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RESEARCH AND ANALYSIS

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Material system analysis

Characterization of flows, stocks, and performance indicators of manganese, nickel, and natural graphite in the EU, 2012–2016

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Abstract

Raw materials form an industrial base to provide the wide range of products and services demanded by industry and society. In particular, manganese, nickel, and natural graphite are examples of materials having a globally consolidated supply chain with interlinked use in steelmaking and essential role in clean energy systems and e-mobility. A stable material supply chain is hence a priority for import-dependent regions like the EU and builds upon quantitative system understanding. To this aim, the EU Material System Analysis is applied to analyze the anthropogenic cycle of manganese, nickel, and natural graphite from 2012 to 2016. We provide a detailed characterization of their material stocks, flows, and changes in selected performance indicators including end-of-life recycling rate (51% ± 3%, 49% ± 8%, and 8% ± 0% for manganese, nickel, and natural graphite, respectively), self-sufficiency potential (40% ± 3%, 32% ± 5%, and 5% ± 1%), old scrap ratio (31% ± 0%, 22% ± 2%, and 90% ± 1%), recycling input rate (25% ± 1%, 38% ± 2%, and 3% ± 0%), recycling process efficiency rate (84% ± 2%, 85% ± 6%, and 48% ± 3%), and pre-consumer losses rate (83% ± 3%, 5% ± 1%, and 24% ± 2%). The achieved results may inform decision-makers engaged with raw materials recovery and recycling as well as the strategic securement of a reliable material supply to the EU for resilient industrial ecosystems.

KEYWORDS
anthropogenic cycle, battery raw materials, circular economy, industrial ecology, in-use stock, recycling rate

1 INTRODUCTION

1.1 Background and motivations

The Raw Materials System Analysis (MSA) was launched by the European Commission (EC) in 2012 within the context of the European Raw Materials Initiative's (RMI) designed to provide the data needed to inform policy ranging from the EU Raw Materials Scoreboard to EU Critical Raw Materials (CRMs) assessment, and EU trade negotiations. The initial MSA effort covered 28 raw materials relevant to the EU economy, which were selected based on the large quantities in which they are used as well as their role in special applications (BIO by Deloitte, 2015).

A recent follow-up assessment covered five "battery raw materials," namely lithium, cobalt, nickel, manganese, and natural graphite (Matos et al., 2020). They were chosen for their strategic relevance and increasing use in battery systems, essential for a transition to clean energy systems and the electrification of transportation systems. The manuscript series discussing the related outcomes consists of four papers, three of which focus on individual raw materials plus one paper applying a multi-material perspective to investigate flows and stocks of cobalt, lithium, manganese, nickel, and natural graphite in LIBs. As part of the battery raw materials manuscripts series (León et al., 2021; Lundhaug et al., 2021; Matos et al., 2021), this work discusses the MSA framework applied to manganese, nickel, and natural graphite.

The presence of manganese, nickel, and natural graphite is so wide and vital in modern technology that these materials got scores for the "Economic Importance" indicator higher than the threshold limit set by the EU for critical materials (European Commission, 2020). However, only natural graphite was estimated to have also a score for the "Supply Risk" indicator higher than the threshold for CRMs, although manganese's score lays closely to it and nickel was assessed to be "particularly susceptible to supply risk" (Thomas et al., 2018). This combination of increasing demand, essential role in strategic uses, and possible supply disruptions have raised concerns toward a sustainable demand for these raw materials. This vulnerability amplifies for EU countries due to their dependency on imports and it may determine rising of criticality scores in the medium–long term also for today's non-CRMs.

Being complementary to primary production, resource recovery and recycling at end-of-life are generally pointed out as key strategies to diversify resource supply, relieve import reliance, secure access to sustainable sources, and reduce elemental criticality potentials. In this view, secondary material sources, also known as anthropogenic stocks or in-use stocks, could secure sustainable resource supply to Europe and pursue closure of material cycles (European Commission, 2017). Improving resource efficiency in anthropogenic cycles is a priority due to limited recycling efficiency (e.g., natural graphite) or respectable but far from ideal recycling performance (e.g., manganese and nickel) generally reported for the raw materials targeted in this study (UNEP, 2011).

Spatial and temporal boundaries are essential constraints in setting strategies to secure reliable and sustainable access to raw materials. As each country or region has its own social, economic, and technological conditions, these developments require data gathering at specific geographical scales and assessment of the anthropogenic metabolism to identify and quantify accessible in-use stocks and flows of secondary materials at end-of-life. This information is a pre-condition for efficient reuse, recovery, and recycling, but it is hardly ever reported in statistics. A system understanding is hence crucial for the development of reliable and long-term strategies to secure future access to strategic raw materials and it comes through quantitative evaluations such as those provided by MSA.

