling forms the indispensable link to closed material cycles in the economy with all the desired economic and ecological relief effects (cf. circular diagram in Figure 1). These include increased domestic value creation, security of supply and raw materials, and significant contributions to climate and environmental protection. In particular, if decarbonisation and defossilisation are to succeed, production must be able to rely on secondary raw materials². To this end, attention must be paid not only to the quantity of recycling but also to its quality[7].

Legal requirements and objectives

The recycling and reuse of recyclates in terms of a substitution rate [8] are very important new approaches in legal acts such as the new EU Battery Regulation[9], the Critical Raw Materials Act (CRMA)[10] and the new EU End-of-Life Vehicles Regulation, which is currently still being drafted. The new aspects here are not so much the increasingly ambitious collection and recycling targets, but rather their material- and element-specific interpretation, as in the case of battery raw materials, and their link to new target values for the use of recycled materials in the relevant products. This means that material cycles – beyond the product life cycle under consideration – are actually taken into account in order to conserve primary raw materials and natural resources as a whole through the use of secondary raw materials. At the same time, incentives are being created to take recyclability into account in design, for example by avoiding composite materials that are difficult to separate [11]. The EU's monitoring framework for the circular economy also currently focuses on waste management indicators, not only in terms of waste generation, but above all in terms of recycling, the use of secondary raw materials, self-

¹ The term "circular economy" is used here in the sense of the National Circular Economy Strategy (NKWS) and the EU Circular Economy Action Plan and therefore encompasses all phases of value creation – from product design and production to consumption, repair, waste management and secondary raw materials that are returned to the economy. The terms "circular economy" and "circular management" are synonymous. In Germany, the Circular Economy Act (KrWG) provides a legal definition: "Circular economy within the meaning of this Act is the prevention and recovery of waste," KrWG § 3 (19). This narrower term is included, but is only part of the comprehensive approach and is therefore not meant here.

² Secondary raw materials include waste, industrial by-products and also low-grade or unprocessed products derived from them. The term does not imply any subordination to primary raw materials. The term "recycled raw material", which is sometimes used synonymously, covers all secondary raw materials that undergo recycling in this paper.

sufficiency rates, import dependencies and macroeconomic relations. A prominent indicator is the circular material use rate (CMUR), which stood at 12% in the EU-27 and 13% in Germany in 2022. This represents the share of total domestic raw material demand that is fed by recycling and is set to double between 2021 and 2030[3]. In addition to the CMUR, the EU Circular Economy Monitoring also reports on the contribution of recycled materials to raw material demand (End-of-Life Recycling Input Rate/EOL-RIR) for individual raw materials every three years for the EU-27.

At national level, the role of recycling and the use of secondary raw materials are equally important. To date, they have formed one of the three pillars of Germany's raw materials strategy for securing the supply of raw materials[12] and are reflected in numerous measures and the indicator system of the ProgRes III (the German Resource Efficiency Programme[13]). Above all, they are directly linked to the target system of the National Circular Economy Strategy (NKWS)[14] adopted in December 2024. This strategy envisages improving recyclability, recycling itself to high material qualities and promoting the use of recycled materials in domestic production and products in all fields of action as design approaches. In terms of targets, it reaffirms European requirements for closing material cycles, such as doubling the circular material use rate (CMUR) by 2030 and increasing the self-sufficiency rates of individual critical and strategic metals. It also explicitly sets the goal of closing relevant data gaps on the import and export of products containing critical raw materials, including those contained in semi-finished and finished goods, by 2030. Furthermore, the NKWS aims to significantly reduce the raw material footprint (Raw Material Consumption / RMC) and thus reduce per capita primary raw material consumption by 2045. The use of secondary raw materials, among other strategies, contributes significantly to this goal[15, 16].

Data gaps

The aforementioned policy programmes, legislation and numerous additional circular economy strategies of individual regions and industries are providing groundbreaking, innovative impetus for the circular economy. However, there is currently a large gap between the formulation of programmes with objectives and measures on the one hand and their possible recording, accounting and monitoring on the other. Data availability is currently unable to keep pace.

"You can't manage what you can't measure" is a maxim of business management³ that also applies to circular economy policy and recycling in particular. This is problematic in three respects:

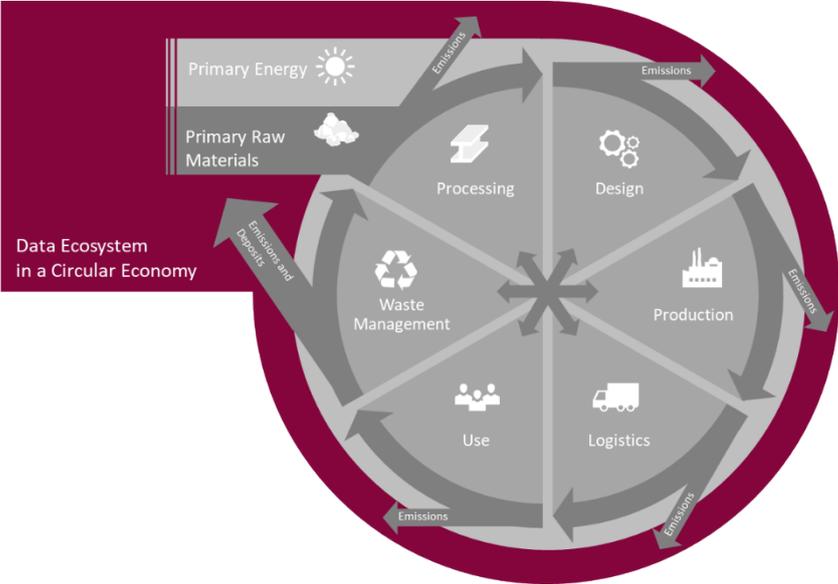
1. The actual, current situation cannot be adequately recorded – "In many cases, we don't know where we stand!" – Yet targets are already being set.
2. The available data is insufficient for reliably deriving targets or scenarios and for monitoring the achievement of targets.
3. With the data available to date, it is hardly possible to develop targeted strategic treatment and processing capacities for recycling or to derive realistic targets for the use of recycled materials.

The reliable provision of data on current and forecast material flows could be an essential success factor for the economy, enabling more targeted investment in plant capacities in the secondary raw materials industry, increasing security of supply, planning reliability and competitiveness in the manufacturing sector through secondary raw materials, and reducing

³ This is attributed to the economist and management thinker Peter F. Drucker.

costs. After all, closing product and material cycles and connecting economic sectors and actors cooperatively – both temporally and spatially – requires not only material and energy flows, but above all data flows whose information content is reflected in relevant, reliable, regularly reported indicators. These data flows extend along material and energy flows and their products on the one hand, and between functional areas such as production, use and disposal on the other, across products and materials. Material systems experience many inflows and outflows in practice and are intertwined, especially in terms of recovery and recycling. Consequently, successful circular economy also requires a new, integrated data ecosystem as a level of observation and evaluation (Figure 1). In order to increase recycling quantitatively and, in particular, qualitatively, the circular economy requires its own database that is much more structured than before, as well as concepts for recording and presenting indicators that do not yet exist in a satisfactory form to actually meet the target system and exploit the potential of a circular economy in line with the European Green Deal, the Circular Economy Action Plan, the Clean Industrial Deal and the National Circular Economy Strategy. The current data situation is insufficient.

Figure 1 **Diagram of a product- and technology-centric circular economy**



Source: Own illustration based on [17]

2 Status quo: Data sources for recycled material flows

2.1 Reference diagram for describing material cycles

This paper describes and examines material cycles for metals in detail using a reference diagram (Figure 2). This diagram illustrates the processes and material flows (a) to (t) along a cycle diagram with typical functional areas and processes.

Basic information on material quantities and concentrations

In principle, the concentrations and qualities of a substance change as a result of the processes of smelting/refining and semi-finished product production, right through to product manufacturing by means of processing. At the beginning of the value chain in ore, metals are found in rocks, bound to valuable minerals, in a mixture with rock-forming minerals, and are concentrated through processing and refining. As a result, they are then present in pure form or bound in an alloy. The production of semi-finished products and, above all, finished products usually dilutes the metal content again. In the waste stream, the diversity of materials typically reaches its maximum due to the heterogeneity of the end-of-life products at the time of collection, which usually involves a great deal of effort in the subsequent processing and recycling in order to separate and enrich the valuable elements (e.g. gold and tin in waste electrical equipment, which are mainly found in printed circuit boards[18]). Imports and exports (t) influence the quantities available throughout the entire material cycle. Foreign trade generally involves all processing, product and scrap qualities and must therefore be considered in the respective aggregate. The balance along the material cycle can have different signs not only overall but also between the various process steps, i.e. it can be accompanied by both export and import surpluses[19, 20].

Explanation of the material flow system

To manufacture a finished product, metals are first refined (b) and processed into semi-finished products (c). Both primary raw materials (a) and secondary raw materials (j, m) can be used for this purpose. In addition, material flows are also managed as internal recycled materials in refining and semi-finished product production, but these will not be discussed in detail here. It should be noted that there is currently virtually no mining of metal ores in Germany (a*) and that ores, and especially their concentrates, have to be imported in their entirety.

The products are then put into use (u). This primarily involves the binding of metals in the anthropogenic stock, which consists of durable goods, with corresponding inflows and outflows (s)[21]. Unlike short-lived goods such as packaging, many metals are only recycled after a considerable time lag following their put onto the market.⁴ When certain products with their material composition become waste and are thus potentially available for recycling depends on how long they remain in the anthropogenic stock. This retention time includes both active periods of use – possibly extended by reuse – and the duration of inactive storage in the stock, for example for decommissioned infrastructure or, hibernating products[22] .

⁴ For a resource-efficient circular economy, long service lives with the use of repair, refurbishment and reuse are ecologically desirable and should be exploited before recycling.

