RESEARCH AND ANALYSIS

Material system analysis

Functional and nonfunctional cobalt in the EU, 2012–2016

María Fernanda Godoy León[1] | **Cristina T. Matos[2]** | **Konstantinos Georgitzikis[2]** | **Fabrice Mathieux[2]** | **Jo Dewulf[1]**

[1]Research Group Sustainable Systems Engineering (STEN), Ghent University, Ghent, Belgium

[2]European Commission, Joint Research Centre (JRC), Directorate for Sustainable Resources, Land Resources Unit, Ispra, Virginia, Italy

Correspondence
María Fernanda Godoy León, Research Group Sustainable Systems Engineering (STEN), Ghent University, Coupure Links 653, 9000 Ghent, Belgium.
Email: maria.godoy@ugent.be

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Abstract

A comprehensive data inventory of the current materials cycle in industry and society is crucial for an informed discussion and for decision-making on the supply of raw materials. Particularly, it is key to understand how these materials are functionally and nonfunctionally recycled, and enable the assessment of recycling indicators needed for the monitoring of circular economy. In this context, a material system analysis (MSA) of cobalt for the European Union (EU) from 2012 to 2016 is presented and discussed. Detailed results are provided for the year 2016, and the evolution of the flows over time is presented from 2012 to 2016. In addition, six indicators are calculated to characterize the cobalt cycle. In 2016, the EU28 embedded around 24,000 metric tons (t) of cobalt in manufactured products, and 33,700 t were put into use. The main losses of the system are due to nonselective collection of postconsumer waste (disposed), and nonfunctional recycling of old scrap. From the years analyzed, it was possible to detect a shift in the imports; the import of primary material decreased more than 99% between 2012 and 2016, and the import of semiprocessed and processed materials increased around 31% in the same period. This indicates that after 2012, the EU became more dependent on imports in downstream stages of the supply chain. One way to decrease this dependency is to establish higher collection targets, and to establish recycling targets based on the recovery of single materials, in order to decrease the amount dissipated through nonfunctional recycling.

KEYWORDS
batteries, cobalt, industrial ecology, life cycle, material flow analysis, recycling

1 | INTRODUCTION

Natural resources provide the base of humankind's existence on Earth. They do not only deliver a broad range of goods and services used in everyday life but they are also required in the development of emerging technologies, the latter being an important driver for the increasing production and use of many metals and minerals (Langkau & Tercero Espinoza, 2018).

In this context, securing access to a stable supply of these raw materials has become a major challenge and a priority for several national and regional economies. The European Union (EU), the USA, and Japan have launched several initiatives to address this issue: The Raw Materials Initiative followed by the recent Action Plan on Critical Raw Materials of the EU (European Commission, 2017, 2020), the Critical Materials Strategy of the USA (USGS, 2018), and the Resource Securement Strategies of Japan (Hatayama & Tahara, 2014). These initiatives aim to build knowledge about the use of natural resources, addressing different aspects such as supply and demand, resource efficiency, and recycling. As part of its strategy, the EU established in 2011 its first list of critical nonenergy raw materials, which has been updated every 3 years (updated in 2014, 2017, and 2020). These lists identify raw materials characterized by economic importance and supply risk for the region (European Commission, 2017).

One of these raw materials is the metal cobalt (Co), which has been identified as critical in all lists. Its criticality relies on different aspects. First, its supply in the EU is highly dependent on imports, and it may possibly remain like this since the region possesses only 0.5% of the global reserves of this metal (Minerals4EU, 2014; USGS, 2020). Second, its main mining producer is the Democratic Republic of Congo (DRC), a politically unstable country (World Bank, 2020). In 2017, the DRC accounted for 68% of the global production of Co, followed by the Philippines, Cuba, and Russia (Darton Commodities Limited, 2018). Third, Co is key in the transition from fossil fuels to more sustainable sources of energy. In the last 20 years, its refined global production increased more than fourfold, from approximately 27,000 to 119,000 metric tons per year (BGS, 2020). This growth has been mainly driven by an increasing use of Co in the production of rechargeable batteries, together with superalloys, catalysts, and hard metals (USGS, 2017, 2010).

For the development of robust mineral strategies, a good understanding of the value chain of the materials is required. In particular, a comprehensive data inventory of the materials cycle in industry and society is crucial for an informed discussion and decision-making on the supply of raw materials. In the case of Co, its cycle has been studied globally and regionally, fully or partially addressing the supply, demand, stocks, and flows of the metal. Many of these studies have been developed through material flow analysis (MFA) tools, applying static and dynamic models. Static studies at a global scale are, for instance, Harper et al. (2012) and Nansai et al. (2014), with both assessing the Co cycle in 2005. Dynamic studies at the global scale comprise, for example, Tisserant and Pauliuk (2016) and Sun et al. (2019). The former assessed the future flows of Co and the latter the past flows of Co. Static studies applied to economies such as the United States and China include Harper et al. (2012), National Research Council (1983), OTA (1985), Shedd (1993), and Zeng and Li (2015). For the EU, a number of studies have been carried out. Some of them have targeted inventory data (Godoy León & Dewulf, 2020; RPA, 2012), and many others have focused on scenarios for future demand and dynamic MFA (Ait Abderrahim & Monnet, 2018; Alves Dias et al., 2018; Bobba et al., 2019; Deetman et al., 2018; Godoy León et al., 2020; Tercero Espinoza et al., 2019). However, to the best of the authors' knowledge, only one study has dealt with static flows of Co in the EU. That study, developed by BIO by Deloitte (2015), aimed to map the flows and stocks of (critical) materials through the EU economy in 2012, in terms of entries into the economy, movements through the economy, and additions to stock. However, several limitations arise from this study. First, it is somewhat outdated, as it assessed the Co cycle of 2012. Second, the study did not consider magnets in the assessment, which currently corresponds to almost 7% of the demand of Co in the EU (Roskill, 2019). Third, the study did not estimate the Co that is nonfunctionally recycled at the manufacturing phase (also known as downcycled, where the metal is incorporated in an associated large-magnitude material stream, ending up in low-end products), and it assumed that there is no nonfunctional recycling at the recycling phase (i.e., all recycled Co is functionally recycled). This stream is of crucial importance, as it is a significant source of dissipation of Co in the technosphere (Godoy León et al., 2020).

In this context, a follow-up study was set up in 2019 by DG GROW and executed by DG-JRC of the European Commission assessing the flows of a number of materials, among them Co, lithium (Li), manganese (Mn), natural graphite, and nickel (Ni). These metals were studied because of their strategic relevance and increasing use in battery systems. The summary results related to these five raw materials were published in Matos, Ciacci, et al. (2020). In addition, four scientific papers were developed, three of them for the single materials and one for a multilayer system assessment (Ciacci et al., 2021; Lundhaug et al., 2021; Matos et al., 2021). This manuscript is one of the scientific papers related to single materials. It examines the results related to the stocks and flows of Co in the EU in 2016, giving special attention to the recycling flows. It also analyses the evolution of the flows between 2012 and 2016.

2 | METHODOLOGY

2.1 | Estimation of stocks and flows

For the estimation of the stocks and flows of Co, the method known as material system analysis (MSA) was used. The MSA is a tool of the MFA family, led by the European Commission to guide its raw materials policies. It is based on specific materials flows of selected raw materials and/or semifinished goods at various levels of detail and application (e.g., cobalt, cobalt hydroxides, and batteries). It considers the different phases of the lifecycle of the material and related applications, taking into account the inputs and outputs of each phase. It is applied for a specific region and a defined time span to assess materials that raise particular concerns related to the sustainability of their use, the security of their supply to the economy, and/or the environmental consequences of their production and consumption (OECD, 2008).

The entire lifecycle was considered for the Co MSA in the EU, including mining and extraction, processing, manufacturing, use, and end-of-life (EoL); the latter comprising collection and recycling. Different aspects were considered to estimate the flows and stocks of Co: Entries into the economy through extraction and import; movements through the economy through production, consumption, and export; additions to the in-use stock; and additions to the stock of EoL products (i.e., EoL products hoarded by users). In addition, the lost flows and stocks were estimated. These include the waste produced in the different phases, and the nonfunctionally recycled material. It is important to indicate that all the aforementioned stocks correspond to cumulative stocks (hereinafter referred to simply as stocks).

In general terms, in nonfunctional recycling, the material is collected and incorporated in an associated large-magnitude material stream, ending up in low-end products where the original function is not required, or as a contaminant. While the material is not dissipated into the environment, it is dissipated in the technosphere, as it is generally unfeasible to recover it from the large-magnitude stream (Buchert et al., 2009; Graedel et al., 2011; Zimmermann & Gößling-Reisemann, 2013; Zimmermann, 2017). In the case of Co, the metal is usually nonfunctionally recycled in the production of stainless steel, where it does not perform any particular or essential function (Akcil et al., 2015; European Commission, 2017).

The stocks and flows were calculated through a set of equations. A description of the phases and the main equations are provided in the following paragraphs (a diagram with the nomenclature is given in the Supporting Information). These include some equations from the original method and some new equations. The original method is available in the document "Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials" by BIO by Deloitte (2015), and in "Material System Analysis of Five Battery-Related Raw Materials: Cobalt, Lithium, Manganese, Natural Graphite, Nickel" by Matos, Ciacci, et al. (2020), where it is possible to find the description of the stocks and flows (there called "parameters") and a full explanation of the model. The applied methodology also considers the improvements presented by Matos, Wittmer, et al. (2020). The results are shown in metric tons (t).

2.1.1 | Mining and extraction

This phase refers to the domestic mining and the following extraction of primary Co from the environment toward the technosphere. It accounts for the extraction as the main product and/or as a byproduct, and the produced waste. A fraction of the primary domestic material is used in the EU, and the rest is exported. For this phase, the stock of the reserves and in tailings are provided. To calculate the Co stock of tailings ($B.1.5$) (metric tons), the following equation was used:

$$B.1.5 = \sum_{t}^{T} B.1.2 \cdot \frac{1 - \lambda_E}{\lambda_E} \tag{1}$$

where $B.1.2$ (metric tons) is the Co concentrate obtained in year t, T is the year of the assessment, and λ_E is the extraction efficiency. The stock was calculated based on historical data, considering the oldest registered production of Co concentrate in the EU.