1.2 Previous works and aims of this study

Methodically, MSA is a specific type of material flow analysis (MFA) (Brunner & Rechberger, 2004) as it applies the principle of mass conservation to identify and quantify flows and stocks of a target raw material in a system defined in space and time. However, MSA is wider in scope as it embeds own requirements related to filling of raw data, add-on calculation of stock and flows, fixed system boundary (i.e., the EU), and its results are systematically linked to the EU RMI tools and databases. Previous MFA studies have contributed to increase the knowledge about anthropogenic cycles of many resources. However, while most attention has been devoted to those metals used in the largest amounts like iron (Cullen et al., 2012; Müller et al., 2006; Ohno et al., 2014; Pauliuk et al., 2013), aluminum (Ciacci et al., 2014; Cullen & Allwood, 2013; Liu & Müller, 2013), and copper (Ciacci et al., 2020; Glöser et al., 2013; Graedel et al., 2004; Wittmer & Lichtensteiger, 2007), a few studies applied MFA techniques to characterize flows and stock of the targeted raw materials in EU, in particular adopting a temporal perspective (i.e., dynamic MFA). Reck et al. (2008) provided the first investigation of the anthropogenic nickel cycle at multiple geographical levels including the EU15 + Norway and Switzerland for the year 2000, which constituted the basis for a follow-up investigation (Reck & Rotter, 2012). Further MFA studies on nickel covered non-EU countries like Japan (Nakajima et al., 2013; Takeyama et al., 2016), China (Huang et al., 2014), Australia (Golev & Corder, 2016), and the world (Nakajima et al., 2018). To our knowledge, this work provides the first investigation of manganese flows and stocks in the EU, with previous material accounting studies mainly focusing at the global level (Elshkaki et al., 2018; Hagelstein et al., 2009; RPA, 2015; Sun et al., 2020) or for non-EU countries (Jeong et al., 2009; Jones, 2004; Nakajima et al., 2008). Lastly, natural graphite was included in the first EU MSA effort (BIO by Deloitte, 2015), which is the basis for further developments in this study.

The present study applies the MSA framework to the EU anthropogenic cycle of manganese, nickel, and natural graphite for the most recent years (i.e., 2012–2016). The overall framework and time span of investigation adopted in this work enabled a first estimate of material in-use stock and flows, which served as a quantitative basis to estimate performance indicators that may inform the pursuing of supply security for the targeted raw materials.

2 | METHODS

The MSA framework was initially defined and tested in 2015 (BIO by Deloitte, 2015), and further developed (Matos et al., 2020a). In its current version, the MSA framework covers the entire life cycle stages of a selected raw material and enables to determine the production of material in the EU, material stocks, losses and waste, trade of commodities and goods containing the target raw material (see Figure S1 and paragraph S1 in Supporting Information S1). While the same system boundaries and main life cycle phases apply to all MSA raw materials ensuring consistency and reproducibility, industrial stages and processes are differentiated on a single material basis to model the inherent characteristics of individual value chains. A general description of material flows and stock accounting in MSA is provided hereafter, while data sources employed in the modeling and limitations (i.e., data uncertainty and assumptions) of the study can be found at paragraph S2 in Supporting Information S1.

The system boundaries of this research are coherent with the formal definition of the EU Member States in 2012–2016 and consist of 28 countries. With the EU boundaries being administrative by definition, the list of EU Member State has evolved in the past and so it will in the future. At the time of writing, the United Kingdom has formally ceased to be an EU Member States and the Withdrawal Agreement that allows for a transition period is close to the end. It can be envisaged that the departure of United Kingdom from the EU (also known as "Brexit") will also have impacts on the life cycle and supply chains of materials. Without claiming to be exhaustive or absolutely predictive, we have attempted to highlight some possible implications of Brexit for the outcomes of this study and we provide in Supporting Information S1 a focus on import and export of commodities for the EU and the EU + UK for extraction and processing stages.

2.1 | Material flows accounting in MSA

The main life cycle phases include exploration of known and estimated reserves, (mine) extraction, processing (e.g., smelting and refining), manufacture (of semi-finished and finished products), use, end-of-life collection, and recycling. Historical information on production and consumption data of the targeted materials in commodities and finished products were gathered from geological bureaus (Minerals Intelligence Network for Europe, 2019; Reichl et al., 2018; USGS, 2015; USGS, 2019), official databases (Eurostat, 2020a, 2020b, 2020c; ProSUM, 2020; UN, 2020), industry statistics and associations reports (IMnI, 2013, 2020; ISSF, 2018; Nickel Institute, 2021a, 2021b; Recharge, 2017; UNEP, 2011; World Steel Association, 2017; Olivetti et al., 2017; BIO by Deloitte, 2015; RPA, 2015; Trinomics, 2018), expert surveys (Mistry & Chhabra, 2019), and the scientific literature (Biswal et al., 2015; Ciacci et al., 2015; Crundwell et al., 2011; Jeong et al., 2009; Matricardi & Downing, 2012; Norgate et al., 2007; Nuss et al., 2014; Passarini et al., 2018; Pauliuk et al., 2013; Reck & Rotter, 2012; Reck et al., 2008; Reidies, 2000; Wellbeloved et al., 2000; Kalyoncu and Taylor, 2014).