Legend

- (a) Input of ore/primary metal through import
- (a*) Input of ore/primary metal from domestic sources
- (b) Refined metal
- (c) Intermediate products/semi-finished products
- (d) Collected quantities EOL
- (e) EOL material flow for treatment/processing
- (f) Material flow in inadequate recycling
- (f*) Losses due to process inefficiencies
- (g) EOL material flow in recycling
- (h) Production waste (in collection/preparation/treatment/reprocessing or direct recycling)
- (h*) Secondary raw material flow out of production through treatment/reprocessing.
- (j) Recycling in semi-finished goods production (remelting scrap)
- (m) Recycling in smelting/refining/melting
- (n) Residues, ashes and slags from smelting/refining/melting and semi-finished goods production
- (o) Dissipative losses and inadequate disposal
- (p) Mining waste and residues
- (u) Goods for domestic use
- (s) Inflows and outflows from anthropogenic stock departments
- (t) Foreign trade (imports and exports of the respective materials according to process step)
-  Secondary raw materials industry

Source: Own illustration

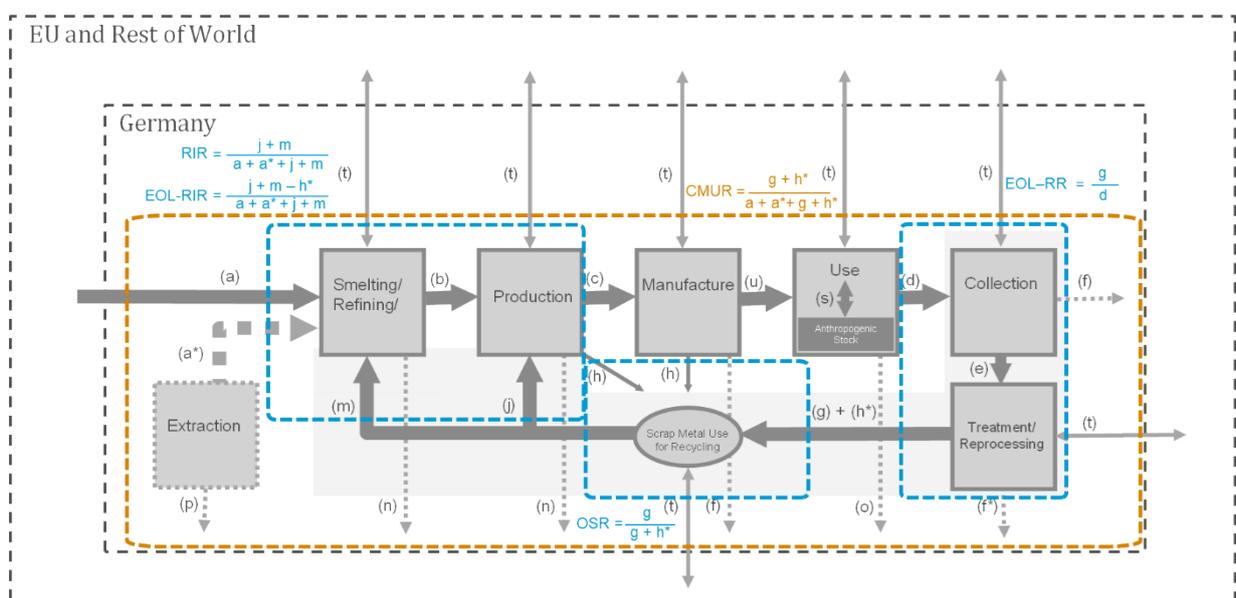
Illustration of material flow indicators for recycling

Relevant material flow indicators (see chapter 1) can also be found in the reference scheme (3). Of particular importance for the description and accounting of recycling are the recycling indicators "Recycled Content (RC)" at product level, often also referred to as "Recycling Input Rate (RIR)" at process level, and the "End-of-Life Recycling Rate (EOL-RR)". Both indicators are used in a large number of publications to quantify recycling [8, 25].

While the RIR and RC describe the proportion of secondary raw materials in production and products and thus represent the use of available quantities (in some cases even more specifically by the EOL-RIR, which shows the proportion of scrap metal from end-of-life waste), the EOL-RR is used to assess the effectiveness of recycling waste from the use phase. It relates the actual quantity of scrap metal recycled (g) to the quantity of scrap available for collection from the waste stream (d) without losses. Since scrap from production (h) is also recycled, it is important to know the proportion of old scrap – only then can the EOL-RR be calculated correctly. The total scrap volume is the basis for the "old scrap ratio (OSR)", the proportion of EOL metals after the use phase (g) in the total amount of existing old and new scrap (g/g+h*) that is recycled (j, m). The circular material use rate (CMUR), which is currently only determined for all material flows in Germany and can only be roughly estimated for metal materials as a whole (Eurostat [26, 27]), can also be assigned. This compares the amount of secondary materials for recycling (g+h*) with the total material input, i.e. the sum of primary material input (a + a*) intended for

domestic use (u) and the amount of secondary material for recycling (g+h*). In order to be internationally compatible, the indicators must be supplemented by exports and reduced by imports (t), which for reasons of clarity are not included in the formulas here.

Figure 3 Reference scheme with relevant recycling indicators



Source: Own illustration

2.2 Data sources for collecting material flows in the recycling system

When collecting data along the metal cycle, the changing responsibilities and ownership structures in the various sectors of the economy, as well as the changing reference goods (ore, alloy, semi-finished products, products, waste) with their very different metal contents, pose an enormous challenge.

While the circular economy, in the sense of a truly circular economy, focuses on product life cycles and material cycles with their qualities, recycling was originally established and recorded in the context of waste management. In the context of waste management, recycling refers to a recovery process by which waste is processed into products, materials or substances for material use (Article 3, No. 17 Waste Framework Directive). The aim here is to produce recyclates that can be reintroduced into production processes to substitute primary materials.

To describe the recycling situation, data is required on the waste generated in the form of products or materials, their compositions, and the capacities for their treatment and recovery, as well as the resulting material flows. This data is collected and potentially made available at various stages of the economic cycle by different stakeholders in different ways. From the authors' point of view, the relevant data sources can be categorised into five categories: **(a) official statistics, (b) data from commercial providers, (c) industry statistics, (d) other studies, data processing and modelling, and (e) individual expertise.** These data are of varying value in terms of the knowledge objectives. This clustering should not be understood as a hierarchical ranking.

2.2.1 Official statistics

Statistical data provided by government authorities is referred to as official statistics. The central but not exclusive authority in this regard is the Federal Statistical Office together with

the statistical offices of the federal states. Official statistics are available free of charge as public property to all users from government, business and the public[28].

Waste statistics are available for the treatment and recovery of waste. These statistics are collected annually by the Federal Statistical Office in accordance with the Environmental Statistics Act (UStatG), also in order to fulfil reporting obligations under European and international law. On the one hand, they are based on the **European Waste Catalogue**, according to which waste is classified uniformly and subdivided into approximately 900 types. On the other hand, they are based on the collected waste streams that end up in treatment and recovery facilities, including recycling plants. While the waste balance sheet evaluated from this data, which is available approximately 18 months after the reporting period, provides important structural insight into waste management, it is severely limited in terms of recording material cycles through recycling. This applies in particular to metals, which occur in almost all waste categories and subgroups but are not considered separately. The waste fractions that occur are classified primarily according to their place of origin in the economic sectors and not according to the materials they contain. Waste codes for hazardous waste are reported separately.

Waste codes therefore do not provide sufficient information about:

- the type and composition of the fractions and materials and the actual loads of certain valuable and harmful substances. This information is not recorded and must be derived from additional databases and evaluations[29, 30]. However, these supplementary sources are insufficient in terms of data quality and are only available to a very limited extent or without a binding basis for collection.
- the recovery and recycling qualities produced, the recovery costs and material losses, and the whereabouts of the materials beyond waste treatment. These are not recorded, although greater differentiation of the output from treatment plants has been planned in principle since 2020.
- by-products and secondary materials that are not or no longer considered waste and are therefore not subject to any waste legislation information or notification requirements. These are not recorded.
- Recycling cycles that take place within production and between processors of primary materials. These are largely not taken into account.

For those products for which **extended producer responsibility** is established, there are in some cases additional specific statistics (e.g. for packaging, electrical appliances, batteries) that generally record data on the quantity put on the market [31] the quantity of waste collected, the place of treatment (domestic, other EU countries, outside the EU) and the final type of treatment (preparation for reuse, recycling, other recovery, disposal). This is done not only for the total product stream, but also broken down into different categories, e.g. into six different product categories for electrical and electronic equipment or the different chemical systems of device batteries[32].

For some products or their waste – such as batteries – there are additional specific data collections and approaches for a more detailed breakdown of the waste type catalogue in order to be able to demonstrate compliance with the legally established collection and recycling quotas.

While material-specific statements can be made for some subgroups of packaging and packaging waste due to their monomateriality, the statistics do not contain such information for complex products such as electrical and electronic equipment. This means that no conclusions can be

drawn about the quantities of certain substances and materials in the quantities placed on the market or generated as waste. Nor is there any information on the proportions of different substances/materials in the quantities recycled. Last but not least, there is no original link to the statistics according to waste code numbers in the European Waste Catalogue for packaging and waste electrical and electronic equipment.

Similar problems arise from other statistical surveys, such as **production and foreign trade statistics**. These are enshrined in law and backed up by European implementing regulations. They are collected monthly by the Federal Statistical Office or provided for the Federal Republic of Germany on the basis of data from the state statistical offices and customs authorities. Foreign trade statistics reflect imports and exports of goods and thus the inflows and outflows of materials from the physical balance sheet area – both low-value and unprocessed materials such as primary and secondary raw materials, as well as materials in the form of semi-finished and finished goods. Both statistics use a harmonised classification based on convertible lists of goods and commodities and record tonnages, quantities and values[33]. The sub-directory for production statistics is used to record data on production in manufacturing companies within the manufacturing sector. The goods list for foreign trade statistics (HS codes, CN codes and TARIC) is used for customs-related recording of foreign trade. While both classification areas make it possible to infer the recyclable material loads of the main materials for extraction-related goods such as ores and ore concentrates, as well as large, predominantly homogeneous material flows on the waste side such as steel scrap, this is only possible with a high degree of uncertainty, if at all, for other alloying, minor and trace elements, as well as for metals and materials that are components of more complex products such as vehicles. This is further complicated by quantity thresholds for reporting requirements for small-scale goods flows. Neither production nor foreign trade statistics reveal, for example, the recycled content (RC) in goods, let alone any further information on the use of recycled materials from EOL product recycling.