2.1.2 | Processing

The input to the processing phase consists of primary and secondary domestically produced Co; and imports of primary, secondary, and semiprocessed material. Based on this input, processed material is produced. In function of the efficiency of the process, the processing waste is also estimated. The processed material is further used in the EU or exported.

In the case of Co, the production of processed material ($C.1.1$) (metric tons) can be obtained from various open data sources, such as geological surveys. Using this data and Equation (2), the mass balance for this phase was closed, estimating the import of semiprocessed material.

$$C.1.1 = (B.1.2 - B.1.3 + C.1.3 + C.1.4 + C.1.8 + G.1.1) \cdot \lambda_P \tag{2}$$

where $B.1.3$, $C.1.3$, $C.1.4$, $C.1.8$, and $G.1.1$ are the export of primary material; the import of primary, secondary, and semiprocessed Co; and a fraction of the functionally recycled Co domestically produced (metric tons), respectively. The parameter λ_P corresponds to the average process efficiency.

2.1.3 | Manufacturing

This phase refers to the production of final products related to the different applications of the material. The embedded material is calculated based on the demand share of processed material between the various applications. This share is specific for the EU. The inputs of this phase

comprise domestic and imported processed material, and domestic and imported secondary material. It may also consider primary material and imports of products that need further manufacturing, although these were neglected in the case of Co. The produced waste (called new scrap) can be sent back to processing, be internally reprocessed, nonfunctionally recycled, or be disposed. The final products are domestically used or exported.

The manufacturing of applications was calculated using the following equation:

$$D.1.1_i = (C.1.1 - C.1.2 + D.1.3 + D.1.9 + G.1.2) \cdot \lambda_M \cdot \alpha_i \tag{3}$$

where $D.1.1_i$ is the manufactured amount of application i (metric tons); and $C.1.2$, $D.1.3$, $D.1.9$, and $G.1.2$ are the export of processed material, the import of processed and secondary material, and a fraction of the functionally recycled Co domestically produced (metric tons), respectively. The parameter λ_M corresponds to the average manufacturing efficiency and α_i to the manufacturing share demand of application i.

2.1.4 | Use

The in-use stock and the stock of EoL products are estimated in the use phase, considering the annual addition to both stocks. It is assumed that finished products enter the use phase in the same year of production. The phase considers the use of domestically produced products and imported ones. Parameters such as the lifetime, the hoarding rate, and the hoarding period of each application are required for this phase. Hoarding (Dewulf et al., 2021; Haig et al., 2011; Sarigöllü et al., 2020) refers to the dead storage of a product that is no longer in use, for example, an old mobile phone kept in the attic. This concept is also known as hibernation (Inghels & Bahlmann, 2021; Rizos et al., 2019; Wilson et al., 2017); nevertheless hibernation is a broader concept since materials can also hibernate at companies (stock piling), in landfills, in tailings, whereas hoarding is hibernation at the user (Dewulf et al., 2021; van Oers et al., 2020). The hoarded products conform the stock of EoL products.

The in-use stock ($E.1.1$) (metric tons) and EoL stock ($E.1.2$) (metric tons) were calculated per application i with the following equations:

$$E.1.1_i = (D.1.1_i + E.1.4_i - D.1.2_i) \cdot \left(\frac{1 - \left(\frac{1}{1+G_i} \right)^{l_i}}{1 - \frac{1}{1+G_i}} \right) \cdot (1 - \varkappa_i) \tag{4}$$

$$E.1.2_i = (D.1.1_i + E.1.4_i - D.1.2_i) \cdot \left(\frac{1}{1+G_i} \right)^{l_i} \cdot \left(\frac{1 - \left(\frac{1}{1+G_i} \right)^{h_i}}{1 - \frac{1}{1+G_i}} \right) \cdot \vartheta_i \cdot (1 - \varkappa_i) \tag{5}$$

where $E.1.4_i$ and $D.1.2_i$ are the import and export of application i in year T (metric tons); G is the annual growth rate of the consumption of application i; l and h are the lifetime and hoarding time of application i (years); and $\varkappa$ and ϑ are the in-use dissipation rate and hoarding rate of application i, respectively. This approach assumes that G cannot be zero, that is, there is an increase or decrease of the consumption.

The losses of this phase are related to the in-use dissipation of the products (i.e., material flows that are not accumulated into anthropogenic stocks, and a lack of collection prevents any form of recovery at EoL) (Ciacci et al., 2015). It can happen because the function of the product is intentionally dissipative (e.g., medicines or vitamins) or because of the wear of the product (e.g., hard metals).

2.1.5 | Collection

When the products reach their EoL after use or hoarding, they are collected. The collected waste (also known as old scrap) can be exported or be domestically treated. The treatment considers recycling (via selective collection) or disposal (via nonselective collection) of the waste domestically collected and imported.

The flow of EoL products collected for treatment ($E.1.6$) (metric tons) was calculated per application as follows:

$$E.1.6_i = (D.1.1_i + E.1.4_i - D.1.2_i) \cdot \left(\frac{1 - \vartheta_i}{(1+G_i)^{l_i}} + \frac{\vartheta_i}{(1+G_i)^{l_i+h_i}} \right) \cdot (1 - \varkappa_i) \cdot (1 - \psi_i) \tag{6}$$

where ψ_i is the export rate of EoL products of application i.

2.1.6 | Recycling

The last phase is recycling. It may consider pretreatment followed by the recycling process itself. The collected old scrap for recycling can be functionally or nonfunctionally recycled (functional recycled and nonfunctional recycled are hereinafter referred to as FR and NFR, respectively). The FR material is sent back to processing, to manufacturing, or can be exported. Depending on the products, different recycling processes can be applied. Based on the efficiency of the involved processes, the waste is also estimated.

The landfill stock ($F.1.5$) (metric tons) was calculated considering the waste produced due to the inefficiency of the processes and the nonselective collection. The NFR stock ($G.1.6$) (metric tons) considers the nonfunctional recycling of new and old scrap. The equations used for the calculation are:

$$F.1.5 = \sum_{i}^{n} (D.1.4_i + F.1.3_i + G.1.5_i) \cdot \left(\frac{1 - \left(\frac{1}{1+G_i}\right)^f}{1 - \frac{1}{1+G_i}} \right) + C.1.5 \cdot \left(\frac{1 - \left(\frac{1}{1+G^*}\right)^f}{1 - \frac{1}{1+G^*}} \right) \tag{7}$$

$$G.1.6 = \sum_{i}^{n} (D.1.11_i + G.1.4_i) \cdot \left(\frac{1 - \left(\frac{1}{1+G_i^*}\right)^b}{1 - \frac{1}{1+G_i^*}} \right) \tag{8}$$

where n is the total number of applications; $C.1.5$, $D.1.4$, $F.1.3$, and $G.1.5$ are the waste produced during processing, manufacturing, (nonselective) collection, and recycling in year T (metric tons); f is the period that the material has accumulated in the landfill (years); G^* is the average annual growth rate of all processed material consumption; $D.1.11$ and $G.1.4$ are the NFR material from new and old scraps in year T (metric tons); and b is the timespan considered appropriate for the calculation of the NFR stock (years). The latter depends on historical data about the production and consumption of the studied material.

2.2 | Cobalt commodities and applications

The MSA method was applied to estimate the stocks and flows of Co in the technosphere. A number of commodities containing Co were considered in the study, classified as primary, secondary, semiprocessed, and processed material. Primary material refers to mined Co and includes Co mined as the main product and as a byproduct from nickel and copper ores. Secondary material refers to Co sourced from secondary sources (e.g., waste and scrap). Semiprocessed material refers to materials that are not fully processed (e.g., crude oxides and hydroxides, and Co–Ni mattes). In this case, they need to be further processed at the processing phase in order to obtain refined (processed) Co. Processed material refers to refined Co obtained from the processing phase in the form of Co metal (e.g., Co powder) or Co compounds (e.g., Co chlorides), which are used in the manufacturing of final products.
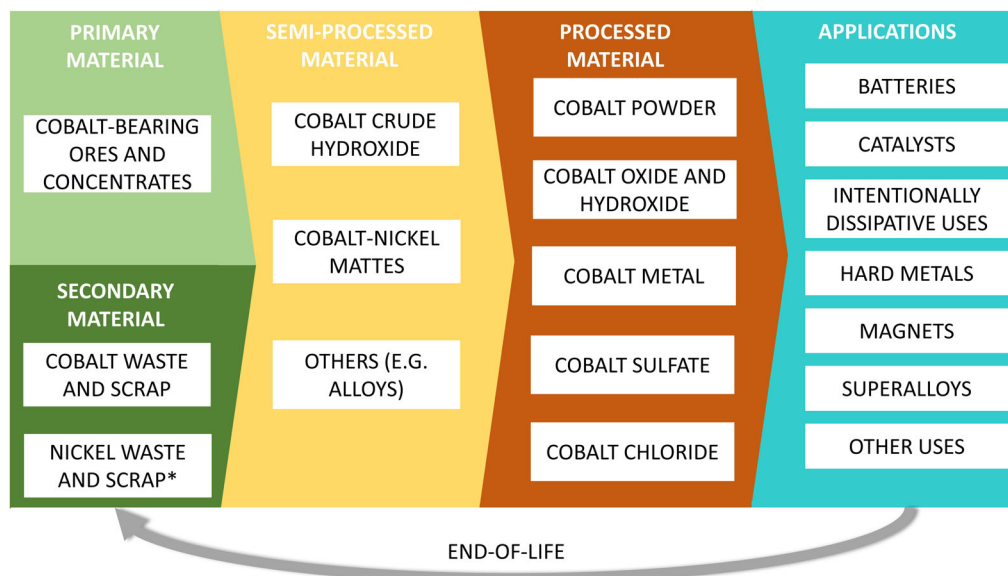
Two commodities were considered as secondary material: Co waste and scrap and Ni waste and scrap originating from superalloys. The latter can contain about 4% of Co (see the Supporting Information).