Trade statistics were used to identify and quantify imports and exports of the targeted raw materials between EU and world partners. A list of commodities, material forms, products, and scrap analyzed per phase is reported in Supporting Information S1, including the related material contents applied to convert total products' gross weight into amount of manganese, nickel, and carbon equivalent.

Finished products are assumed to enter the use phase in the same year of production. Residence time models are applied to simulate the accumulation of in-use stocks (see section 2.2) and generation of end-of-life products by main end-use application segment. Material flows collected at end-of-life split among those exported outside the EU or further treated in this region, in which they may (i) be sorted and separated for functional recycling, (ii) undergo non-functional recycling in other materials' cycle, or (iii) be lost through final disposal.

2.2 | Material stocks accounting in MSA

The MSA framework differentiates between geogenic and anthropogenic stocks. Geogenic or natural stocks are accounted for under exploration and comprehend proven reserves of the targeted raw materials. In contrast, anthropogenic stocks may include material accumulated in tailings, in landfills, and in use, which ultimately determines the total amount of end-of-life material generated that is theoretically recoverable.

The total amount of material in tailings is calculated as product of the average amount of each targeted raw material extracted from natural mines prorated annually for the last 20 years and assuming stationary average extraction process efficiency rates. Total stock in landfill is instead estimated as a function of processing waste for all types of materials supplied at the manufacturing phase and the related average annual growth rate as well

TABLE 1 List of performance parameters considered in this study

Indicator	Abbreviation	Short description
Total scrap recycling input rate	TS–RIR	It measures the fraction of total scrap input to recycling (i.e., new scrap + old scrap) over the total material input mining-to-manufacture in a given year
(Domestic) old scrap ratio	OSR	It measures the amount of old scrap as fraction of the total scrap (i.e., new scrap + old scrap) domestically processed in a given year
End-of-life recycling rate	EoL–RR	It measures the fraction of old scrap recycled over the total amount of old scrap generated in a given year
Recycling process efficiency rate	RPER	It measures the fraction of total recycled scrap (i.e., new scrap + old scrap) over the total scrap input to recycling in a given year
Self-sufficiency potential	SSP	It measures the amount of primary and secondary material input domestically supplied over the total inflow to use
Pre-consumer losses rate	PC–LR	It measures the fraction of total mining-to-manufacture material loss over the total inflow to use in a given year

Based on Graedel et al. (2011), Espinoza and Soulier (2018), UNEP (2011) and further developed.

as of manufacturing waste, end-of-life products, and recycling waste by end-use segment, and the average annual growth rate of consumption in that end-use segment. As for stocks in tailings, landfill stocks are also computed over the last 20 years as the maximum level.

For material in-use stocks two different approaches were followed, respectively, for rechargeable battery and non-battery applications. In-use stock of non-battery applications is computed using the MSA equations previously reported (BIO by Deloitte, 2015). The main explanatory parameters include inflow to use by application segment in the reference year, the related annual growth rate of (apparent) consumption, the in-use dissipation rate, the lifetime of each application segment, the rate of end-of-life products kept by users, the time during which those end-of-life products are kept by users, and the rate of end-of-life products exported for reuse. Stock and flows parameters used in MSA calculations for manganese, nickel, and natural graphite were gathered from several data sources (Eurostat, 2020a; IMnI, 2013; Jeong et al., 2009; Olivetti et al., 2017; Crundwell et al., 2011; Graedel et al., 2015; ISSF, 2018; Mistry & Chhabra, 2019; Passarini et al., 2018; Pauliuk et al., 2013; ProSUM, 2020; Recharge, 2017; Reidies, 2000; UN, 2020; Nickel Institute, 2021a, 2021b; Balde et al., 2015; BIO by Deloitte, 2015; Ciacci et al., 2015; Clark, 2016; Kalyoncu & Taylor, 2002; Norgate et al., 2007; Reck et al., 2008; Trinomics, 2018; Tsakalidis & Thiel, 2018; USGS, 2015) (see Supporting Information S1 for more details).