2.2.2 Data from commercial providers

Commercial providers offer data that is sometimes very up-to-date, but often only estimated based on industry and company knowledge. The quality and representativeness of the data varies significantly depending on the provider. In addition, some of the studies are not transparent in terms of the specific collection and estimation methods used. There are no commercial studies for numerous minor and trace elements. For some metals, various institutions offer individual studies that are subject to a fee, but these are updated irregularly and their continuation is not reliable. In addition, some of these studies are subject to licence conditions that do not allow the data they contain to be made available to the public or passed on.

2.2.3 Industry statistics

Trade associations usually publish annual statistical reports on industry developments. Even data derived by trade associations from anonymised data provided by member companies or from market observations is not always fully representative, as it depends on the market coverage of the associations and the response rates of member surveys. Above all, with regard to material use and secondary raw material information, these are highly aggregated and, in some cases, not very meaningful. More detailed information may be provided to member companies. Industry statistics can be very up to date. However, the continued and future availability of this data cannot be guaranteed, as more and more associations are refraining from further publication for competition law reasons despite anonymisation, are no longer publishing time series and key figures, and are therefore not enabling monitoring.

2.2.4 Further studies, data processing and modelling

Scientific studies describing material flow systems, individual process steps or mass flows are another important source of data. These are mostly commissioned studies from departmental research, funded third-party projects from research institutions or internal research reports. In many cases, these projects are published in scientific journals. This type of source is often characterised by high data resolution and a high level of detail. Efforts to harmonise product, component and material descriptions have been pushed forward in recent years[34], but are not yet applied across the board, which limits the use of this data. Individual studies are important sources for filling data gaps[35], but are not particularly suitable for long-term, reliable data provision due to their selective, discontinuous nature and dependence on funding.

Data compilations, such as the Recycling Atlas of the German Raw Materials Agency[25], provide a good, concentrated overview of company-relevant key figures and element-related recycling data (e.g. recycling indicators), but also suffer from a lack of (publicly) available data, such as production data for recycled metals. The more restrictive attitude of companies and their associations – partly due to the applicable competition law reservations – also makes improved and more transparent reporting difficult.

With a view to providing detailed information on material flows, the Federal Environment Agency has created a secondary raw materials portal[20] based on individual research projects, which evaluates a wide range of data sources. It is based on the summarisation, processing and modelling of available data, including recycling volumes, recyclable material content, sector-related and internal production and trade volumes, material dissipation, and imports and exports in foreign trade. However, the usefulness of this portal is currently limited due to a lack of binding updates and thus declining relevance.

Other important data compilations and modelling are the EU Material System Analysis (MSA) studies[36]. These are an important information tool for promoting the circular economy and resource efficiency in Europe. The studies analyse the flows of different materials such as metals in the EU and are used to calculate indicators such as the EOL-RIR at EU level as part of CE monitoring[37] and the assessment of criticality[38]. The studies are based on uniform processes and system boundaries, are produced regularly for the European Commission and published in the Raw Materials Information System (RMIS) of the EU Joint Research Centre (JRC) – albeit only in aggregated form for the EU 27. They are based on freely available data and also suffer from a lack of available data, which is why a large part of the modelling is also based on estimates.

2.2.5 Individual expertise

Another frequent source is surveys of individuals with individual expertise on missing or disputed data. Due to their professional experience and fields of activity in relevant topics, these experts have extensive implicit or explicit knowledge that is not available in this form in publications. This individual expertise can be used to fill specific data gaps. This is usually done on an ad hoc basis, but does not ensure long-term data provision. Often, the experts consulted also disagree in their assessment of the facts. The data collected on this basis can therefore be subjective.

2.3 Summary assessment of data sources

Overall, the five source types have different strengths and weaknesses when it comes to the current collection and availability of recycling-related data. The quality criteria of relevance, accuracy, timeliness and punctuality, availability and transparency, comparability and coherence, which were developed in the European Statistical System (ESS), are applied here[39].

Relevance refers to how well the data fits the needs of users, **accuracy** refers to measurement or processing errors in the collection, **timeliness and punctuality** refer to the timely provision of data as a basis for decision-making processes, **availability and transparency** for accessibility and the degree of documentation, **comparability** for reliability for temporal, spatial and technical comparisons, and **coherence** for consistency for different statistics relating to the same population or subject matter.

The criteria are rated from a high degree of fulfilment (+) to a low degree of fulfilment (-) based on the explanations in chapter 2.2 and the authors' assessment.

Table 1 Evaluation of currently available data sources on recycling-related issues according to six statistical quality criteria

	Relevance	Accuracy	Timeliness and punctuality	Availability and transparency	Comparability	Coherence
Official statistics	-	0	0	+	+	+
Data from commercial providers	0	0	0	-	0	-
Industry statistics	-	0	0	-	0	-
Further studies, data processing and modelling	0	+	-	+	-	-
Individual expertise	+	+	-	-	-	-

Key	
+	High degree of fulfilment of the criterion
0	Medium degree of fulfilment of the criterion
-	low degree of fulfilment of the criterion

Accordingly, further studies, data processing and modelling, in addition to the integration of individual expertise, prove to be very relevant sources of recycling-related data on issues of the circular economy and its political implementation. However, they are equally deficient in terms of consistency, comparability and timeliness. Official statistics can be rated as very good in the latter categories. However, their relevance to recycling-related issues is generally considered to be weak. One of the main reasons for this is that official statistics are not usually material- or substance-specific in their systematics, but rather oriented towards products and product categories in the case of production and trade, and towards hazardousness and place of origin in the case of waste. The composition of products and waste – in terms of alloying elements, recyclable materials, impurities and pollutants – is not recorded. Even though official statistics systematically reflect quantitative phenomena in the aforementioned segments, convey a comprehensive overall picture and are also of significant value in terms of providing information, they have so far been of little relevance to the urgent issues surrounding material

cycles. Industry statistics and data from commercial providers present a mixed picture, with connectivity and availability also having to be rated as low. In terms of the timeliness and punctuality of publications, all types of data sources are subject to considerable delays in some cases.

3 Data basis using the example of relevant industrial metals

To illustrate the data situation regarding the life cycle and cycles of metals, the initial data for assessing the cycles of aluminium and cobalt are used as examples, and the existing database is examined and evaluated in case studies. This is done for Germany as an economy.

Aluminium is an example of a base metal that is extracted, processed and recycled in large quantities. Thanks to its thermal, mechanical and electrical properties, it has a wide range of applications as an industrial metal. Cobalt, on the other hand, is an example of a special metal that is mined in comparatively small quantities, mainly as a by-product, but thanks to its chemical properties is used in very specific fields of application, where it is experiencing significant growth in demand.

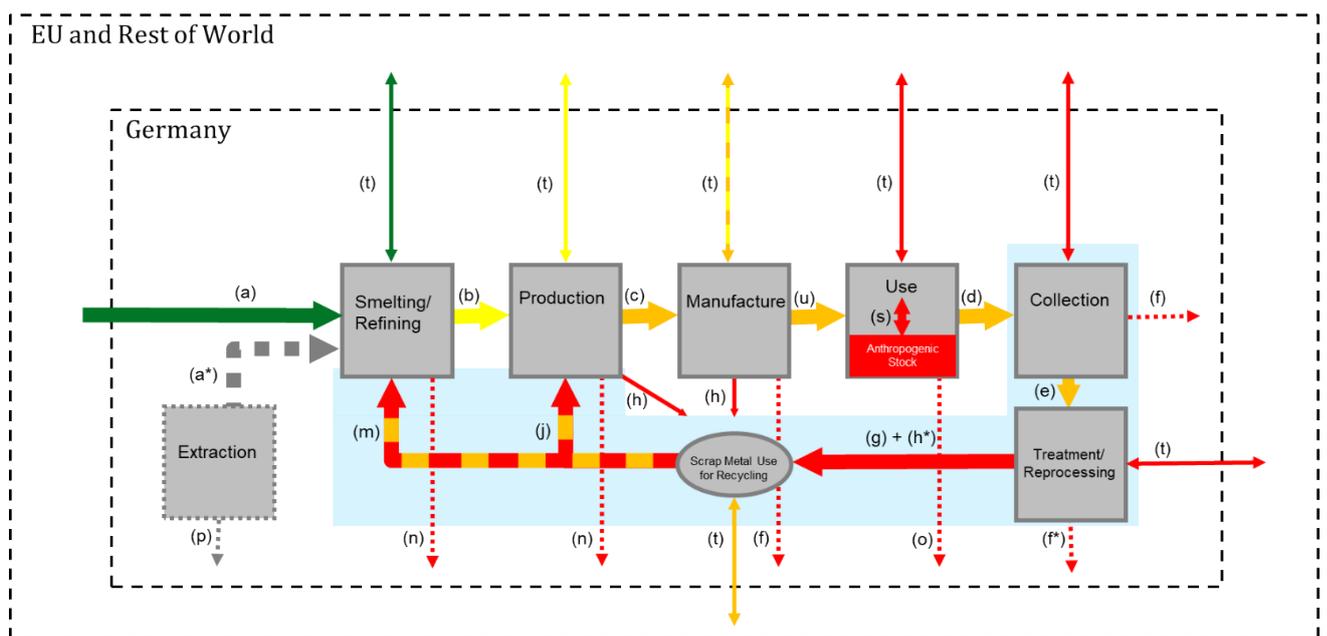
For both metals, the data situation along the value chain was examined in detail using the reference scheme at 2.1 : from extraction, smelting, refining and semi-finished product production, through product manufacturing, product use and the collection, treatment/processing of end-of-life products and scrap, and the scrap trade, to the recycling of scrap. The aim of the data analysis was not to quantify material flows, but to evaluate the data situation, i.e. the availability of data, including its quality and origin. For this purpose, the assessment of the respective data situation for individual elements in the reference scheme was colour-coded.