In addition, the Co contained in final products was studied. These products were categorized into seven high-end applications: Batteries, catalysts, intentionally dissipative uses (modeled mainly as pigments), hard metals, magnets, superalloys, and other uses (e.g., tool steels) (Figure 1). Three subcategories were studied for batteries: Portable batteries, industrial batteries, and mobility batteries (including e-bikes). The focus was on Co-bearing rechargeable batteries. In the case of catalysts, three subcategories were studied: For hydroprocessing, for hydroformylation, and for the production of polyester (PET) precursors. For intentionally dissipative uses, the focus was on pigments. A description of these applications can be found in Godoy León and Dewulf (2020). The Co that is NFR ends up in stainless steel, which is not considered a high-end application of the metal.

The Co-containing commodities and applications considered in the study are listed per life cycle phase in the Supporting Information. It also indicates to which classification they belong (see Figure 1), and their PRODCOM and Combined Nomenclature (CN) codes.

2.3 | System boundaries and temporal coverage

The flows and stocks of Co were assessed for the EU between 2012 and 2016. The calculations were made per year. The year 2016 was chosen as the most recent year for the assessment since it had the most complete dataset (information on more recent data is provided in the paper about the multilayer system assessment) at the moment of the study. The analysis was done for the EU plus the UK, as the EU still was composed of

FIGURE 1 Classification of the commodities and applications containing Co. The commodities were classified as primary, secondary, semiprocessed, and processed material. The applications consider seven categories. Co-bearing ores and concentrates include Co mined as the main product and as a byproduct of nickel and copper mining. * Nickel waste and scrap originating from superalloys

28 member states in the considered time span. Given the current transition of the EU, a short discussion will be given about the impact of Brexit on the results. The dataset for the EU without the UK is available in the Supporting Information.

The scope of this research considers a complete analysis for 2016, regarding Co's production, trade, and stocks according to the different commodities and applications containing the metal. The aim was to better understand the Co cycle for the most recent assessment year, giving special attention to EoL and recycling flows. In addition, the evolution of the flows over time was assessed between 2012 and 2016 to examine the trends of the cycle along these 5 years.

2.4 | Data and assumptions

Two approaches were applied for the data acquisition and following calculations. A bottom-up approach was used for the steps of extraction and processing, since data on production and trade was reasonably available and it was possible to estimate the Co content due to the limited number of commodities involved at these steps in the EU. A top-down approach was applied for the manufacturing and following steps, mostly because of the large number of semifinished and finished products, data gaps regarding the flows of specific products, and the lack of data related to their material content. Here, a brief description of both approaches is given. An exhaustive explanation of both approaches is available in BIO by Deloitte (2015).

Data about the produced material of the extraction and processing phases was obtained directly from various open data sources, such as geological surveys (bottom-up approach). The main consulted sources were the British Geological Survey (BGS, 2020), the US Geological Survey (USGS, 2020), and the Austrian Federal Ministry of Sustainability and Tourism (BMNT, 2019). The stock of tailings was calculated through Equation (1) using the data of BGS, considering the oldest registered production of Co in Finland (which corresponds to production in 1970). The trade was obtained for specific compounds from the Eurostat database (Eurostat, 2019). The trade statistics for semiprocessed Co was incomplete since no data was reported for some key countries such as Finland. However, using data from the UN Comtrade database (UN Comtrade, 2019) and the Finnish customs database (ULJAS, 2019), it was possible to estimate a trade balance for semiprocessed Co, in order to close the mass balance between the extraction phase and the processing phase.

From the manufacturing phase to the recycling phase, the flows and stocks were calculated based on trade statistics of finished products, average lifespan of products, and collecting and recycling practices (top-down approach). As in the previous phases, the Eurostat database was consulted for the trade. From the values provided by the database, the percentages of the import and the export of applications in relation to their domestic production were obtained. Based on these numbers and the manufacturing of applications calculated with Equation (3), the trade of applications was estimated. The manufacturing demand of Co per application was obtained from Roskill (2019).

Regarding the recycling phase, three recycling routes were considered: A chemical process for functional recycling, obtaining Co metal or a Co compound; the Zn process for functional recycling, obtaining W-Co powder; and a nonfunctional recycling process. The products recycled by the first route are batteries, catalysts, hard metals, and superalloys. The obtained material can be used to produce any of the cobalt-intended

applications described in section 2.2 (high-end applications). The Zn process is only used to recycle EoL materials classified under the application of hard metals for the production of new materials; and the nonfunctional recycling process is used for catalysts, hard metals, magnets, and other uses. The obtained material is used in the production of stainless steel (Godoy León & Dewulf, 2020). Given the purpose of this study, the recycling process routes were not analyzed in detail, as the model only requires the efficiency of the whole phase (shown in the Supporting Information). However, it is important to keep in mind that these routes consist of subprocesses. In the case of Li-ion batteries, for example, there is pretreatment that includes mechanical separation (applying crushing, shredding, sorting and sieving steps, magnetic separation and air separation methods), a thermal process (heating the samples at 150–500°C), a dissolution process (using solvents), and physical–chemical methods (using high-energy ball milling to induce physical and chemical changes of active materials). Functional recycling processes have been classified as hydrometallurgy-dominant methods, where valuable metals are separated by leaching, precipitation and solvent extraction; pyrometallurgy-dominant methods, where high temperature (higher than 1400°C) is used to enhance the physicochemical separation of valuable metals; and mild recycling methods, where hydrometallurgy-dominant and pyrometallurgy-dominant methods are integrated (Liu et al., 2019; Zhang et al., 2014).

For the calculation of the NFR stock, the UN Comtrade database was used as a reference. Based on its records about the trade of processed material and applications, which are from the late 1980s or early 1990s, a time span of 25 years was assumed to calculate the NFR stock (see Equation (8)). This assumption is in line with the trend of the refined global production of Co, which skyrocketed from 1993 onwards (BGS, 2020).

Several parameters per life cycle phase were required to calculate the stocks and flows along the value chain. Some examples are the extraction, processing, manufacturing, and recycling efficiencies; the lifetime, hoarding rate, hoarding period, and annual growth rate of consumption of the applications; and the collection and recycling rates of old scrap. Some of the values were obtained from or calculated based on private markets reviews, and others from scientific papers and public reports (Asari & Sakai, 2013; Baldé et al., 2017; Godoy León & Dewulf, 2020; Harper et al., 2012; Huisman et al., 2020; Nomura and Suga, 2013; thinkstep AG, 2017). In addition, due to the lack of data, some of the parameters were assumed based on expert estimations and some as hypotheses. These were made based on the assumptions considered in BIO by Deloitte (2015). In the Supporting Information, the value of the parameters together with the description of the assumptions is presented.

An updated database of the H2020 ProSUM project (Huisman et al., 2020; RMIS, 2019) was used to estimate the stocks and flows related to the manufacturing and use phases of batteries. The in-use stock and the EoL stock were provided aggregated, and it was not possible to further differentiate between one and another. For this reason, the in-use stock and EoL stock of Co are presented together in the results. Nevertheless, the ProSUM dataset integrates several data sources to get a comprehensive picture of the overall battery flows entering the European market. Data originating from Avicenne on the volumes of rechargeable batteries are combined with information sourced from Eurostat and European Alternative Fuels Observatory. These are linked with statistics from several national authorities as well as with the ProSUM data for batteries contained in electronic equipment. The data structure takes into account average battery lifetimes to calculate trends of the battery stocks and related waste-generation trends. It allows for a clear differentiation between electrochemical systems and battery applications of portable, industrial, and mobility batteries.

An overview of the inputs (data and assumptions) and outputs (calculated values) of the model per life cycle phase is given in the Supporting Information.

2.5 | Indicators

Six indicators were calculated to characterize the Co cycle in the EU: Total scrap recycling input rate (TS-RIR), old scrap ratio (OSR), end-of-life recycling rate (EoL-RR), recycling process efficiency rate (RPER), self-sufficiency potential (SSP), and pre-consumer loss rate (PCLR). The former four were obtained from UNEP (2011) (in UNEP (2011) the TS-RIR is named RIR), and Tercero Espinoza and Soulier (2018); the fifth one comes from Eurostat (2021); and the last one was developed by Matos, Ciacci, et al. (2020) to characterize the results of the Co system and the other four battery-related raw materials systems. These indicators are calculated due to their importance for the EU's policy. For example, the SSP and EoL-RR are part of the EU's monitoring framework for the circular economy (European Commission, 2018). Table 1 shows a brief description of the indicators. More details about the indicators and their equations are available in the Supporting Information and the paper about the multi-layer system assessment (Matos et al., 2021).

3 | RESULTS AND DISCUSSION

3.1 | Co cycle in the EU in 2016

Based on the dataset collected and the model's equations (see the Supporting Information), the Co cycle for the EU in 2016 was estimated, which is presented in Figure 2. The trade of commodities and applications is shown per life cycle phase. The stocks of Co are also presented, which include the stock of the reserves in the EU and the stocks of Co in-use and EoL products, tailings, landfills, and NFR material.