For battery applications, alignment with an update of data of the ProSUM project (ProSUM, 2020) was instead preferred as it provides an exhaustive dataset on battery flows at the use stage and because of the need of harmonizing the MSA results across the five targeted raw materials used in lithium-ions batteries (LIBs). More precisely, the ProSUM dataset included a review of the world market of battery types, cross checking of the battery chemistry according to the applications as well as changes in chemical compositions over time, a review of quantities placed on the market and their residence times in different uses. The ProSUM model calculated the batteries residing in stock and the expected waste generation in the EU according to four battery applications including portable batteries (i.e., portable PC, cellphones, tablets, cordless tools, cameras and games, and other portables), mobility batteries (i.e., hybrid electric vehicles, plug-in hybrid electric vehicles, and battery electric vehicles), e-bikes, and industrial batteries. For more details on the methodology, sources, and quality of data see Huisman et al. (2017).

2.3 | Performance indicators

Elemental information for manganese, nickel, and natural graphite generated by MSA were used to compute results for the set of performance indicators listed in Table 1. These six indicators, based on Graedel et al. (2011), Espinoza and Soulier (2018), UNEP (2011) and further developed in this study, provide measure of the contemporary resource efficiency in each raw material's cycle and pinpoint where the greatest efforts should be focused to approach securing sustainable demand and supply strategies. Accounting equations for the set of performance indicators are reported in Supporting Information S1.

3 | RESULTS

In this article, we investigate the industrial characteristics of the targeted materials through the analysis of material flows, performance indicators, and material stocks.

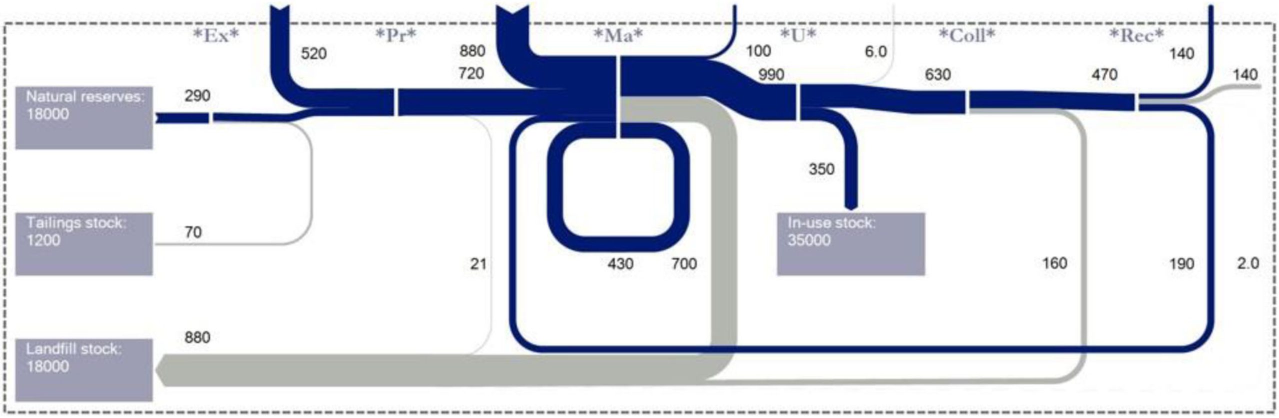

FIGURE 1 The anthropogenic manganese cycle in the EU in year 2016. All stocks and flows are expressed in kilo tons of manganese equivalent (kt Mn). Value chain manganese flows are in blue, manganese losses in grey. Coll, collection; Ex, mine extraction; Ma, manufacture; Pr, processing; Rec, recycling; U, use. Values may not match due to rounding