Detailed case studies on aluminium and cobalt can be found in the **Appendix** .

3.1 Conclusions on the general data situation

By examining the data situation of the two selected case studies, conclusions can be drawn about other metals based on analogies, the examination of relevant data sources and the authors' empirical knowledge. The result of this evaluation is visualised in the reference scheme (see Figure 4) using colour coding.

Figure 4 Overall assessment of data availability for metal material flows



Legend

Green: Data on quantities and qualities largely available

Yellow: Data on quantities in official statistics incomplete, no information on qualities

Orange: Data on quantities incomplete or irregular via other data sources, no information on quality

Red: No or only sporadic data available on quantities and qualities (from individual expertise, individual studies, models, etc.)

Source: Own illustration

The following aspects apply to the description of material cycles for many bulk and special metals with regard to the data situation. The letters refer directly to the labels in the reference scheme ().

Table 2 Findings on the general data situation for metal cycles

Material flow	Description
a, a*, b, t	<p>With regard to the extraction of raw materials or refinery production in Germany, the data is generally available to the public via production statistics. However, as these often relate to individual producers, this data is often subject to confidentiality and is therefore not available, or only available to a limited extent, unless it is published by the companies themselves.</p> <p>Furthermore, there are commercial providers who can supply some of this data. This involves comparatively high costs.</p> <p>If extraction or refining production does not take place in Germany, but raw and basic materials are only imported or exported, trade data must be evaluated. Although the classification system used in foreign trade involves a very detailed breakdown of goods, it is primarily designed for customs purposes. It is therefore only sufficient for raw materials or minimally processed goods in order to measure the quantities and qualities of metals contained therein. In the case of trace and minor elements, there are usually aggregated commodity codes, which means that individual raw materials cannot be considered separately.</p>
c, t	<p>The accounting of raw material quantities is essentially based on individual production data for products, which is recorded in production statistics. There is no overall recording for individual metals. The respective material contents must be estimated from the production quantities of the products. Quantities of specifications for a raw material (various alloys, etc.) are also not usually reported and must also be estimated. Price information can be used to infer the actual recyclable material contents and concentrations. This applies to production data as well as foreign trade data. In this section of production, commodity codes already include more highly processed products, which makes it much more difficult to break down the quantities to the element level. The estimation is even more difficult for minor and trace elements, or for metals that are used in a wide variety of products. As a result, although these primary statistics provide fragmentary insights, they do not provide a comprehensive overview of the quantities of specific metals or their alloys used in which products.</p>
u, t	<p>Production and trade statistics broken down into commodity codes include data on the total quantities of products and product groups. For some products (vehicles, batteries, electrical appliances, packaging), specific data exists for the quantities placed on the market in Germany, which vary in terms of how detailed they are. Conclusions about the material composition can only be drawn with the help of specific manufacturer information or studies on the composition of products. With the help of these results, projections can be made with considerable effort to estimate the total quantity, but</p>

Material flow	Description
	these are subject to significant uncertainty due to the complexity of the products and changes in composition as a result of further developments.
s	<p>In order to measure the material bound in the anthropogenic stock, it is necessary to evaluate the quantities of durable goods placed on the market in contrast to short-lived circulating goods and consumer goods. Production and foreign trade statistics in conjunction with other inventory statistics such as census data and surveys on fixed capital can be used for this purpose. In addition, waste management flows must be evaluated in order to calculate net stock changes. The latter can only be reported as a material-unspecific balance as a residual from the existing statistical system from the material account. In order to examine the flows of the anthropogenic stock and its composition in a material-differentiated manner, a large amount of additional data on the typical composition of goods is required. If, on the other hand, forecasts of emerging secondary raw material quantities are also to be possible, dynamic calculations with goods retention times are necessary. All these evaluation and accounting approaches have so far only been developed in special studies in the field of urban mining.</p>
d, t	<p>For collected waste, information is recorded on the mass of end-of-life products, but not on the raw and basic materials they contain. The total masses of end-of-life products are largely subject to reporting requirements, but are highly aggregated. Metal contents must be estimated based on the quantities of specific end-of-life products contained. This also applies to the quantities in the import and export data of foreign trade statistics. There are commodity codes for waste and scrap of certain metals, but the actual proportions of recyclable materials can vary greatly. Price information in conjunction with information on processing costs can make an estimate possible.</p> <p>Since the commodity codes are not designed for the availability of secondary raw materials, they are generally unsuitable for distinguishing between qualities, alloys, etc. Many minor and trace elements that are considered critical raw materials are not reported separately with their own commodity codes or those for products that contain them.</p> <p>In order to project when which goods and products will become waste and thus determine their recycling potential, it is necessary to refer to usage and retention periods. Corresponding data on usage and retention periods are only available from individual studies and for a few goods/products. It should also be noted that usage and retention periods change due to usage habits and are generally not identical to accounting depreciation periods.</p>
e, t	<p>Treated and processed quantities of waste and scrap are recorded, at least in part. For certain product groups (e.g. packaging, batteries, electrical appliances), there are additional requirements and data on recycling rates. In principle, the input into treatment should correspond to the output from collection, which is why frequently collected data on input into treatment is assumed to be the quantity recorded. Otherwise, see d</p>
g, h*	<p>The quantities of scrap metal from large metal streams (steel, light and non-ferrous metals) and precious metals are well documented in some cases thanks to data from associations and commercial suppliers. However, this is not the case for minor and trace elements, especially since a large proportion of these are recycled together with a main element, thereby becoming diluted and not recorded separately. In foreign trade, there are commodity codes for waste and scrap of certain raw materials, but the proportions of raw materials in waste and scrap can vary significantly. Similarly, the resolution of the commodity codes is not sufficient to distinguish between individual qualities, alloys, etc. For instance, in the case of trace and minor elements, there are usually aggregated commodity codes. It is generally not possible to determine which products the quantities of scrap metal originate from. Based on the available data, it is</p>

Material flow	Description
	currently not possible to differentiate between scrap metal (g) and treated new scrap metal (h*) (e.g. punching waste, de-oiled chips and material residues, unsorted production residues).
h	The quantities of new scrap produced are only recorded when they are traded. There is no centralised recording system. Recycling often takes place directly at the factory. Only estimates are possible.
j, m	For the large mass flows, there is some information available on the use of scrap in refinery production and processing. However, these are often only estimates. There is no information on the quality of the scrap. Apart from a few individual studies with estimates that are sometimes decades old, there is no information available on minor and trace elements.
f, f*	Losses in the respective areas can only be estimated on the basis of individual studies [40]. There is no ongoing monitoring. For losses that occur during collection, sorting that is not 100 % accurate and allocation to the respective recycling route, there is no data available beyond estimates of values for individual materials from individual studies. Losses due to inadequate or inefficient disposal also lead to metal loads in landfilled waste streams, which may be of interest in the context of landfill mining. Only estimates and projections based on individual projects are available for this.
n	Material losses from smelting (burn-off, slag, dust) and the production of semi-finished and finished products are not recorded centrally. Only estimates based on individual studies and company surveys are possible.
o	There is no data on dissipative losses during the use phase or losses resulting from incorrect disposal that goes beyond selective estimates for individual materials based on individual studies.
p	Data on ore mining waste is not relevant for Germany, as ore mining for the purpose of metal refining is no longer taking place in Germany. However, there are historical spoil heaps that could also provide secondary metallic materials for processing in the future in the course of landfill mining. A database for this is available in part on the basis of individual projects/studies.

3.2 Conclusion on the data situation

The data analysis shows that there are numerous data gaps in the metal value chains. While there is still a comparatively good database in the area of raw material extraction and refinery production, this decreases with the increasing complexity of the products and their areas of application along the value chain. This has a particular impact on data relating to the collection and accounting of secondary materials, the recording of recycling effectiveness in terms of quantities and qualities produced, and the whereabouts of these materials. These cannot be satisfactorily derived from product and manufacturer information, collection rates and recycling rates from the existing statistical recording system and the available, officially collected database in terms of their structure and resolution. The domestic supply rate of individual metals from end-of-life products (recycled material quantities) or the substitution rates achieved from primary to secondary materials (recycled material proportions) in production can only be estimated with individual expertise, individual surveys and modelling in studies, and in some cases only on the basis of generic European or global data sources, many of which are older [24].

Last but not least, the quantification of historically accumulated anthropogenic deposits at the level of individual metals has so far been available at best in exemplary individual studies for the world or large economic areas. However, it is precisely this structural information that is an

essential determining factor for effective management in material cycles (urban mining). All these significant data gaps and quality deficiencies are problematic because they do not provide sufficient quality and reliability to answer fundamental questions about recycling and recyclates in a circular economy, even at the national level. The problem is even more acute on an international scale. These assessments are consistent with other evaluations of data availability, particularly for critical raw materials for the energy transition. [41]

4 How can the data base be improved and what are the implications?

Improving the data base appears necessary in order to be able to measure and evaluate the success of measures aimed at achieving the announced political objectives. This is an essential basis for steering the future direction of the circular economy. Beyond the political design of a circular economy with the help of this data, an improved data situation is a key element for effective cooperation between the players in the circular economy, e.g. waste disposal companies and product manufacturers. This helps the secondary raw materials industry in particular to adapt in good time to changing material flows and material flow compositions in recycling. Data collection should serve as a helpful tool for the numerous stakeholders, such as companies, authorities and society. An ongoing joint exchange should be established for this purpose.