TABLE 1 Description of the indicators

Indicator	Abbreviation	Description
Total scrap recycling input rate	TS-RIR (RIR according to UNEP (2011))	It represents how much of the inputs to processing and manufacturing come from domestic and imported scrap, considering both new and old scrap.
Old scrap ratio	OSR	It describes the fraction of old scrap in the recycling flow of new and old scrap. It only considers functionally recycled scrap that is produced domestically.
End-of-life recycling rate	EoL-RR	It indicates how much of the collected old scrap is functionally recycled.
Recycling process efficiency rate	RPER	It gives the overall recycling efficiency rate, considering functional recycling of both old and new scrap.
Self-sufficiency potential	SSP	It indicates the amount of material going to the use phase that comes from domestic production. Domestic production includes primary material and secondary material produced by functional recycling of old scrap.
Pre-consumer loss rate	PCLR	It describes the losses that occur before the use phase.
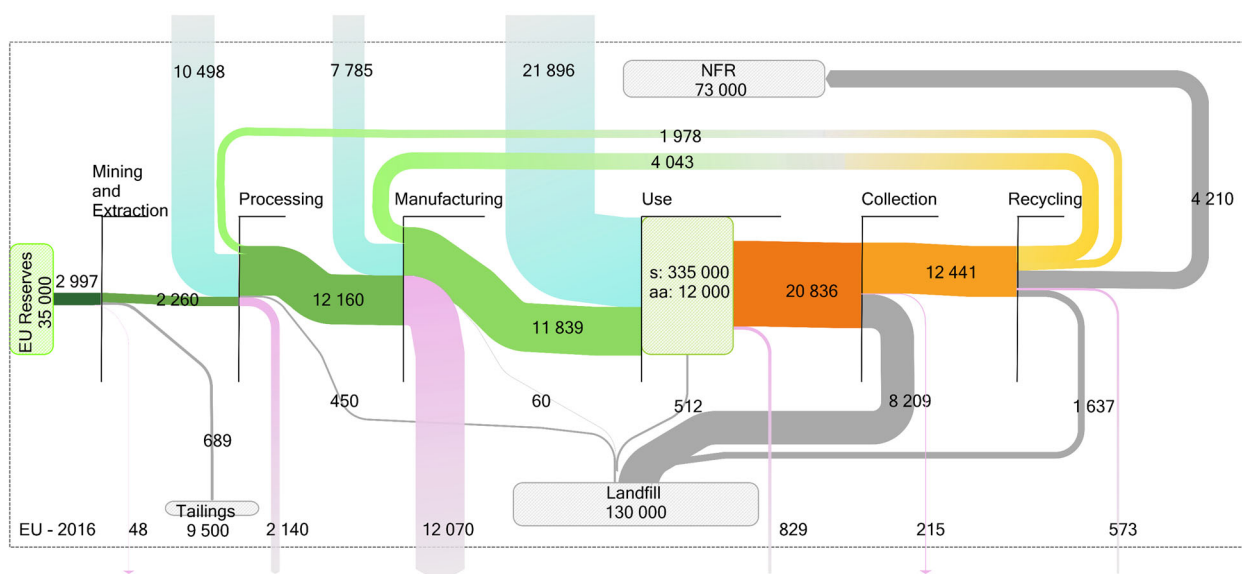
FIGURE 2 Co stocks and flows in the EU in 2016. Values are shown in metric tons (t). The trade is aggregated per lifecycle phase. Textured rectangles represent stocks. s: stock, aa: annual addition, NFR: non-functional recycled. Green: preconsumer flows within the system, orange/yellow: postconsumer flows within the system, light blue: imports, pink: exports, grey: waste. The width of the streams represents the magnitude of the flows. Because of this, flows with low content are barely depicted in the figure. Three streams are not shown due to their low contribution: the flow from manufacturing to the NFR stock (5 t), the flow from manufacturing to processing (14 t), and the import to collection (28 t)

In 2016, around 3000 t of primary Co were mined within the EU (specifically in Finland), and about 2300 t were extracted as Co concentrates. After considering imports of secondary material (400 t) and semiprocessed material (around 10,000 t), and adding up a fraction of the domestic FR material (1900 t), almost 15,000 t of Co were used for the production of processed material. This means that the domestic production of primary Co contributed only 16% to the processing input. Afterward, after considering the trade of secondary material (import of 400 t) and processed material (net import of 5600 t of Co) and the rest of the domestic FR material (4000 t), almost 24,000 t were used for the manufacturing of final products of the different applications. This phase was characterized by a high efficiency, as most of the waste was internally reprocessed. Accordingly, 23,800 t of Co ended up in final products, of which half was exported. The other half was domestically used, together with 21,800 t of Co imported in final products. About 33,700 t were put into use. Figure 2 shows an estimated stock of 334,000 t of Co for the use phase, which corresponds to the in-use stock plus the EoL stock. For most of the applications, these stocks were calculated separately through Equations (4) and (5). However, an aggregated stock (i.e., in-use + EoL) was obtained for batteries from ProSUM. Therefore, the stock presented in the figure also corresponds to an aggregated stock. The net annual addition to this stock was 12,000 t. After the use phase, about 21,000 t of Co in old scrap were collected for

further treatment. It was estimated that 60% went to recycling facilities through selective collection and 40% to disposal facilities through nonselective collection. The collected amount was calculated using Equation (6), which depends on the annual growth rates of the products' consumption (consider constant and different from zero between 2012 and 2016), and the manufacturing, import, and export flows of the applications of the assessed year. This is one of the limitations of the applied methodology, since it assumes that the production and trade of the applications in the past follows the same trend as in the present. Therefore, the dynamics of the market are not captured by the methodology, which could result in an overestimation or underestimation of the stocks. This is a considerable assumption, especially in the case of mobility batteries, for which the demand has increased considerably in the last years.

It is observed that the nonselective collection of old scrap represents one of the major losses of Co in the whole value chain, accounting for 52% of the total losses. Finally, from the recycling phase, 53% was FR, 34% was NFR, and 13% was disposed. From the FR Co, 30% was sent to processing, 61% to manufacturing, and the rest was exported.

The earlier-described flows and stocks are for the EU considering all its member states in 2016 (28 member states). However, an overall reduction in the amount of Co going into the EU economy is expected due to the departure of the UK. According to the BGS (Petavratzi et al., 2019), the manufacturing demand of Co in the UK was around 1500 t in 2017, which represents about 6% of the EU demand. The UK is not a producer of primary Co. It is a net importer of cobalt scrap and small quantities of ores and concentrates; and it is a net exporter of unwrought, wrought, and cobalt oxides. The metal is mainly used to produce superalloys for the aerospace sector, hard metal, magnet, and special steel industries. Co chemicals are mainly used by glass and ceramic manufacturers and, increasingly, in battery manufacture. Regarding the refining of Co, it is reported that Vale-owned nickel refinery at Clydach in South Wales processes nickel intermediates, which may contain Co (Petavratzi et al., 2019). However, cobalt is not recovered on-site during nickel's refining but outside the UK after an initial processing (Vale, 2018). In the Supporting Information (table S1), it is possible to observe how the departure of the UK from the EU affects the trade of Co-containing commodities. It is observed that for 2016, the EU without the UK presents a higher import of primary Co, Co powders, Co oxides and hydroxides, and Co chlorides; and a lower import of secondary Co and Co sulfates. In terms of export, it is higher for primary and secondary Co, Co powders and Co sulfates; and lower for Co oxides and hydroxides and Co chlorides. Regarding the trade between the EU and the UK, it is observed that the UK was mainly an importer of Co powders from the EU. It was also an exporter of nickel waste and scrap and Co oxides and hydroxides. Depending on the commodity, Brexit affects the EU trade to different degrees. For example, for nickel waste and scrap, the import to the EU from the UK corresponded to 23% of the total import in 2016. In the case of the export of Co sulfates, only about 1% of the total EU export was to the UK.

3.1.1 | Co trade flows

As it was mentioned in Section 1, the presented research was developed in the context of a study commissioned by the European Commission and some information is considered sensitive, the reason why it is not disclosed in the manuscript. Actors in the value chain are few and this makes them reluctant to disclose market information. For this reason, the trade flows of Co are presented aggregated per lifecycle phase, and the analysis of the trade is presented per category and not per commodity.

The primary raw material used in the EU mainly was sourced domestically (the trade was almost negligible), which was used primarily within the region. Regarding secondary Co, the EU was neither a major importer nor exporter of this material.

It is observed that the EU is a net importer of semiprocessed and processed material. As mentioned before, imports of semiprocessed material were key in the EU Co cycle, as it was one of the main inputs of the processing phase. The imported processed material was also relevant in the cycle, corresponding to 31% of the total manufacturing input. In 2016, the leading exporter of semiprocessed material to the EU was the Democratic Republic of Congo. In the case of processed material, the main exporters to the region were the United States, Madagascar, Zambia, Norway, and Russia, accounting together for 68% of the total export to the region (Eurostat, 2019; UN Comtrade, 2019).

Finally, the largest share of the trade, for both imports and exports, corresponded to applications (about 22,000 and 12,000 t of Co, respectively). As presented in Table 2, superalloys, magnets, and portable batteries were the main imported applications; and superalloys and dissipative uses, the main exported ones. Overall, the EU was a net importer of most of the applications.

In regard to batteries, Table 2 presents the results for all the batteries that contain Co. Co imported in Li-ion batteries represents 90% of Co imported in all portable batteries, 81% of Co imported in all mobility batteries, and 100% of Co in industrial batteries. This demonstrates the dominant use of Co in Li-ion batteries in comparison with its use in other battery chemistries as Ni metal hydride.