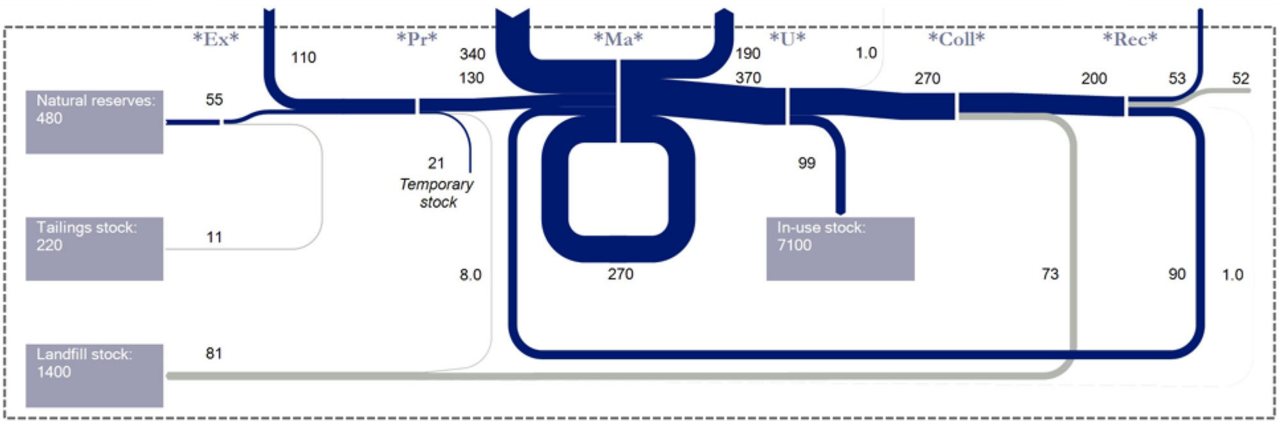

FIGURE 2 The anthropogenic nickel cycle in the EU in year 2016. All stocks and flows are expressed in kilo tons of nickel equivalent (kt Ni). Value chain nickel flows are in blue, nickel losses in grey. Coll, collection; Ex, mine extraction; Ma, manufacture; Pr, processing; Rec, recycling; U, use. Values may not match due to rounding

3.1 | Characterization of material flows and performance indicators

The contemporary (i.e., for year 2016) anthropogenic cycles for manganese, nickel, and natural graphite in the EU are depicted in Figures 1–3. The year 2016 was chosen as reference as it was the latest year available for the target materials. Values are expressed in amount (i.e., kilo tonnes [kt], 1 kilo tonne = 1 kt = 10^6 kg) of manganese (kt Mn), nickel (kt Ni), and carbon (kt C) equivalent, respectively. A detailed description of the anthropogenic cycles of manganese, nickel, and natural graphite in the EU is reported at paragraph S4 in Supporting Information S1.

Figure 4 shows, instead, flows of the main life cycle phases of manganese (4a), nickel (4b), and natural graphite (4c) for the five years analyzed. It is worth noting that Figure 4 includes only material mined in the EU in extraction. Similarly, flows to recycling and recycled materials refer only to old scrap sourced in the EU. The reason for focusing only on domestic flows is aiming at individuating hot spots in material cycles where EU strategies and policies may achieve the greatest impact to improve resource efficiency.

The three materials show a reverse V trend across the material life cycle that peaks in manufacture, reflecting the inherent EU's characteristic of being a main global producer of finished products. Mass flows profiles of manganese and nickel flows are quite similar, while some differences can be observed for natural graphite results. For the former two materials, the value chain is more distributed from extraction to end-of-life recycling, with inflow to manufacture being two to three times higher than other flows. From manufacture to use flows halved, while from use to recycling there is a constant decline, which in part reflects the losses occurring in these stages. In contrast, natural graphite's value chain is more concentrated from processing to collection. Domestic mining and end-of-life recycling is quite modest, with the EU consumption being mainly dependent on imports. Natural graphite processing is about as relevant as manufacturing due to preprocessing operations generally taking place at mine sites. Little reduction is detected from inflow to manufacture to that of use, while flows halve at end-of-life collection.

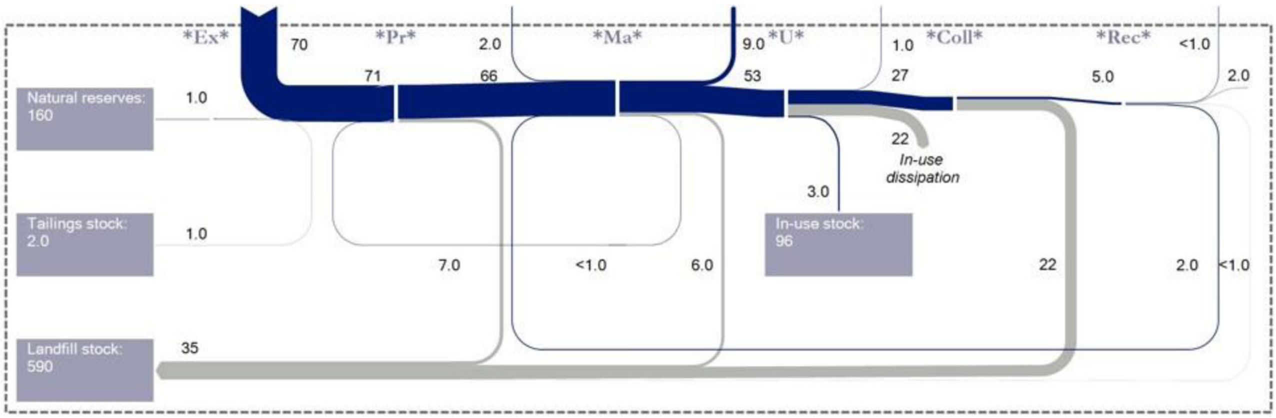

FIGURE 3 The anthropogenic natural graphite cycle in the EU in year 2016. All stocks and flows are expressed in kilo tons of carbon equivalent (kt C). Value chain carbon flows are in blue, carbon losses in grey. Coll, collection; Ex, mine extraction; Ma, manufacture; Pr, processing; Rec, recycling; U, use. Values may not match due to rounding