Although this publication focuses on the situation regarding direct material flow indicators for recycling and their data bases, the derivation of indicators relating to supply risks, import dependencies and self-sufficiency rates is also very relevant in this context, both for Germany and, in the spirit of the CRMA, for the EU. Furthermore, it is necessary to be able to measure the environmental impacts associated with material flows and to explore the social aspects of raw material supply and processing. All these aspects – providing plant capacity, reducing environmental impacts, increasing security of supply, enabling social prosperity for current and future generations – require sufficiently differentiated, valid data on material flows and material stocks. The data currently available is not sufficient for this purpose.

Starting points for improving the data situation have emerged from studies, workshops, discussions and exchanges of experience with various stakeholders from industry, public authorities and society in recent years, or result from changing framework conditions (e.g. regulations) in the future. Against the background of the data analysis carried out here, the authors present a non-prioritised list of ideas that could improve the quality and complexity of the data situation in the future. These starting points are primarily intended to serve as a basis for discussion, must be examined in context and always weighed up with regard to proportionality, taking into account the intended reduction of bureaucracy.

4.1 Refine and establish terminology and nomenclatures

Differentiated definitions of terms and nomenclatures tailored to the circular economy mindset are a basic prerequisite for collecting and providing reliable data.

- **Differentiated definitions of terms:** On the path to a circular economy, production must be able to rely on secondary raw materials. This means that the precise description of qualities and the steering of recycled materials into the appropriate areas of application are becoming increasingly important. The legally defined term "recycling" must therefore be substantiated. For example, it would make sense to define what is meant by "high-quality recycling", "material recycling", "downcycling", "functional recycling" or "closed-loop" recycling. Only in this way is it possible to provide a differentiated description of the degree of degradation of material flows. Similarly, it would be more transparent, especially for the end user, if the degree of recyclability of materials and products were also defined in such a way that it would be clear how highly recyclable a product is.
- **Finding practical nomenclatures:** Existing classifications, nomenclatures and taxonomies do not always provide the data and information required for the circular

economy in a useful way, e.g. the requirements for the differentiated description of material qualities. Further development in consultation with industry should therefore be considered; for example, whether the material composition, end-of-life scrap content and impurity levels of steel scrap types could be mapped more specifically. An example at product level would be a more detailed breakdown of data on electrical appliances according to UNU keys[42]. In order to be able to combine data sources from different origins (e.g. official statistics, association data, scientific studies, bills of material) into a consistent overall picture, taxonomies that enable standardised and granular data resolution could be harmonised and anchored in statistical methodology and science.

4.2 Considering official statistics in a comprehensive manner and evaluating them better with regard to material cycles

- **Linking existing statistical regulatory areas:** There are largely transferable systems for reporting on economic activities, goods production, goods produced and international trade in goods – at the level of individual countries such as Germany, regional groups such as the EU and the rest of the world. One link here is the Combined Nomenclature with up to 8-digit CN codes, which can establish comparability of the designated goods in a very detailed structure. This also corresponds to other classifications such as HS and TARIC and can be translated into the goods production classification system. On the waste side, the EU's waste type catalogue provides an independent system for recording waste, which was developed with the aim of distinguishing between hazardous and non-hazardous waste. There is no link to the CN codes.

The various statistics on production and waste management fulfil legally regulated reporting purposes and follow an inherent logic, but they are not comparable with each other and cannot be translated at the level of material flows. In order to make this possible in the future, it should be examined to what extent **translation tables from goods and merchandise statistics into the waste code system and vice versa** could be developed and made available. This concerns expected waste codes by area of use and treatment method. These should be supplemented by the material categorisation of the environmental economic accounts (UGR). Eurostat has made an attempt to do this with the "waste management indicator"[30], which could be further developed with more valid, differentiated data from the EU Member States.

The added value of such a link lies in the improved traceability of metal flows in material cycles throughout the life cycle up to the waste phase, especially cross-border flows. As these are independent sources, if they are easily translatable, they could serve to mutually validate the data quality and completeness or to reveal gaps. Double counting is also a challenge, as recycled content is implicitly included in the codes used in goods and merchandise statistics. In many cases, it will not be possible to compile directly equivalent codes because the assignment is too vague and processing takes place across several stages. Therefore, the long-term goal could be a dialogue on the further development of classifications against the backdrop of a circular economy[43].

4.3 Check targeted data collection

- **Collection of data on the recycling of critical and strategic raw materials:** With the European Critical Raw Materials Act (CRMA), the EU has set itself the goal of improving and diversifying the EU's supply of 34 critical raw materials, including 17 strategic raw materials, strengthening recyclability, including recycling, and supporting research and innovation in the areas of resource efficiency and the development of substitutes. The

regulation contains specific targets. For example, by 2030, recycling capacities for 25% of the EU's own demand for strategic raw materials are to be established. In consultation with stakeholders such as industrial companies and associations, it should be examined to what extent the Federal Republic of Germany could monitor the achievement of these targets by establishing a survey of the recyclates of critical raw materials produced and their use, with the help of an amendment to the Environmental Statistics Act (UStatG) and the Act on Statistics in the Manufacturing Industry (ProdGewStatG). To date, there is no basis for collecting this data. The more data collection (e.g. for the CRMA) is revised and adapted to the data requirements of a successful circular economy, the more it remains to be examined whether other data collection efforts can be reduced instead in order to reduce bureaucracy overall – this would benefit both industry and the authorities.

- **Targeted refinement of waste statistics for the circular economy:** The waste code system is primarily based on the origin and hazardousness of the waste. Accordingly, certain data requirements regarding recyclable content, scrap quality, etc. (see chapter 2.2.1) cannot currently be sufficiently met. In order to make the collected data more useful for questions relating to material cycles, a pragmatic interim step could be to subdivide the 6-digit waste codes into 8-digit codes. This tool is already established in practice for official statistics and is used by Destatis for various waste codes in the survey forms of the federal states. One example is the very unspecific waste code 160215 "hazardous components removed from used equipment", which has been subdivided into "16021501* mercury-containing waste" to "16021512* photoconductor drums containing cadmium or selenium" in order to obtain data on the individual separation requirements from Annex VII of the Waste Electrical and Electronic Equipment Directive 2012/19/EU[44] . In this way, specific information on material composition (recyclable materials, pollutants) can be generated. Other informative examples of further uses of the 8-digit waste code with regard to metals are:
 - the more detailed subdivision of shredder output fractions in group 1910, in particular of "191002 non-ferrous metal waste" by metal (e.g. copper, aluminium, stainless steel),
 - differentiation of the entry for end-of-life vehicles (waste code 160104*) into the various drive technologies (electric vehicles, combustion engine vehicles) and vehicle classes,
 - the realignment or reduction of waste codes for waste electrical and electronic equipment in accordance with the categories of the WEEE Directive and the UNU keys, taking into account material aspects, in particular for fractions from treatment.

Such differentiations may provide an opportunity to obtain specific data on waste streams containing certain recyclable materials (e.g. precious metals or critical raw materials). It should be noted, however, that those required to provide information must first be motivated by the regional statistical offices to use these eight-digit waste codes, which are not required by law. This is sometimes very time-consuming and requires a lot of queries for both the state statistical offices and the companies. Even for cross-border waste shipments and the survey on hazardous waste, only the six-digit waste codes are available, as these secondary surveys rely on data from the official consignment notes. In the long term, therefore, the gradual further development of the European Waste Catalogue is essential. A good example of this is the current preparation for the inclusion

of a number of new and highly differentiated waste codes for lithium-ion and other batteries, which have previously been predominantly subsumed under waste code 16 06 05 "Other batteries and accumulators"[45]. With such further development, new structural approaches could be examined in consultation with those required to provide information in order to better meet the data and material management requirements of the circular economy.

- **Introduction of statistics for the export of used products:** The extent of the recyclable waste potential is highly relevant for the recycling industry. However, for a number of end-of-life products, e.g. end-of-life vehicles and waste electrical and electronic equipment, the waste potential cannot be determined from the quantity placed on the market and the distribution of retention times, for example. This is because (partly due to the wealth gap) relevant quantities of certain products leave Germany as used products during their useful life. Accordingly, these quantities do not accumulate as waste in Germany. The domestic potential for secondary raw materials is calculated from domestic consumption minus exports of used products. Information on the volume of exports is therefore necessary in order to determine urban mining potential, e.g. for vehicles, electrical and electronic equipment and wind turbine generators (CRM relevance), and to be able to interpret (missed) collection rates. This is an important data basis for managing and assessing the collection infrastructure and for investment decisions in the recycling industry.

Due to their volume thresholds, foreign trade statistics hardly cover exports and imports by smaller companies involved in the second-hand goods trade. In principle, foreign trade statistics are designed to be a complete survey. In extra-trade (trade with non-EU member states), almost 100% of all imports and exports in Germany are recorded due to the close link to customs formalities. In intra-Community trade (Intrastat), however, a reporting threshold has been introduced to ease the burden on small and medium-sized enterprises (SMEs). Currently, companies whose intra-Community trade in goods does not exceed €500,000 per year for dispatches or €800,000 for imports are exempt from reporting. The volume of intra-Community trade below the reporting threshold is estimated on an undifferentiated basis using data provided by the tax authorities.[46] In view of these volume thresholds, which are intended to reduce the administrative burden on SMEs, further differentiation of goods codes into new and used products would therefore be of limited use. Even in the case of vehicles, for which such a differentiation already exists, foreign trade statistics only cover around one-fifth of the actual exports of used vehicles from Germany to other Member States.

In contrast, new statistics are promising in other areas where legal registration and recording already exist in order to avoid additional bureaucracy. For vehicles, the management data of the Federal Motor Transport Authority could be used[47]. For electrical and electronic equipment, a starting point can be found in the existing product-specific data collections under the WEEE Directive.

4.4 Better determination of raw material potential in various waste streams

- **Conducting nationwide waste sorting analyses and waste analyses:** Due to their high cost, sorting analyses are only carried out irregularly in studies and, as a rule, only for residual waste and other municipal waste fractions. However, they are essential for tracking material flows that may be recycled improperly, meaning that they are lost for adequate recycling.