3.1.2 | Anthropogenic Co stock

In 2016, the biggest stock corresponded to the in-use and EoL stock, which comprises (i) the Co embedded in products being used and (ii) the Co embedded in consumer-hoarded products. This stock was calculated using Equations (7) and (8) for all applications except for batteries, for which direct data from ProSUM (Huisman et al., 2020) was used. The use of this data allowed including in the analysis e-bikes (accounted in mobility

TABLE 2 Trade flows of Co per application in the EU in 2016

Application	Imported (metric tons Co)	Exported (metric tons Co)
Portable batteries	3600	0
Mobility batteries	890	440
Industrial batteries	310	0
Catalysts	280	280
Intentionally dissipative uses	450	1760
Hard metals	1330	440
Magnets	4830	420
Other uses	30	20
Superalloys	10,180	8720
Total	21,900	12,080
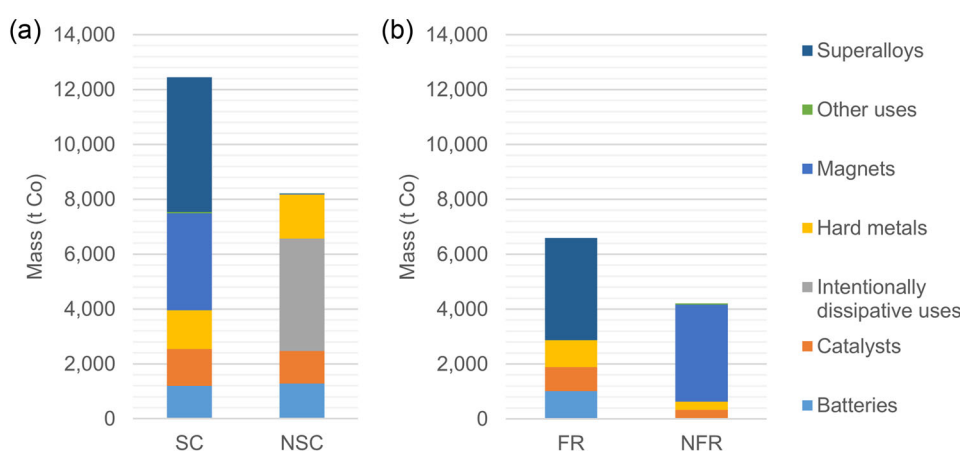
FIGURE 3 (a) Selective collection (SC) and non-selective collection (NSC) of Co per application in 2016. (b) Functional recycling (FR) and non-functional recycling (NFR) of Co per application in 2016. The applications refer to the source of scrap for recycling. Underlying data for this figure are available in Tables S10 and S11 of Supporting Information S2

batteries due to their low contribution) and industrial batteries, and it permitted to harmonize the data related to rechargeable batteries for all the involved raw materials (Co, Li, Ni, Mn, and natural graphite).

The main addition to the in-use and EoL stock in 2016 came from superalloys, magnets, and intentionally dissipative uses. On the one hand, the three applications are the main ones used in the EU (30, 18, and 17%, respectively, see the Supporting Information). On the other hand, compared to the other applications, they also have the longest lifetime (between 11 and 16 years, see the Supporting Information), staying longer in the use phase.

The in-use and EoL stock represents the potentially recoverable Co from the technosphere in the short-medium term (within 25 years, see Dewulf et al. (2021)). As such, it provided the main input to the recycling phase through selective collection. As shown in Figure 3, the main contributors to this flow were superalloys and magnets, followed by catalysts, hard metals, and batteries. Of the latter, 86% corresponded to portable batteries, 7% to mobility batteries, and 7% to industrial batteries.

3.1.3 | Co losses

The stocks of lost Co comprise the stock in tailings, landfills, and of NFR material. The former two correspond to the stock of Co that has been lost in the technosphere due to the inefficiency of the processes and the nonselective collection. The latter corresponds to the stock of Co that has been dissipated in the technosphere through nonfunctional recycling. According to Dewulf et al. (2021), metals present in these three stocks are most probably not recoverable in the short-medium term, but could be potentially recovered in the long term. According to the authors, the best estimate to recover materials from tailings and landfill is 65 years. In the case of NFR material, the best estimate is 500 years. Some of the main constraints to recover these materials are socio-economic and technological constraints. In the case of materials contained in tailings and

landfills, their inaccessibility arises from the lack of proper technology to make use of the materials (e.g., too low concentrations) or lack of interest in particular raw materials (e.g., co-occurring metals) at the point of their generation. In addition, economic recovery may be influenced by the spatial context and the presence of penalty elements. Related to Co, there are a few initiatives taking place. For example, the French Geological Survey (BRGM) developed a bioleaching technology for the reprocessing of sulfidic mine wastes, being applied at the Kasese tailings site in Uganda, where Co was produced from old copper mining waste tailings (Blengini et al., 2019). In the DRC, a project is under construction, which comprises the reprocessing of old Co and copper tailings from previous mining operations, with an annual capacity of 24,000 t of Co (Mining Weekly, 2018). In the case of NFR material, Dewulf et al. (2021) indicate that there is hardly any information on developments on economically viable technologies that are capable to recover particular raw materials or metals out of anthropogenic stocks.

Remarkably, the total losses in 2016 corresponded to 37% of the total input of Co to the system (considering imports and domestic production). Among the lost stocks, the landfill stock corresponded to the largest one in 2016, with the highest annual addition per year (about 10,000 t compared to 700 and 4000 t to the tailing stock and NFR stock, respectively). Its main contributor was the nonselective collection of old scrap, comprising almost 80% of the annual addition. Fifty percent of the nonselective collection flow corresponded to intentionally dissipative uses, as this application is not recycled. This application was modeled mainly as pigments, the reason why it is considered disposed at the end of its life and not dissipated in-use. The rest corresponded to hard metals (20%), batteries (15%, of which 95% was portable batteries), and catalysts (14%) (see Figure 3).

Even though landfills were the biggest lost stock, the stock produced by nonfunctional recycling was equally large, being the second main reason for Co losses in the technosphere (27% of the total losses). The main contribution to this stock is the nonfunctional recycling of old scrap.

Through nonfunctional recycling, cobalt ends up embedded in stainless steel at low concentrations. Currently, there is no technology available to recover Co from steel. Therefore, nonfunctional recycling of cobalt does not contribute to the circularity of the metal, the reason why here it is considered a loss. In fact, according to Dewulf et al. (2021), nonfunctional recycling is one of the six actions that leads to (long-term) inaccessibility of the metal.

This is one of the main findings of this work since previous assessments barely considered what is lost in the technosphere through nonfunctional recycling. From a policy perspective, to keep Co longer in the cycle, efforts should be concentrated not only in the collection phase with, for example, better take-back systems, but also in the recycling phase. Nowadays, collection and recycling targets in the EU are based on total mass and not on recovery rates of specific materials. This is the case, for example, for batteries and WEEE (waste electrical and electronic equipment). The target for batteries was to collect at least 45% in weight of the amount placed on the market by 2016, with a recycling of at least 50% by average weight (European Parliament, 2006). A new regulation concerning batteries and waste batteries is proposed by the European Commission, in which mandatory minimum levels of recycled content for industrial and electric-vehicle Li-ion batteries are set for 2030 and 2035 (e.g., 12% cobalt in active materials in those batteries as of January 1, 2030, increasing to 20% from January 1, 2035) (European Parliament, 2021). Recovery targets established per specific material would drive companies to improve their processes (and/or to invest in further research) in order to achieve them.

In addition, researchers should systematically consider nonfunctional recycling of Co in future assessments. To do so, it has to be taken into account that the share between functional and nonfunctional recycling varies over time, as materials are functionally or nonfunctionally recycled due to economic and/or technological constraints. For instance, to date there are no industrial facilities to recover Co from magnets (Liu & Chinnasamy, 2012; BRGM, 2018; CMI, 2018; UK Magnetics Society, 2018), although laboratory research continues to develop (Van Loy et al., 2020). In the case of superalloys, functional and nonfunctional recycling depends on the value of Co in the market (Glencore-Nikkelverk, 2018). In this study, it was assumed that superalloys are 100% FR, taking into account the increasing Co price since 2012 (Alves Dias et al., 2018).

Finally, it is observed that the NFR material in 2016 could have covered about 17% of the EU's manufacturing demand of the same year if replaced by functional recycling.

3.1.4 | Indicators

Six indicators were calculated to characterize the Co cycle. The calculated values are presented in Table 3. Focusing on 2016, it is observed that the input of scrap accounted for 45% of the total input to processing and manufacturing, which means that more than 50% of the input still comes from primary material. In addition, less than 40% of the input of scrap corresponded to old scrap, indicating that most of the recycled scrap is new scrap. If one considers only the input of old scrap (EoL-RIR), this value becomes 22% for the EU (without the UK) and 23% for the EU28 (Matos, Ciacci, et al., 2020). From the collected old scrap, only 32% became secondary material, as the rest was lost mostly due to nonselective collection and nonfunctional recycling. The nonfunctional EoL-RR corresponded to 20%, which explains why the RPER was 74%, even though the average recycling efficiency considered in the calculations was around 80% (see the Supporting Information, table S2).

When compared to the global cycle, several differences are noted. For instance, in the work of Sun et al. (2019) the global TS-RIR in 2015 corresponded to 11%, which means that the EU processed about four times the amount of secondary Co per refined product in a year. The UNEP reported in 2011 a value between 25% and 50% for the OSR and more than 50% for the EoL-RR (UNEP, 2011). The EU presents a matching value for the OSR

TABLE 3 Indicators of the Co cycle in the EU from 2012 to 2016

Indicator	Abbreviation	2012	2013	2014	2015	2016
Total scrap recycling input rate	TS-RIR	42%	42%	44%	45%	45%
Old scrap ratio	OSR	36%	36%	36%	37%	38%
End-of-life recycling rate	EoL-RR	33%	33%	29%	30%	32%
Recycling process efficiency rate	RPER	80%	79%	71%	72%	74%
Self-sufficiency potential	SSP	24%	27%	23%	24%	25%
Preconsumer loss rate	PCLR	4%	5%	3%	3%	4%

and a lower one for the EoL-RR. These differences could be explained by different geographical and temporal EoL practices; and due to differences in the share of the demand, as the recycling (and nonfunctional recycling) of Co depends strongly on it.

Remarkably, the nonfunctional recycling of Co has not received much attention in previous studies, the reason why it is difficult to compare our findings. To the best of the authors' knowledge, there are no other estimations of how much Co is dissipated via nonfunctional recycling at the EU level. At the global level, Harper et al. (2012) estimated that the NFR material corresponded to about 9% of the collected old scrap, about half of the value found in this study.

The SSP indicator shows that 25% of the material used by final consumers was domestically sourced, which means that 75% of this material was imported, exhibiting that the EU is highly dependent on imports of Co. In addition, this indicator can be calculated per phase. As shown in the Supporting Information, the highest SSP was for the processing and manufacturing phases, with values of 70% and 71%, respectively (values of this indicator for the EU without the UK are reported in Matos, Ciacci, et al., 2020). In contrast, it corresponded to only 18% for extraction, indicating a high import reliance of the EU at the upstream stage of the value chain.