TABLE 2 2016 results of performance indicators for manganese, nickel, and natural graphite

Material\indicator	TS–RIR (%)	OSR (%)	EoL–RR (%)	RPER (%)	SSP (%)	PC–LR (%)
Manganese	25	31	51	84	40	83
Nickel	40	25	49	89	36	5
Natural graphite	3	90	8	48	5	24

Abbreviations: EoL–RR, end-of-life recycling rate; OSR, old scrap ratio; PC–LR, pre-consumer loss rate; RPER, recycling process efficiency rate; SSP, self-sufficiency potential; TS–RIR, total scrap recycling input rate.

Temporal variations are somewhat less significant for the time frame investigated in this study. For nickel, annual growth rates are positive for all flows, with the exception of input to manufacture. A similar trend is also detectable for manganese, for which also inflow to processing decreased over the time span. Natural graphite shows, instead, some fluctuations from year to year, in particular from inflow to processing to inflow to use.

A comparison with previous literature results for nickel in Europe aligns our results to those estimated by Reck et al. (2008). Despite different model assumptions (e.g., EU15 + Norway and Switzerland were covered by Reck et al. while the latter two countries are excluded from the EU-28 definitions considered in this study), the analysis of nickel flows revealed that the EU industrial network of nickel have likely stabilized in the last two decades and no big changes occurred in EU over the time span considered.

Although the EU's profile has maintained its features almost stationary, the global demand for nickel has increased remarkably since 2000s. The growth of Asian markets has certainly influenced the role of world countries in nickel value chain and expanded the demand for this metal in the anthroposphere. While at the beginning of the XXI century Europe and Asia each contributed about 35% of global nickel manufacture (Reck et al., 2008), in 2014 the EU's relevance reduced to 20% (Nickel Institute, 2021b). Nickel apparent consumption stabilized at about 400 kt Ni/year in the EU, attesting the same order of magnitude quantified previously (Nickel Institute, 2021a; Reck et al., 2008). In contrast, China's demand for nickel increased from about 200 kt Ni in 2000 to 1000 kt Ni in 2015 (Huang et al., 2014; Zeng et al., 2018).

For natural graphite, the results of this study update previous estimates for the EU (BIO by Deloitte, 2015) and provide a more detailed insight into carbon flows, with particular emphasis related to batteries and miscellaneous uses.

A lack of literature studies focusing on manganese flows in the EU prevents a comparison with our estimates. A recent study (Sun et al., 2020) investigated the global trade network of manganese: China dominates the global supply chain of manganese products, with France, Germany, and Italy being the only EU countries that stand out in the global ranking of manganese suppliers. These countries are the main top producer of crude steel (World Steel Association, 2017) in the EU and their total manufacture production was estimated at 990 kt Mn in Sun et al. (2020): a value that is relatively close to 1100 kt Mn estimated in this study for the whole EU. Sun et al. quantified the apparent consumption of manganese in the three countries at 480 kt Mn, which is about half of our estimate for the entire region.

Table 2 lists the results of the six performance indicators calculated for the year 2016, while Figure 5 shows 2012–2016 averages and the related standard deviations for the targeted materials. Annual results are reported in Tables S11–S13 in Supporting Information S1. While some variations in the magnitude of nickel flows may occur at given years, the ratios provided by the set of performance indicators is less sensitive to common annual variations occurring in the magnitude of resource flows so that 2012–2016 averages may be better representative of the contemporary anthropogenic cycle of the targeted materials in the EU.