In recent years, regular (every four or five years) investigation and reporting obligations

have been introduced at EU level for several types of waste, such as plastic packaging waste (according to Implementing Regulation (EU) 2023/595), packaging waste of all materials (according to the Guidance Document on Decision 2005/270/EC of the EU COM), waste batteries (under Battery Regulation (EU) 2023/1542) and food waste (under Delegated Decision (EU) 2019/1597). The sorting analyses carried out by the Member States must determine the proportions of these types of waste in household waste and, in some cases, in other waste streams and commercial municipal waste. If it were possible to supplement these regular sorting and waste analyses with studies on other waste streams, relevant data on the status and further development of recycling could be collected very efficiently. These regular waste analyses would have to be carried out in close consultation with the companies concerned.

In addition to determining the collection of valuable waste in waste streams in which it is not recycled, sorting analyses of separately collected waste such as waste electrical and electronic equipment are informative in determining the current proportions of specific devices or device groups as well as materials and raw materials. To this end, the waste must be examined before treatment (determination of incorrect disposal, differentiation of specific waste sub-streams within a waste stream, e.g. proportion of IT equipment). In addition, chemical analyses after treatment are important in order to be able to make statements about alloy groups and the transfer of impurities. Regularly repeating this process allows the existing system of waste analysis data to be kept continuously up to date. However, the high cost of data collection can be reduced by means of representativeness analyses, combinations of questions and time intervals, e.g. every five years[48] . This can help legislators to identify potential for improvement in the circular economy and is useful for plant operators' investment and cost accounting. The analysis data should be made publicly available in databases such as ABANDA. A cost-benefit analysis should also be agreed with stakeholders for this purpose.

- **Better use of waste analysis data from federal state enforcement:** For the disposal of waste subject to documentation requirements, waste producers submit a disposal certificate to the waste authorities, which often includes a declaration analysis of the waste (Section 3 NachwV). These analyses thus represent a source of information, usually on pollutant content and, in some cases, on metal content. In order to evaluate the pollutant levels and recyclable material potential of certain types of waste over time, an (anonymised) systematic collection of the data available to the waste authorities would be helpful. One example is the ABANDA database[29] of the Information Portal for Waste Assessment (IPA), which collects waste analysis data from specialist authorities in several federal states and enables evaluation. In this way, the data situation could be improved by linking to existing databases.
- **Making data from sorting processes usable:** Data on the quantities and qualities of the processed materials are at least partially available to scrap processing and shredder operators if they use automated detection and separation techniques (e.g. LIBS, XRF). In consultation with the operators, this data could be retrieved retrospectively for individual financial years in aggregated form and separated by alloy groups and commercial grades. This would provide an overview of the material flows processed.

4.5 Develop further information bases with systemic data modelling

- **Regular material flow analyses (MFA) for critical, strategic and environmentally relevant raw materials:** At EU level, material system analyses (MSA) are regularly carried out for critical and strategic raw materials. These studies serve as an important data basis for calculating key figures in the context of EU criticality studies and for

monitoring the circular economy. The results impressively show that the recycling availability of key raw materials for the energy transition, such as lithium or neodymium, is currently almost zero. The EU MSA studies provide an established framework for material flow analyses and the collection of data and indicators on the circular economy. On this basis, Germany could conduct national MSA studies for strategically relevant raw materials in order to close data gaps in official statistics. Synergies with data collection at EU level, in particular by the Joint Research Centre (JRC), should be taken into account here. The aim would be to close existing data gaps and derive concrete targets and key figures for German circular economy policy.

4.6 Integrate new data sources

- **Review and evaluate data from mandatory sustainability reporting:** The Corporate Sustainability Reporting Directive (CSRD[49]) stipulates comprehensive and verified reporting on environmental, social and corporate governance (ESG) issues using transparent standards, providing more detailed insights into the sustainability risks and opportunities of companies. The associated new European Sustainability Reporting Standard (ESRS) E5 introduces mandatory reporting on resource use, waste generation and circular business models such as the recovery of end-of-life products and materials. It must be examined whether this data can be systematically evaluated in order to draw conclusions about recycled content and quality, even when aggregated across numerous companies and industries. Together with the Supply Chain Directive (CSDDD), the CSRD is being adapted as part of an omnibus package by the European Commission, meaning that the resulting regulations on ESRS E5 will be particularly important.
- **Taking CBAM data into account:** An approach comparable to sustainability reporting is also possible with regard to foreign trade flows affected by the Carbon Border Adjustment Mechanism (CBAM)[50] . This will be implemented at the beginning of 2026 and will cover energy-intensive goods, including those made of steel and aluminium. Importers will then have to calculate and document the direct and indirect emissions generated in the production process of goods imported from non-EU countries. Due to the nature of the process, the use of recycled material results in 5 to 18 times lower CO₂ emissions in metal processing routes. This data can be used to record the recycled content in the flow of goods.
- **Industrial Emissions Portal Regulation (IEPR) – Using reporting for relevant raw materials:** The Industrial Emissions Portal (IEPR) fulfils international reporting obligations (UNECE PRTR Protocol and Aarhus Convention) and provides the public with access to important environmental data from industrial facilities in the EU. Together with the similarly amended Industrial Emissions Directive (IED), the associated regulations and reporting requirements are intended to improve the protection of human health and the environment by reducing harmful emissions from industrial facilities while promoting energy efficiency, the circular economy and decarbonisation. The regulation provides for the publication of information on the use and consumption of raw materials in the operations of these facilities. By the end of 2025, the EU Commission will draw up and present a list of raw materials with corresponding criteria. In order to harmonise the requirements of the Critical Raw Materials Act (CRMA) and the EU's overall circular economy targets, critical and secondary raw materials should be taken into account in reporting.
- **Designing and utilising digital product passports (DPP):** The European Ecodesign Regulation (ESPR[51]) makes more sustainable products the norm and provides for the

use of digital product passports (DPP) for all product categories in the long term. The introduction of DPP will enable the provision and transfer of various product information along value chains (see Art. 77 EU BattV[52] , Art. 9 to 15 ESPR[51]). This includes components, materials and chemical substances, but also information on reparability, spare parts, proper disposal and ecological parameters. A significant improvement in recycling quality can be expected, particularly with regard to special metals, as major obstacles to high-quality recycling are the lack of information on the quantity and location of materials and information on separation on the part of recyclers. Data from the DPP can also be used to explore (prospect) and map the anthropogenic repository by incorporating it into typologies, material registers and databases with scenario analyses. Combined with information on the service life of product groups, this enables economic forecasts to be made as to when (secondary) raw materials will become available again from the anthropogenic stock after the end of a product's service life (dynamic MFA modelling). The necessary conditions for this must be created at European level. This means that government institutions such as specialist authorities, enforcement agencies and customs must be given access to the DPP and, in particular, to substance and material declarations in order to perform their tasks, so that they can evaluate aggregated recycling-relevant data and make it available to the public.

- **Digitalisation opens up new data opportunities:** many modern products are networked, which opens up new data sources. For example, various data from vehicles is regularly transmitted to manufacturers. An analysis that complies with data protection regulations could support official vehicle statistics in order to better track the outflow of vehicle fleets from Germany. In combination with information on material composition (in particular via a DPP), it would be possible to track the significant anthropogenic material stock of vehicles in Germany.
- **Low-bureaucracy collection and evaluation of new data sources.** In its work programme until 2029, the EU Commission has proposed so-called omnibus packages[53] , which are intended to either reduce the bureaucratic burden in various areas, including the environment and sustainability, before they come into force, or to reduce existing documentation and reporting requirements. The Commission is aiming to reduce the administrative burden on businesses by at least 25% by 2029, and by as much as 35% for small and medium-sized enterprises. As the German waste management and recycling industry is dominated by small and medium-sized enterprises, the planned increase in the minimum operating sizes for reporting threatens to make industry and trend characterisations more incomplete. When designing the omnibus packages, specific options for intelligently combining reporting obligations should therefore be sought in order to avoid completely losing control-relevant data and information in the course of reducing bureaucracy. Reporting on material flows in a circular economy can be improved by bundling them without imposing additional reporting requirements. It also remains to be seen what contribution artificial intelligence and big data can make in connection with the collection, aggregation and standardisation of data.

4.7 Mapping anthropogenic storage dynamics and providing forecasts for urban mining

- **National urban mining data platform:** Anthropogenic raw material stocks are at the heart of national, resilient raw material management, which is increasingly based on resource-saving secondary raw material sources from recycling. Germany's anthropogenic stocks are growing by around 600 million tonnes per year[54] , which is

around 50% of domestic primary material use for consumption and investment. To accompany the adoption of an urban mining strategy with fields of action for particularly relevant goods groups, a national urban mining data platform should be created. As a publicly accessible data portal, this could highlight potential and support the planning of plant capacities and self-sufficiency rates for the effective processing of the materials released from the anthropogenic stock. To this end, the data platform should bundle information bases and data sources that record the development of goods stocks with their specific material contents and evaluate them prognostically with the aid of product usage durations and residence time functions. Preliminary scientific studies on this mapping of the anthropogenic repository are already available and need to be updated and regularly processed[55]. In this context, the NKWS also plans to create a dynamic material register that provides information on material flows, alloy types and their chemical composition, including the occurrence of critical and technology metals in products and waste streams. Digital product passports, building resource passports and material registers are expected to provide new, essential information for the national urban mining platform in the future.

4.8 Improving data provision

- **Cross-departmental data collection and central provision of secondary raw material data:** It should be examined whether it should be considered a sovereign task to provide data on secondary raw material production in a differentiated material structure – analogous to the already established reporting on primary raw material production. In consultation with industry, structures should be created with as little effort as possible to enable better measurability and thus control of the circular economy. Existing open data infrastructures can be used in an unbureaucratic manner to prepare the data and make it available in a form suitable for the target audience[56].