Finally, as shown in Figure 2, the preconsumer losses only represented a small fraction of the total losses.

3.2 | Evolution over time

Next to the assessment of the Co cycle in 2016, an analysis of the temporal behavior of the flows was performed. It is important to mention that most of the parameters (such as the share of the Co demand for the manufacturing of applications) were considered constant in time in the calculations. Figure 4 represents the Co flows from 2012 to 2016. Figure 4a shows the annual input flow of Co to each one of the analyzed lifecycle phases (extraction, processing, manufacturing, use, collection, and recycling). In general, the flows increased over time, except from 2014 to 2015 where a rather small decrease is observed. An increase of almost 50% from 2012 to 2013 is observed for domestic extraction. However, after 2013, the flow stayed relatively constant, with an average content of 2800 t of Co per year. In contrast to the extraction phase, the input flows to the other phases do not present a substantial change from 2012 to 2013 (less than 10% difference). However, they exhibit a significant increase from 2013 to 2014, mainly in the recycling phase (72% higher), collection phase (59% higher), and use phase (52% higher). The main reason for this increase was a higher import; 40% higher than in 2013, with the exports increasing only 17%. The growth of the imports was mainly due to the higher import of applications (52% higher), semiprocessed material (39% higher), and processed material (28% higher). Among the applications, magnets and hard metals presented the highest rise (308 and 62%, respectively).

According to Sinha et al. (2017), recent advances in defense and aerospace have escalated the demand for SmCo magnets, which could explain the enormous increase in the imports and the domestic production of magnets. According to a previous study (Godoy León et al., 2020), the manufacturing Co demand for magnets in 2012 was 1.6% of the Co demand in the EU. This means that between 2012 and 2016, the demand increased on average 42% per year, considering a demand in 2016 of 6.6% (see the Supporting Information).

There was a decrease in the flows between 2014 and 2015. The main reason for this decrease is a lower import of semiprocessed material (26% lower compared to the previous year). From 2015 to 2016, there was an increase in the flows, proportional to the decrease between 2014 and 2015. Again, this was due to the import of semiprocessed material. A possible explanation of this variation is the fluctuation of the Co price in the market (around US$27, US$34, and US$24 per thousand metric tons, in 2014, 2015, and 2016, respectively) (Alves Dias et al., 2018). Years with low prices may imply a stocking period by the industry (built by imports) and a year with high prices a destocking period.

The preconsumer stages present a shift of the imports, from primary material to semiprocessed and processed material, which indicates that between 2012 and 2016, the EU became more dependent on imports in later stages of the supply chain. Imports decreased by 99.7% for primary material, from around 700 t in 2012 to about 2 t in 2016, and imports of semiprocessed and processed materials increased by 31% in the same period 2012–2016, from around 13,000 t in 2012 to about 17,000 t in 2016.

Figure 4b shows the evolution over time of functionally and nonfunctionally recycled Co. Overall, both flows have increased over time. The annual change of the FR Co occurred at a similar rate to that of the input flow to the use phase presented in Figure 4a. The NFR Co, however, presented a
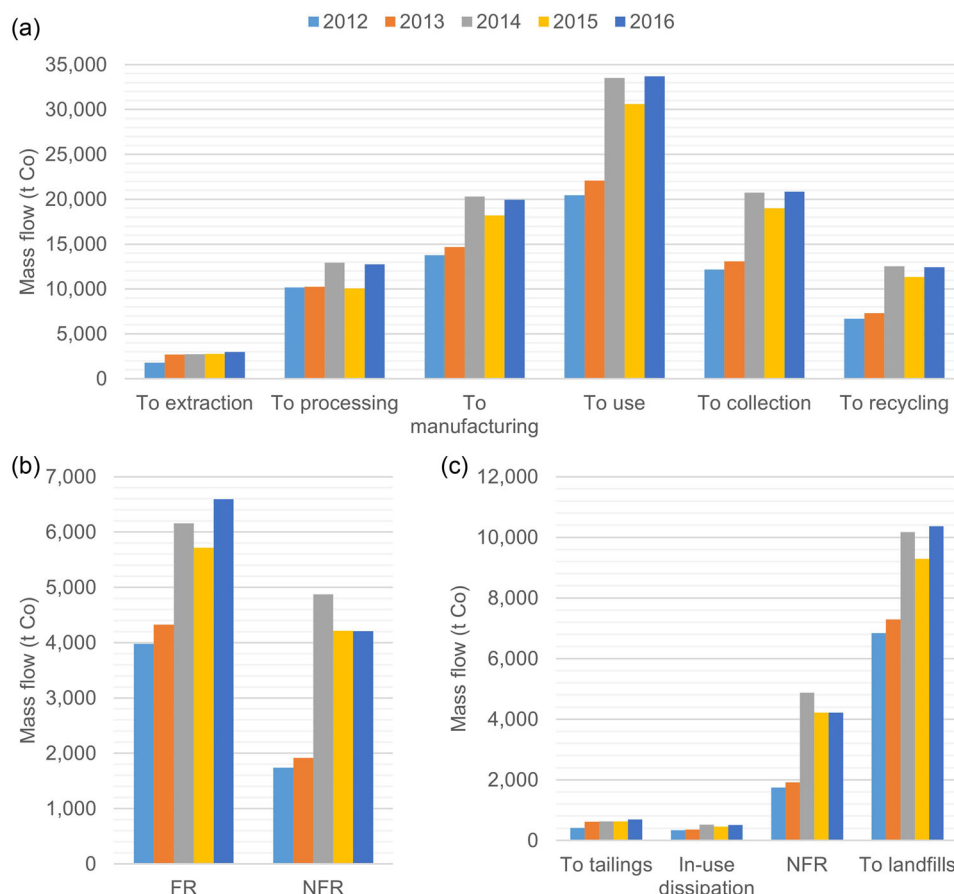
FIGURE 4 Evolution between 2012 and 2016 of the mass flows of Co in the EU. (a) Co flow to the different phases of its life cycle. (b) Co functionally recycled (FR) and non-functionally recycled (NFR). (c) Losses of Co to tailings, due to in-use dissipation, due to non-functional recycling, and to landfills. Underlying data for this figure are available in Tables S12–S14 of Supporting Information S2

different behavior. The bigger change took place between 2013 and 2014. In 2014, a higher collection flow of magnets was estimated as the import of magnets for the use phase was higher. Therefore, the NFR Co also increased, as magnets are fully nonfunctionally recycled.

Finally, Figure 4c presents the evolution of the losses of Co. Regarding tailings, it is observed that the evolution of this loss is in line with the evolution of the input flow to extraction. The main change is between 2012 and 2013, where the losses increased 49%. The losses due to in-use dissipation evolved at a similar rate to that of the input flow to use, where the main change took place between 2013 and 2014. The applications that were lost in this way are catalysts and hard metals. As mentioned before, there was a substantial increase in the imports of hard metals between 2013 and 2014, which explain the higher amount of in-use dissipation. It is important to mention that intentionally dissipative uses were modeled mainly as pigments, the reason why this application was not dissipated during the use phase but assumed to be landfilled after its use. Finally, for the Co going to landfills, it is observed that the main variation occurred between 2013 and 2014, in line with the higher input of Co to the phases from processing to recycling.

This graph shows that despite the efforts to increase the recycling of EoL products, there is still a significant amount of Co lost in the techno-sphere, which has increased over time. Table 3 shows that the EoL-RR has been relatively constant in time, but the RPER has decreased between 2012 and 2016, mostly due to the higher amount of NFR Co. Therefore, improvements are required in order to reduce the lost flows, especially at the collection and recycling phases.

Another way to establish the changes between 2012 and 2016 is by comparing our results with the results obtained in the previous MSA (BIO by Deloitte, 2015). This comparison is provided in the Supporting Information (see figure S1).

3.3 | Limitations of the study

Despite the several improvements in the methodology and the inclusion of new aspects in the analysis, the earlier-mentioned results have to be considered carefully. The results from the manufacturing phase to the recycling phase have a high uncertainty mainly related to data availability

and quality. They are estimative, calculated based on average consumption growth rates, trade statistics of finished products, average lifetimes of products, and collection and recycling practices. This is driven by the fact that the available production and trade codes are highly aggregated. An increase in the resolution of these codes could improve the understanding of how the different Co materials and products are produced and traded.

Furthermore, the use, collection, and recycling phases rely considerably on assumptions due to data limitations. For example, several assumptions were considered for the applications intentionally dissipative uses, magnets, and other uses for the use phase. These assumptions mainly affect the calculation of the in-use and EoL stock. These applications cover about 35% of the Co embedded in finished products used in the EU, which means that the assumptions could have a high impact on the calculated stock. However, by modifying the values of the hoarding times and hoarding rates by 10%, 20%, and 30%, the in-use and EoL stock only varies between 1.1% and 4.6%.

In addition, the availability of data also affected the temporal coverage of this study. The most recent year of the study corresponds to 2016, depicting the Co societal metabolism of already 6 years ago. Nevertheless, it is important to keep in mind that the data collection for a certain year is time-consuming, and that 2016 was the year with the most complete dataset. Despite the time gap, the results of this study support the raw material policy development, and in the mid-term provide a basis for developing sustainable resource-management strategies. It is used, for example, in the criticality assessment, which is based on data from the recent past. It also provides useful information supporting other activities, such as the monitoring of the circular economy. The European Commission already commissioned a new MSA study, being developed between 2021 and 2022, covering data up to 2018 (European Commission, 2021).

Other limitations of the study arise from the applied methodology, the geographical coverage of the data, and the lack of consistency of the data when obtained from different sources (e.g., the USGS, BGS, and BMNT report different values of the mineral production). Further research is required especially for the latter, in order to compare data from different sources and identify the extent and reasons for their differences.