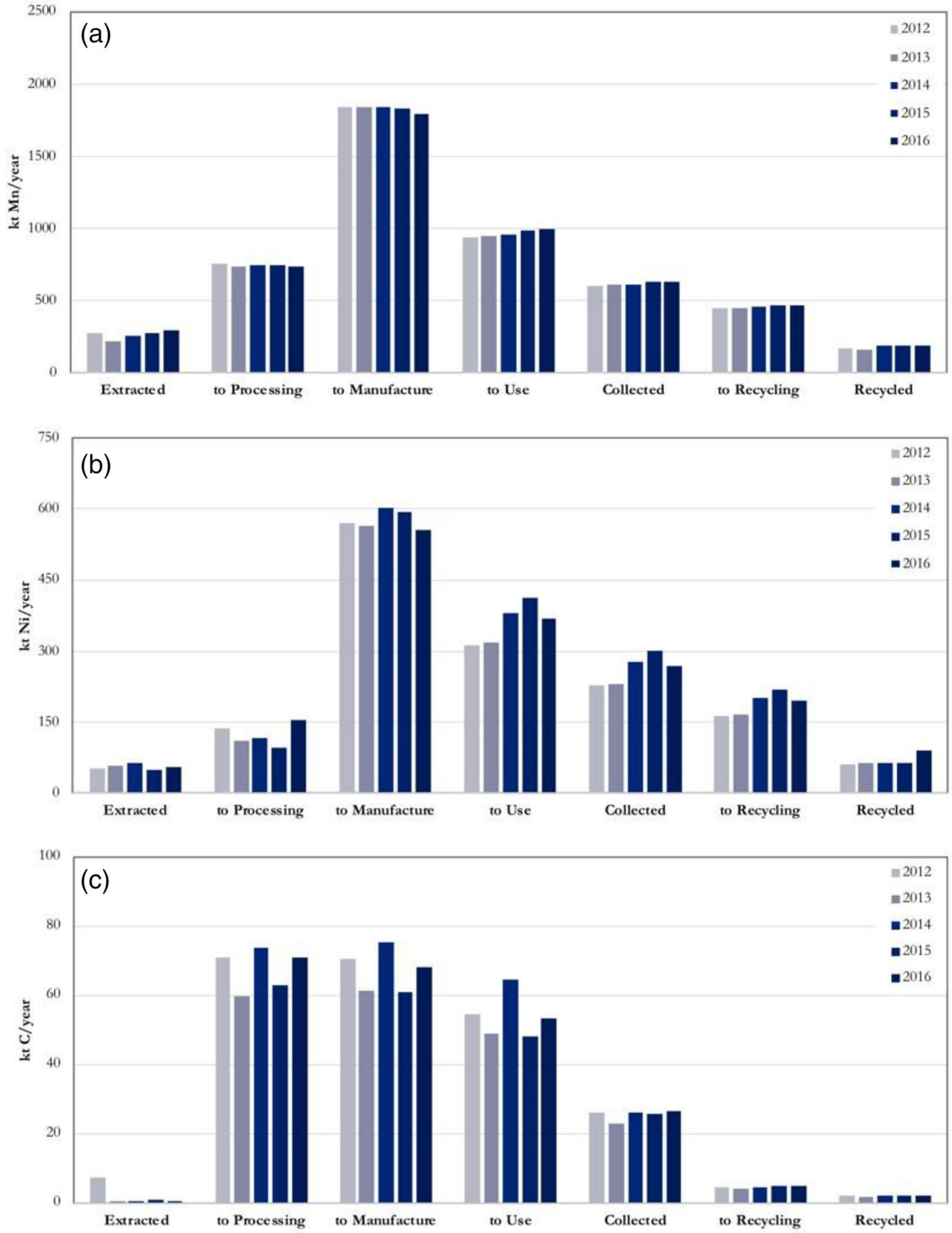

FIGURE 4 Evolution between 2012 and 2016 of the mass flows of (a) manganese, (b) nickel, and (c) natural graphite for the different phases of its life cycle. Underlying data for Figure 4 are available in Supporting Information S2

3.2 | Characterization of material stocks

Figure 6 shows a comparison between geogenic and anthropogenic stocks of manganese (6a), nickel (6b), and natural graphite (6c). Total material stocks (including both geogenic and anthropogenic reserves) resulted in about 71,000 kt Mn, 9200 kt Ni, and 860 kt C, respectively. Overall, material in-use stock is between two and four times (i.e., manganese and natural graphite) and 15 times (nickel) higher than the related natural deposits, and it constitutes the main reserve of manganese and nickel in the EU. For natural graphite, instead, landfills embed the largest domestic stock of inorganic carbon among those considered in this study.

Natural deposits in the EU are relatively marginal for nickel and natural graphite, but relevant for manganese (24% of total material stock). EU's reserves of manganese amount to 18,000 kt Mn, that is, less than 3% of global estimates (USGS, 2019). Nickel reserves are estimated to be around 480 kt Ni in the EU, approximately representing 1% of the world's nickel reserves (USGS, 2019). Natural reserves of graphite in the EU (approximately in the order of 160 kt C) are instead far below the global value of 250,000 kt C. Compared to manganese and nickel, which