4.9 Access rights to data while safeguarding the interests of all parties involved

- **Creating public data rooms with data governance:** The circular economy requires its own, much more detailed database than has been available to date, covering aspects such as the composition of products placed on the market, in order to increase the quality and quantity of recycling. To this end, public and private data systems would need to be connected in a decentralised manner, and the use of data across national borders, sectors and actors along circular value chains and within a defined, trustworthy data space would need to be enabled[57, 58]. For example, based on Catena-X[59], a collaborative and open data ecosystem designed to improve transparency, efficiency and sustainability in the automotive industry's value chains, Manufacturing-X[60] is a platform initiative by the German government that aims to create an open digital ecosystem for all manufacturing industries in order to streamline processes and enable new digital business models.

These data rooms should enable more symmetrical exchange while respecting sensitive company data and empower both companies and the public sector to make better decisions in a circular economy. This requires dedicated circular data governance, i.e. a set of rules that precisely defines how product-related information should be generated, stored, used and shared[61]. This requirement is manifested first and foremost in the Digital Product Passport (DPP). The business and confidentiality interests of the companies involved must be taken into account, as must the information needs of politicians, scientists and the public in order to further develop the circular economy.

Depending on data requirements and access rights, automated anonymisation and spatial and temporal aggregation can be carried out for this purpose. In the course of implementing the NKWS, a set of rules should be developed to define access requirements and rights to the data bases of the circular economy in a concerted manner and to harmonise them at European level. Government agencies such as the UBA or the DERA are important user groups in this context and must be taken into account in order to be able to evaluate recycling-relevant data and make it and the results available to the public.

A Appendix

A.1 Aluminium – case study on the data situation

Characteristics

Aluminium is the second most recycled metallic material in the world after steel, with an annual production of almost 3 million tonnes of recycled aluminium (2022) in Germany alone[25] . When exposed to atmospheric oxygen, the light metal forms a protective passivation layer that prevents further corrosion. It is easy to shape, and its strength can be increased by adding alloying elements. Aluminium also has high electrical and thermal conductivity. Due to these material properties, it is used in the form of aluminium alloys in various fields of application, including transport (such as cars, trucks, railways, ships and aviation), construction, packaging (such as cans and foils), mechanical engineering, electrical engineering, consumer goods and in smaller, mostly dissipative applications[62] .

There are two main types of aluminium alloys: wrought alloys and cast alloys. Wrought alloys are classified into alloy groups "1xxx – 8xxx" according to EN 573. This classification is mainly based on the main alloying elements such as magnesium, silicon, copper, zinc and manganese. Wrought alloys are used for food packaging, beverage cans, heat exchangers, vehicle frames and applications in aviation, among other things. The main area of application for cast alloys is primarily in engine blocks in vehicle construction. Typical cast alloys are AlSi, AlSiCu and AlMg.

Approximately one third of global demand for aluminium alloys consists of 6xxx wrought alloys. Other wrought alloy groups that are relevant in terms of volume are 1xxx, 3xxx, 5xxx and 8xxx, while the 2xxx, 4xxx and 7xxx wrought alloy groups tend to serve niche applications. Cast alloys account for around a quarter of demand.

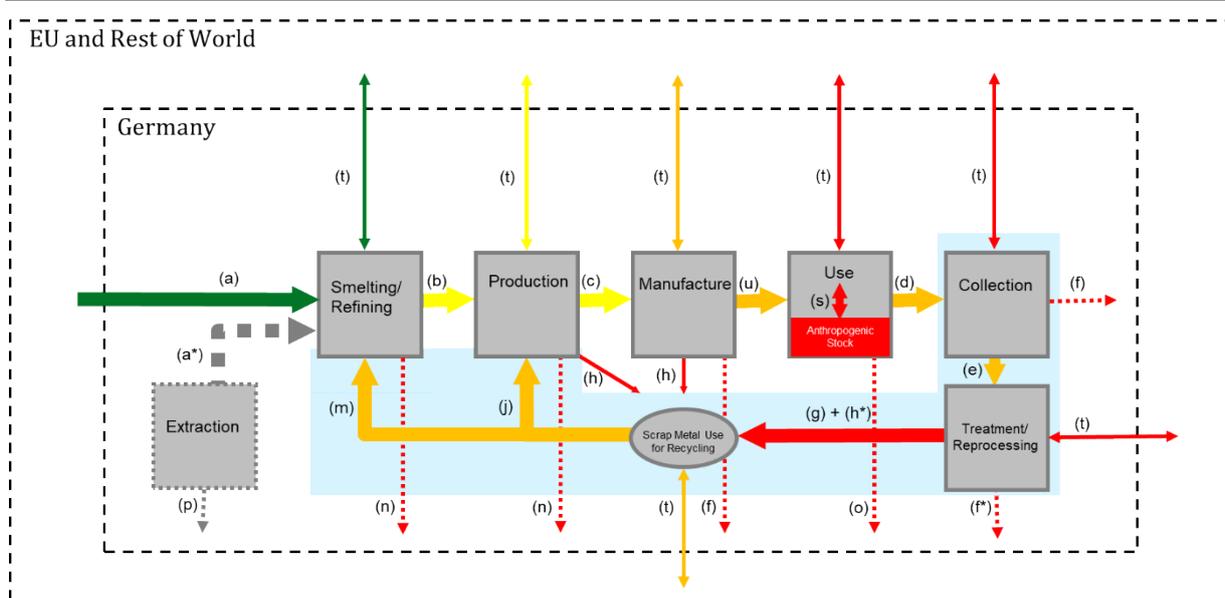
For the recycling of aluminium scrap, identification and subsequent separation are crucial in order to enable high-quality recycling without mixing the alloy groups and thus preventing a loss of quality (downcycling). This is the only way to produce high-quality wrought alloys from secondary raw materials.

Data situation

The data situation for extraction, smelting, refining and semi-finished product production is comparatively good thanks to publicly available statistics. However, access to current global production data is deteriorating as many commercial providers are entering the market and selling this data in increasingly small increments. In the case of aluminium in particular, it should be noted that important production and export countries such as Russia, Jamaica and Guinea do not publish import and export statistics, meaning that we are reliant on data from importing countries (mirror data). When it comes to product manufacturing and, in particular, the collection, treatment/processing, scrap trading and recycling of aluminium alloy scrap, there is a significant lack of information about quantities and chemical composition.

In Figure5 , the data situation for the aluminium material flow is visualised in colour and explained below. The letters refer directly to the labels in the reference scheme (). The categories of sources are abbreviated in square brackets: official statistics [OS], data from commercial providers [CP], industry statistics [IS], other studies, data processing and modelling, and [OS] individual expertise [IE].

Figure 5 Data availability for aluminium material flows



Legend

- Green: Data on quantities and qualities largely available
- Yellow: Data on quantities in official statistics incomplete, no information on qualities
- Orange: Data on quantities incomplete or irregular via other data sources, no information on quality
- Red: No or only sporadic data available on quantities and qualities (from individual expertise, individual studies, models, etc.)

Source: Own illustration

- a, a*: No bauxite (aluminium ore) is mined in Germany, so no data is required for this; import and export data from DESTATIS is available for bauxite imports and exports. [OS]
- b: The production of alumina (aluminium oxide) in Germany is recorded, but only one company produces aluminium oxide. Data could be obtained from the company or, with a delay of several years, from the British Geological Survey (BGS). Import and export data are available from DESTATIS. Overall, these data can be considered reliable. Aluminium production in Germany is recorded by the association "Aluminium Deutschland (AD)" and is generally available in a relatively timely manner. Here, too, there is only one company that produces primary aluminium in Germany and provides data in its annual reports. Otherwise, data is only available via the BGS with a delay of several years. Import and export data is collected and published by DESTATIS. [BS, AS] Data on the production of individual aluminium alloys is not available. However, AD allows the recycled quantities to be differentiated according to refiner and remelter or according to the scrap and new scrap used in Germany. Together with the existing waste statistics, it is possible to derive information on the respective alloy groups. [IS]
- c, u: The quantities of aluminium must be quantified based on the content in the respective fields of application. Data collection for end-of-life vehicles, construction and commercial waste, packaging and waste electrical equipment is decisive here. Data is

collected for packaging (especially cans). The aluminium content in other material flows is not statistically recorded and is only available for specific products in individual cases. Accordingly, no specific data is available at alloy level. An estimate for aluminium in vehicles, electrical appliances and batteries, both for quantities placed on the market and in anthropogenic storage and in the waste stream, was made in the ProSUM research project[63] and, in part, in KartAL III[64] . However, the data is not updated regularly and, due to confidentiality agreements, is sometimes only available in a highly aggregated form. Data on usage and retention periods for predicting the waste generation of products made of or containing aluminium is also only available on a selective basis. [AS, WS, IE]

- d: Data on aluminium loads in EoL waste streams is only partially collected statistically. Aggregated data on metals as a whole is provided by the waste code numbers for municipal waste (AVV 20 01 40) and packaging (AVV 15 01 04). Aluminium is only reported separately for construction and demolition waste (EWC 17 04 02). [AS, WS, IE]
- o: There is no data on material losses in other waste fractions from which aluminium is not recovered. Only selective, limited estimates are possible (e.g. via analysis of waste incineration ash). This also applies to other losses from anthropogenic sources. [IE]
- e: There is no recording of quantities and qualities between collection and treatment/processing. In some areas, data on quantities can be calculated and qualities estimated (e.g. via the Regulation (EU) 2025/40 on packaging and packaging waste). [WS, IE]
- f: Losses from product manufacturing and collection are not recorded and are only available to the companies. [IE]
- f*: Losses due to inefficient processing are not systematically recorded. [IE]
- g, h*: The quantities of processed scrap and new scrap from treatment are usually not recorded centrally. However, information on quantities and qualities is available at the processing/treatment facilities (e.g. shredder plants). Waste from waste treatment facilities only records non-ferrous metals as a total and does not report aluminium separately. For example, AVV 19 10 02 lists non-ferrous metal waste from shredding metal-containing waste and AVV 19 12 03 lists non-ferrous metals from the mechanical treatment of waste (e.g. sorting, crushing, compacting, pelletising) n.e.c. [AS, WS, IE]
- h: Data on the quantities and qualities of new scrap from the manufacture of semi-finished products and products are not recorded. Only estimates based on individual studies and company surveys are possible. [WS, IE]
- j: Data on the use of recycled materials in the semi-finished product industry is generally not available. Otherwise, see m. [BS, WS, IE]
- m: Data on the use of new scrap (in "remelters") and old scrap (in "refiners") is indirectly available from the statistics of the AD association. An indirect estimate of the OSR is possible based on the published quantities used in remelters and refiners. However, no alloy qualities are recorded. [BS, WS, IE]

- n: Material losses from smelting and the production of semi-finished and finished products are not recorded centrally. Only estimates based on individual studies and company surveys are possible. [BS, WS, IE]
- s: For the amount of aluminium bound in anthropogenic deposits and the annual inflows and outflows, only estimates exist in individual studies in the field of urban mining.
- t: The quantities of imports and exports of aluminium and various product groups are available from the Federal Statistical Office (DESTATIS). A rough estimate could also be made here at alloy group level. Aluminium scrap can be partially recorded via the HS codes 262040 and 7602 in public statistics. [AS, WS, IE] However, more specific data or data series on aluminium imports in higher-processed goods such as cars are not available.
- p: Not relevant, as there is currently no bauxite mining in Germany.