Many of the limitations found in this study (see the Supporting Information for further discussion of the limitations of the study) are not only of scientific nature but rather related to the (un)availability of information at national and international bodies. The availability is limited because of the complexity and the volume of information to be collected, in addition to economic interests that complicate the acquisition. For example, the high aggregation of trade codes in combination with the multitude of products in which cobalt is traded, as well as the lack of published information by the industry, were obstacles in obtaining more solid results.

It is clear that the Co cycle in the EU has undergone a significant change. Moreover, considering the recently launched European Green Deal (European Commission, 2019) and the current situation derived from the COVID-19 outbreak, it is expected to continue changing in the coming years.

4 | CONCLUSIONS

An MSA was applied to study the cobalt (Co) cycle in the EU between 2012 and 2016. A number of commodities of Co were considered in the study, classified as primary, secondary, semiprocessed, and processed material. In addition, seven final applications were studied: Batteries, catalysts, intentionally dissipative uses, hard metals, magnets, superalloys, and other uses.

The Co cycle of 2016 was quantified, describing the production, trade, and usage patterns of Co in the EU. It was found that the primary material extracted in the EU was almost fully used in domestic refining industries, and a significant share of semiprocessed and processed material was imported for the production of applications. Around half of this production was exported, and the rest was domestically used together with almost 22,000 t of Co imported in final products. This accounted for almost 34,000 t of Co that were put into use. With an EoL recycling rate of 32%, around 6600 t of Co were recovered from old scrap, both for domestic use and exports to non-EU countries. The main losses of the system were from nonselective collection and nonfunctional recycling of old scrap, which accounted for 52% and 27% of the total losses, respectively. The applications that mostly contributed to these losses were intentionally dissipative uses and magnets.

The flows of Co changed substantially from 2012 to 2016. For example, the input to the use phase increased by around 1.7 times. In addition, a shift of the imports is observed at the preconsumer stages, from primary material to semiprocessed and processed material. The import of primary material decreased more than 99% between 2012 and 2016, and the import of semiprocessed and processed materials increased around 31% in the same period.

The uncertainty of the study depends mainly on data quality and gaps. The estimates could be improved by developing more disaggregated trade codes and improved industry data (more transparent and available). Nevertheless, a number of improvements were introduced in this study compared to the predecessor study of 2015 (BIO by Deloitte, 2015). Two major differences are the introduction of magnets as one of the assessed applications, and the nonfunctional recycling of Co, not only at the EoL phase but also at the manufacturing phase. This was of high importance to better describe the Co cycle, as nonfunctional recycling is one of Co's main sources of losses.

The results can be an input for policymakers, industries, and researchers, contributing to the sustainable management of the metal in the EU. First, the estimated indicators are key in a circular economy, and the estimated values can be used, for example, in criticality assessment. Second, it is clear that collection targets should be higher, and that recycling targets should be established based on the recovery of single materials. This could help to increase the circularity of Co in the EU, decreasing the dependency on imported material. Third, the estimated secondary sources of

Co indicate a significant stock of the metal in landfills, which could be exploited in the future. This would also help decrease the dependence of the EU on third parties.

This study contributes to a better understanding of the Co cycle in the technosphere. Another publication (Matos et al., 2021) was developed from the presented results, using a multilayer system approach for Li-ion battery systems, involving Co and other four materials: Lithium, nickel, manganese, and graphite. This allows analyzing the links between the different materials and how their cycles can affect each other.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

ORCID

María Fernanda Godoy León 🄳 https://orcid.org/0000-0003-1073-1758

Cristina T. Matos 🄳 https://orcid.org/0000-0002-9890-5371

Fabrice Mathieux 🄳 https://orcid.org/0000-0002-7746-9929

Jo Dewulf 🄳 https://orcid.org/0000-0003-1870-4930

REFERENCES

Ait Abderrahim, A., & Monnet, A. (2018). *Report on major trends affecting future demand for critical raw materials.* (SCRREEN project, deliverable D2.2).

Akcil, A., Vegliò, F., Ferella, F., Demet, M., & Tuncuk, A. (2015). A review of metal recovery from spent petroleum catalysts and ash. *Waste Management, (New York, N.Y.), 45*, 420–433. https://doi.org/10.1016/j.wasman.2015.07.007

Alves Dias, P., Blagoeva, D., Pavel, C., & Arvanitidis, N. (2018). *Cobalt: Demand–supply balances in the transition to electric mobility.* Publications Office of the European Union. https://doi.org/10.2760/97710

Asari, M., & Sakai, S. (2013). Li-ion battery recycling and cobalt flow analysis in Japan. *Resources, Conservation and Recycling, 81*, 52–59. https://doi.org/10.1016/j.resconrec.2013.09.011

Baldé, C. P., Forti, V., Gray, V., Kuehr, R., & Stegmann, P. (2017). *The global e-waste monitor—2017* (116 p.). United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA).

BIO by Deloitte. (2015). *Study on data for a raw material system analysis: Roadmap and test of the fully operational MSA for raw materials.* Prepared for the European Commission, DG GROW.

BGS. (2020). *World mineral statistics data.* https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

Blengini, G. A., Mathieux, F., Mancini, L., Nyberg, M., & Viegas, H. M. (Eds.). (2019). *Recovery of critical and other raw materials from mining waste and landfills: State of play on existing practices.* Publications Office of the European Union. https://doi.org/10.2760/600775

BMNT. (2019). *World mining data.* https://www.world-mining-data.info/?World_Mining_Data

Bobba, S., Mathieux, F., & Blengini, G. A. (2019). How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. *Resources, Conservation and Recycling, 145*, 279–291. https://doi.org/10.1016/j.resconrec.2019.02.022

BRGM. (2018). Personal communication.

Buchert, M., Schüler, D., & Bleher, D. (2009). *Critical metals for future sustainable technologies and their recycling potential.* United Nations Environment Programme & United Nations University. 112.

Ciacci, L., Reck, B. K., Nassar, N. T., & Graedel, T. E. (2015). Lost by design. *Environmental Science & Technology, 49*(16), 9443–9451. https://doi.org/10.1021/es505515z

Ciacci, L., Matos, C. T., Reck, B. K., Wittmer, D., Bernardi, E., Mathieux, F., & Passarini, F. (2021). Material system analysis: Characterization of flows, stocks, and performance indicators of manganese, nickel, and natural graphite in the EU, 2012–2016. Manuscript submitted for publication.

CMI. (2018, June). Personal communication.

Cobalt Institute. (2020). *Ores containing cobalt.* https://www.cobaltinstitute.org/ores-containing-cobalt.html

Commonwealth of Australia. (2019). Australia's critical minerals strategy *(22 pp.). Department of Industry, Innovation and Science,* Australian Government.

Darton Commodities Limited. (2018). *Cobalt market review* (59 pp.).

Deetman, S., Pauliuk, S., van Vuuren, D. P., van der Voet, E., & Tukker, A. (2018). Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. *Environmental Science & Technology*, *52*(8), 4950–4959. https://doi.org/10.1021/acs.est.7b05549

Dewulf, J., Hellweg, S., Pfister, S., Godoy León, M. F., Sonderegger, T., Matos, C. T., Blengini, G. A., & Mathieux, F. (2021). Towards sustainable resource management: identification and quantification of human actions that compromise the accessibility of metal resources. *Resources, Conservation and Recycling*, *167*, 105403. https://doi.org/10.1016/j.resconrec.2021.105403

European Commission. (2017). Study on the review of the list of critical raw materials. Critical raw materials factsheets (515 p.). Prepared for DG for Internal Market, Industry, Entrepreneurship and SMEs Raw Materials. https://doi.org/10.2873/398823

European Commission. (2018). Measuring progress towards circular economy in the European Union—Key indicators for a monitoring framework (60 p.). Commission Staff Working Document. SWD(2018) 17 final.

European Commission. (2019). *The European green deal* (24 p.). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions.

European Commission. (2020). Critical raw materials resilience: Charting a path towards greater security and sustainability (24 p.). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

European Commission. (2021). *Horizon Europe—Work programme 2021–2022, 7. Digital, industry and space*. (511 p.).

European Parliament. (2006). *Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC.* (14 p.).

European Parliament. (2021). *New EU regulatory framework for batteries. Setting sustainability requirements* (9 p.).

Eurostat. (2019). *COMEXT database on production and trade of cobalt and related commodities and applications.*

Eurostat. (2021). *EU self-sufficiency for raw materials.* https://ec.europa.eu/eurostat/cache/metadata/en/cei_pc010_esmsip2.htm

Glencore–Nikkelverk. (2018). Personal communication.

Godoy León, M. F., Blengini, G. A., & Dewulf, J. (2020). Cobalt in end-of-life products in the EU, where does it end up? The MaTrace approach. *Resources, Conservation and Recycling*, *158*, 104842. https://doi.org/10.1016/j.resconrec.2020.104842

Godoy León, M. F., & Dewulf, J. (2020). Data quality assessment framework for critical raw materials: The case of cobalt. *Resources, Conservation and Recycling*, *157*, 104564. https://doi.org/10.1016/j.resconrec.2019.104564

Graedel, T. E., Allwood, J., Birat, J., Buchert, M., Hagelüken, C., Reck, B. K., Sibley, S. F., & Sonnemann, G. (2011). What do we know about metal recycling rates? *Journal of Industrial Ecology*, *15*, 355–366. https://doi.org/10.1111/j.1530-9290.2011.00342.x

Haig, S., Morrish, L., & Morton, R. (2011). Market flows of WEEE materials. Final Report into the Study of Market Flows of WEEE Materials, Including Development of a Mass Balance Model. WRAP.