The description of the aluminium cycle is currently quite good for the first stages of the value chain. However, the data situation deteriorates as the product character increases and at the transition to use. Unrecorded quantities and losses in use and at the end of the (product) life cycle make it difficult to draw conclusions about recycling. For EOL materials, the data is based on individual reporting requirements for products (e.g. packaging), association data, (commercial) studies and estimates by experts. It is generally not possible to make differentiated statements about (wrought and cast) alloys.

A.2 Cobalt – case study on the data situation

Characteristics

Cobalt is a transition metal and is mainly obtained as a by-product of copper and nickel mining. In its elemental form, it is a shiny, grey-silver, brittle metal. Cobalt is very hard, tough and ferromagnetic and can form alloys with many other metals such as iron, chromium, molybdenum and nickel. Cobalt retains its strength and magnetic properties at high temperatures and has relatively low thermal and electrical conductivity.

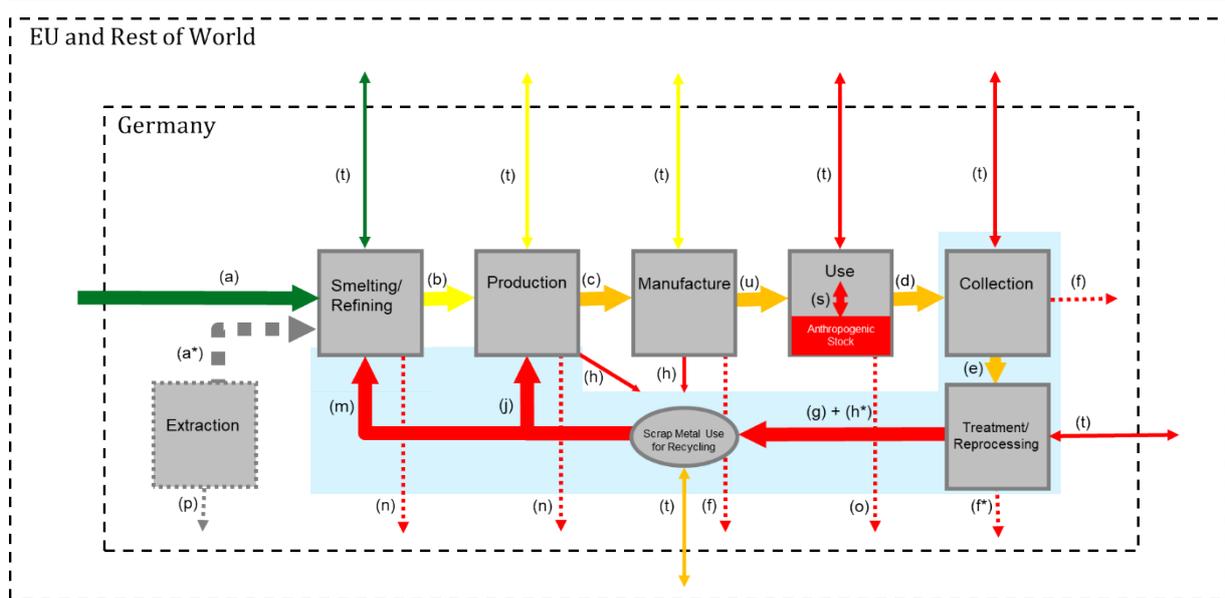
Globally, primary production is expected to rise sharply due to the continuing high demand for batteries for electric mobility. The electric mobility sector and portable electronics are now the largest users of cobalt, accounting for around 70% of consumption.

Due to the transformation in the transport sector and the rapidly increasing use of lithium-ion batteries (LIB), cobalt is also becoming significantly important in the recycling industry. In particular, the many projects planned for Germany for comprehensive LIB recycling will result in a sharp increase in recycling volumes.

Data situation

In Figure 6, the data situation for the cobalt material flow is visualised in colour and explained below. The letters refer directly to the labels in the reference scheme (). The categories of sources are abbreviated in square brackets: official statistics [OS], data from commercial providers [CP], industry statistics [IS], other studies, data processing and modelling, and [OS] individual expertise [IE].

Figure 6 Data availability for cobalt material flows



Legend

- Green: Data on quantities and qualities largely available
- Yellow: Data on quantities in official statistics incomplete, no information on quality
- Orange: Data on quantities incomplete or irregular via other data sources, no information on quality
- Red: No or only sporadic data available on quantities and qualities (from individual expertise, individual studies, models, etc.)

Source: Own illustration

- a, a*: A comprehensive database is available on deposits, information on metal contents, and resources and reserves for different types of deposits. This data is publicly accessible, e.g. via geological services (BGR, USGS, BGS). Production figures for mining output are also provided in part by public institutions (BGR, USGS, BGS, Cobalt Institute[65]) and in the form of market analyses in the annual reports of individual companies and commercial providers, such as Darton Commodities[66] . Price data on primary raw materials is collected by the BGR. [AS, BS, WS] As no cobalt is mined in Germany, no data needs to be provided for this.
- b: Data on refined cobalt production is provided by public institutions and can also be purchased from commercial providers. No refined cobalt is produced in Germany; data on imports and exports is available from the import and export data in the public statistics[67] . Different forms of cobalt are often grouped together under the same HS code, which reduces the quality of the import and export data. Example: "Cobalt matte, intermediate products of cobalt metallurgy" is combined with "cobalt in raw form; cobalt powder" in HS code 81052000, although the cobalt content of these two forms of cobalt is very different. In 2023, 2,177 tonnes of this product group were imported into Germany. This is particularly important when trying to track global cobalt flows, as the majority of the material shipped from the DR Congo, the main mining country, is an intermediate product. In contrast, only 44 tonnes of declared cobalt ores and their concentrates (HS code 260500) were imported into Germany in 2023. [OS]

- c, u, d, e: Currently, there is little data available on production, the exact distribution of specific products, the collection of these products at the end of their life as waste, and the recycling of cobalt from these end-of-life products in Germany. A further study based on data from 2016 provides EOL recycling rates (EOL-RR) and recycling input rates (RIR) for the European Union at[68] . This also corresponds to the data available in the EU's Raw Materials Information System (RMIS). [WS, IE] Data on the useful life and retention periods of the various cobalt-containing products, which are necessary for predicting waste generation, are only available in isolated cases from studies and modelling. [OS]
- f: No data is available on cobalt losses during product manufacturing, collection and the treatment/processing of waste and scrap in Germany.
- f*: Losses due to inefficient processing are not recorded. [IE]
- g, h*: No precise data is available on the quantities of cobalt recovered from magnets, hard metals and cobalt-containing alloys and scrap. Detailed information on the cobalt content in intermediate and finished products of the treatment/processing of waste products and scrap, as well as product-related recycling rates for cobalt, e.g. in magnets, is therefore not available.
The cobalt content in the cathode material of a lithium-ion battery could be estimated on the basis of the reporting requirements under Regulation (EU) No 493/2012 "on the calculation of recycling efficiencies of recycling processes for waste batteries and accumulators", provided that this data were published. [OS] Based on the available data, it is currently not possible to differentiate between waste scrap (g) and treated new scrap (h*).
- h: Material waste from the production of semi-finished products and products is not recorded centrally; only estimates by experts or company surveys are possible. [IE]
- j: No data is available on the quantities of cobalt returned to semi-finished product production and thus on the recycled materials used here.
- m: Scrap quantities for smelting are not recorded centrally; estimates can only be made on the basis of company data or expert opinions. For batteries, the new EU Battery Regulation specifies minimum recycled content requirements. [IE, AS]
- n: There is no production of refined cobalt in Germany, so no data on residues and slag is available.
- o: There are no data sources on dissipative losses of cobalt.
- p: Not relevant, as there is currently no cobalt ore mining in Germany.
- s: For the amount of cobalt bound in anthropogenic deposits and the annual inflows and outflows, there are only projections in individual studies on the expected stock increases in the coming decades.
- t: Data on German imports of cobalt-containing waste and scrap (HS code 810530) are available, but are not differentiated by alloy. Trade data on cobalt are often of poor quality due to many inconsistencies between HS codes and production data. [OS]

The availability of data on the cobalt cycle varies greatly along the value chain. Quantities for extraction and smelting can be covered in particular by quantitative and, in some cases, qualitative data. As the product character increases and the utilisation phase begins, the data

basis deteriorates considerably. Data on new scrap quantities and losses during the collection and treatment/processing of waste and scrap are not recorded and are therefore unavailable for quantifying the cobalt material in the recycling process. Statements on EOL quantities can only be made with statistical certainty for batteries within the framework of product-specific reporting requirements (EU Battery Regulation). Other waste battery streams can be estimated using (commercial) studies and individual expert assessments.

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