Harper, E. M., Kavlak, G., & Graedel, T. E. (2012). Tracking the metal of the goblins: Cobalt's cycle of use. *Environmental Science & Technology*, *46*(2), 1079–1086. https://doi.org/10.1021/es201874e

Hatayama, H., & Tahara, K. (2014). Criticality assessment of metals for Japan's resource strategy. *Materials Transactions, JIM.*, *56*(2), 229–235. https://doi.org/10.2320/matertrans.M2014380

Huisman, J., Ciuta, T., Mathieux, F., Bobba, S., Georgitzikis, K., & Pennington, D. (2020). *RMIS—Raw materials in the battery value chain*. Publications Office of the European Union. https://doi.org/10.2760/239710

Inghels, D., & Bahlmann, M. D. (2021). Hibernation of mobile phones in the Netherlands: The role of brands, perceived value, and incentive structures. *Resources, Conservation and Recycling*, *164*, 105178. https://doi.org/10.1016/j.resconrec.2020.105178

Langkau, S., & Tercero Espinoza, L. A. (2018). Technological change and metal demand over time: What can we learn from the past? *Sustainable Materials and Technology*, *16*, 54–59.

Liu, J., & Chinnasamy, C. (2012). Rare earth magnet recycling. (Rare Earth Elements Workshop, Colorado, USA. Presentation).

Liu, C., Lin, J., Cao, H., Zhang, Y., & Sun, Z. (2019). Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review. *Journal of Cleaner Production*, *228*, 801–813. https://doi.org/10.1016/j.jclepro.2019.04.304

Lundhaug, M. C., Matos, C. T., Georgitzikis, K., Petavratzi, E., Mathieux, F., & Müller, D. B. (2021). Material system analysis: Mapping the flows and stocks of lithium in the EU, 2012–2016. Manuscript submitted for publication.

Matos, C. T., Ciacci, L. G., León, M. F., Lundhaug, M., Dewulf, J., Müller, D. B., Georgitzikis, K., Wittmer, D., & Mathieux, F. (2020). *Material system analysis of five battery-related raw materials: Cobalt, lithium, manganese, natural graphite, nickel*. Publication Office of the European Union. https://doi.org/10.2760/519827

Matos, C. T., Mathieux, F., Ciacci, L., Lundhaug, M. C., Godoy León, M. F., Müller, D. B., Dewulf, J., Georgitzikis, K., & Huisman, J. (2021). *Material System Analysis: A novel multi-layer system approach to correlate EU flows and stocks of Li-ion batteries and their raw materials*. Manuscript submitted for publication.

Matos, C. T., Wittmer, D., Mathieux, F., & Pennington, D. (2020). *Revision of the material system analyses specifications*. Publications Office of the European Union. https://doi.org/10.2760/374178

Minerals4EU. (2014). *European minerals yearbook*. http://minerals4eu.brgm-rec.fr/m4eu-yearbook/theme_selection.html

Mining Weekly. (2018). *ERG's Metalkol Roan Tailings Reclamation project, Phase I nearing completion*. https://www.miningweekly.com/article/ergs-metalkol-roan-tailings-reclamation-project-phase-i-nearing-completion-2018-12-07/rep_id:3650

Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Suh, S., Shigetomi, Y., & Oshita, Y. (2014). Global flows of critical metals necessary for low-carbon technologies: The case of neodymium, cobalt, and platinum. *Environmental Science & Technology*, *48*(3), 1391–1400. https://doi.org/10.1021/es4033452

National Research Council. (1983). Cobalt conservation through technological alternatives *(205 pp.)*. National Academy Press.

Neef, C., & Thielmann, A. (2018). *Preparatory study on ecodesign and energy labelling of batteries under FWC ENER/C3/2015-619-Lot 1 TASK 2 markets—For ecodesign and energy labelling*. Prepared for the European Commission, DG for Internal Market, Industry, Entrepreneurship and SMEs.

Nomura, K., & Suga, Y. (2013). *Asset service lives and depreciation rates based on disposal data in Japan* (29 p.). Economic Measurement Group Workshop Asia.

OECD. (2008). *Measuring material flows and resource productivity. Volume I. The OECD Guide*. OECD.

OTA. (1985). Strategic materials: technologies to reduce U.S. import vulnerability *(411 p.)*. U.S. Congress, Office of Technology Assessment.

Petavratzi, E., Gunn, G., & Kresse, C. (2019). *Commodity review: Cobalt*. British Geological Survey.

Rizos, V., Bryhn, J., Alessi, M., Campmas, A., & Zarra, A. (2019). *Identifying the impact of the circular economy on the fast-moving consumer goods industry. Opportunities and challenges for businesses, workers and consumers—Mobile phones as an example*. Prepared for the European Economic and Social Committee [EESC]. https://doi.org/10.2864/775626

Roskill. (2014). *Cobalt: Market outlook to 2018.*

Roskill. (2019). *A socio-economic analysis of the cobalt industry in the EEA, 2010–2017*. Summary report for the Cobalt Institute.

RMIS. (2019). *RMIS—Raw materials in the battery value chain*. European Commission. https://rmis.jrc.ec.europa.eu/apps/bvc/#/

RPA. (2012). *Study on data needs for a full raw materials flow analysis*. Final report prepared for DG Enterprise and Industry.

Sarigöllü, E., Hou, C., & Ertz, M. (2020). Sustainable product disposal: Consumer redistributing behaviors versus hoarding and throwing away. *Business Strategy and the Environment*, *30*(1), 340–356. https://doi.org/10.1002/bse.2624

Shedd, K. B. (1993). *The materials flow of cobalt in the United States* (31 p.). U.S. Bureau of Mines, Information circular 9350.

Sinha, M. K., Pramanik, S., Kumari, A., Sahu, S. K., Prasad, L. B., Jha, M. K., Yoo, K., & Pandey, B. D. (2017). Recovery of value added products of Sm and Co from waste SmCo magnet by hydrometallurgical route. *Separation and Purification Technology*, *179*, 1–12. https://doi.org/10.1016/j.seppur.2017.01.056

Sun, X., Hao, H., Liu, Z., Zhao, F., & Song, J. (2019). Tracing global cobalt flow: 1995–2015. *Resources, Conservation and Recycling*, *149*, 45–55. https://doi.org/10.1016/j.resconrec.2019.05.009

Tercero Espinoza, L. A., & Soulier, M. (2018). Defining regional recycling indicators for metals. *Resources, Conservation and Recycling*, *129*, 120–128. https://doi.org/10.1016/j.resconrec.2017.10.022

Tercero Espinoza, L. A., Loibl, A., Langkau, S., de Koning, A., van der Voet, E., & Michaux, S. (2019). *Report on the future use of critical raw materials*. SCRREEN project, deliverable D2.3.

thinkstep AG. (2017). *PEFCR—Product environmental footprint category rules on high specific energy rechargeable batteries for mobile applications* (104 p.). Prepared for the European Commission, DG Environment.

Tisserant, A., & Pauliuk, S. (2016). Matching global cobalt demand under different scenarios for co-production and mining attractiveness. *Journal of Economic Structures*, *5*(1), 4. https://doi.org/10.1186/s40008-016-0035-x

UK Magnetics Society. (2018, December). Personal communication.

ULJAS. (2019). Finnish customs database. International trade in goods statistics. https://uljas.tulli.fi/uljas/

UN Comtrade. (2019). *Database on production and trade of cobalt and related commodities*.

UNEP. (2011). *Recycling rates of metals—A status report*. A report of the working group on the global metal flows to the International Resource Panel.

USGS. (2010). *Mineral commodity summaries 2010: U.S. Geological Survey* (193 p.).

USGS. (2017). *Mineral commodity summaries 2017: U.S. Geological Survey* (202 p.). https://doi.org/10.3133/70180197

USGS. (2018). *Interior releases 2018's final list of 35 minerals deemed critical to U.S. national security and the economy*. https://www.usgs.gov/news/interior-releases-2018-s-final-list-35-minerals-deemed-critical-us-national-security-and

USGS. (2020). *Mineral commodity summaries 2020: U.S. Geological Survey* (200 p.). https://doi.org/10.3133/mcs2020

Vale. (2018). *Vale's production and sales in 2018*.

Van Loy, S., Önal, M. A. R., Binnemans, K., & Van Gerven, T. (2020). Recovery of valuable metals from NdFeB magnets by mechanochemically assisted ferric sulfate leaching. *Hydrometallurgy*, *191*, 105154. https://doi.org/10.1016/j.hydromet.2019.105154

van Oers, L., Guinée, J. B., Heijungs, R., Schulze, R., Alvarenga, R. A. F., Dewulf, J., Drielsma, J., Sanjuan-Delmás, D., Kampmann, T. C., Bark, G., Uriarte, A. G., Menger, P., Lindblom, M., Alcon, L., Ramos, M. S., & Torres, J. M. E. (2020). Top-down characterization of resource use in LCA: From problem definition of resource use to operational characterization factors for dissipation of elements to the environment. *The International Journal of Life Cycle Assessment*, *25*(11), 2255–2273. https://doi.org/10.1007/s11367-020-01819-4

Wilson, G. T., Smalley, G., Suckling, J. R., Lilley, D., Lee, J., & Mawle, R. (2017). The hibernating mobile phone: Dead storage as a barrier to efficient electronic waste recovery. *Waste Management*, *60*, 521–533. https://doi.org/10.1016/j.wasman.2016.12.023

World Bank. (2020). Worldwide governance indicators. http://info.worldbank.org/governance/wgi/index.aspx#reports

Zeng, X., & Li, J. (2015). On the sustainability of cobalt utilization in China. *Resources, Conservation and Recycling*, *104*, 12–18. https://doi.org/10.1016/j.resconrec.2015.09.014

Zhang, X., Xie, Y., Cao, H., Nawaz, F., & Zhang, Y. (2014). A novel process for recycling and resynthesizing $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ from the cathode scraps intended for lithium-ion batteries. *Waste Management*, *34*(9), 1715–1724. https://doi.org/10.1016/j.wasman.2014.05.023

Zimmermann, T. (2017). Uncovering the fate of critical metals: Tracking dissipative losses along the product life cycle. *Journal of Industrial Ecology*, *21*(5), 1198–1211. https://doi.org/10.1111/jiec.12492

Zimmermann, T., & Gößling-Reisemann, S. (2013). Critical materials and dissipative losses: A screening study. *Science of the Total Environment*, *461–462*, 774–780. https://doi.org/10.1016/j.scitotenv.2013.05.040

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