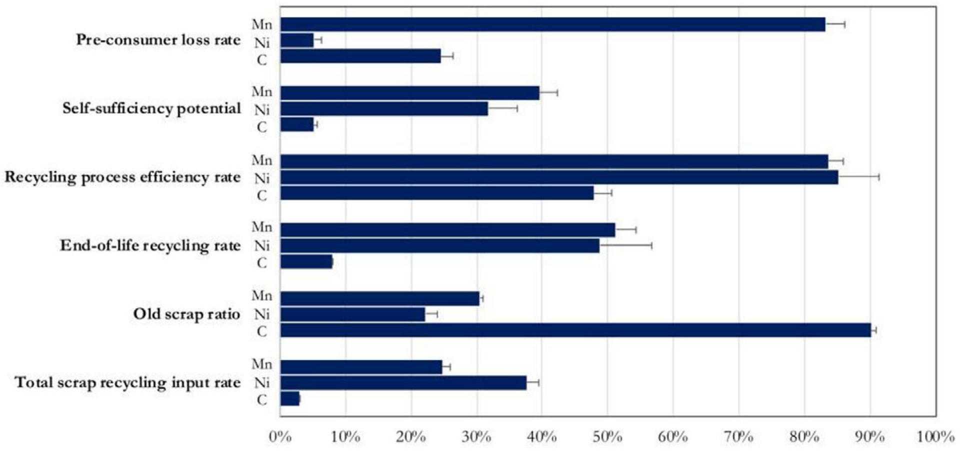

FIGURE 5 Performance indicators results for manganese (Mn), nickel (Ni), and natural graphite (C) in EU. Averages and standard deviations for 2012–2016. Underlying data for Figure 5 are available in Supporting Information S2

have a relatively distributed primary mineral extraction, natural graphite supply is highly concentrated (65% of world production) in China (USGS, 2019).

Material stock in tailings is estimated at 1200 kt Mn and 220 kt Ni for manganese and nickel, respectively, while it is negligible for natural graphite reflecting the mine production levels occurring in this region. The magnitude of landfill stock varies from 14% (nickel) to 81% (natural graphite), and ultimately provides a measure of the unsustainable characteristic of the linear economy model. Manganese stock in landfill amounts to 18,000 kt Mn: that is, it almost approximates the known domestic reserve of this raw material. Manufacture waste and slag largely constitute the main fraction of manganese stocks in landfill, followed by manganese from obsolete products, and processing waste. Nickel stock in landfill is quantified at about 1400 kt Ni, 90% of which is mainly constituted by end-of-life products, with the remaining part being processing waste. Landfill stock of natural graphite (i.e., 590 kt C) is mainly composed of end-of-life materials, while processing and manufacture waste contribute almost evenly for the rest.

In-use stocks of the targeted materials in the EU were estimated at 35,000 kt Mn, 7100 kt Ni, and 96 kt C, respectively. A sectoral breakdown for each elemental in-use stock is shown in Figure 6.

4 | DISCUSSION

4.1 | Secondary sources and potentials for material circularity

In general, a few applications cover the majority of the targeted materials accumulated in use: that is, building and construction, transportation and engineering products for manganese (in total, about 92% of its in-use stock) and nickel (72%), while refractories (56%) for natural graphite. These application sectors have relatively long useful lifespans and have embodied historically large material inflows to use, mainly driven by a consolidated and wide use of steel products in the anthroposphere. The demand for nickel and manganese is traditionally linked to steel alloys manufacturing, but interconnections with the steel cycle may be also extended to natural graphite considering (i) the predominant use of graphite-containing refractories in iron furnaces, steelmaking, and casting operations, and (ii) the use of natural graphite as a lubricant during sintering operation to form steel, pressing as well as carbon raising in steel products (Kalyoncu and Taylor, 2014).

Building and construction, transportation, engineering equipment, and refractories are also the main applications driving annual inflow to use of the targeted raw materials, although some stabilization has occurred in developed countries in recent years (Henckens & Worrel, 2020). This characteristic is likely dictated by the achievement of initial levels of iron products in-use saturation (Fishman et a. et al., 2015; Müller et al., 2011; Wiedenhofer et al., 2015) and it is enhanced by material efficiency strategies such as lightweighting of certain goods (e.g., vehicles) and product lifetime extension (Hertwich et al., 2019), which in the end influence material accumulation in use.

Compared to metallurgy uses, the battery market is evolving quickly, and it is highly competitive. In 2016, EU batteries demanded about 10% of total manganese processed, 2% of nickel manufactured, and 3% of natural graphite. The relative contribution of this sector to in-use stock accumulation is still marginal compared to more traditional uses of the targeted materials, but the overall trend is certainly increasing (Henckens & Worrel, 2020; Olivetti et al., 2017).

While comparing geogenic versus anthropogenic stocks may be relatively straightforward, implications for material supply and circularity are more complex. Improving mining, smelting, and refining efficiencies may increase primary material inputs to the EU industry and the SSP results

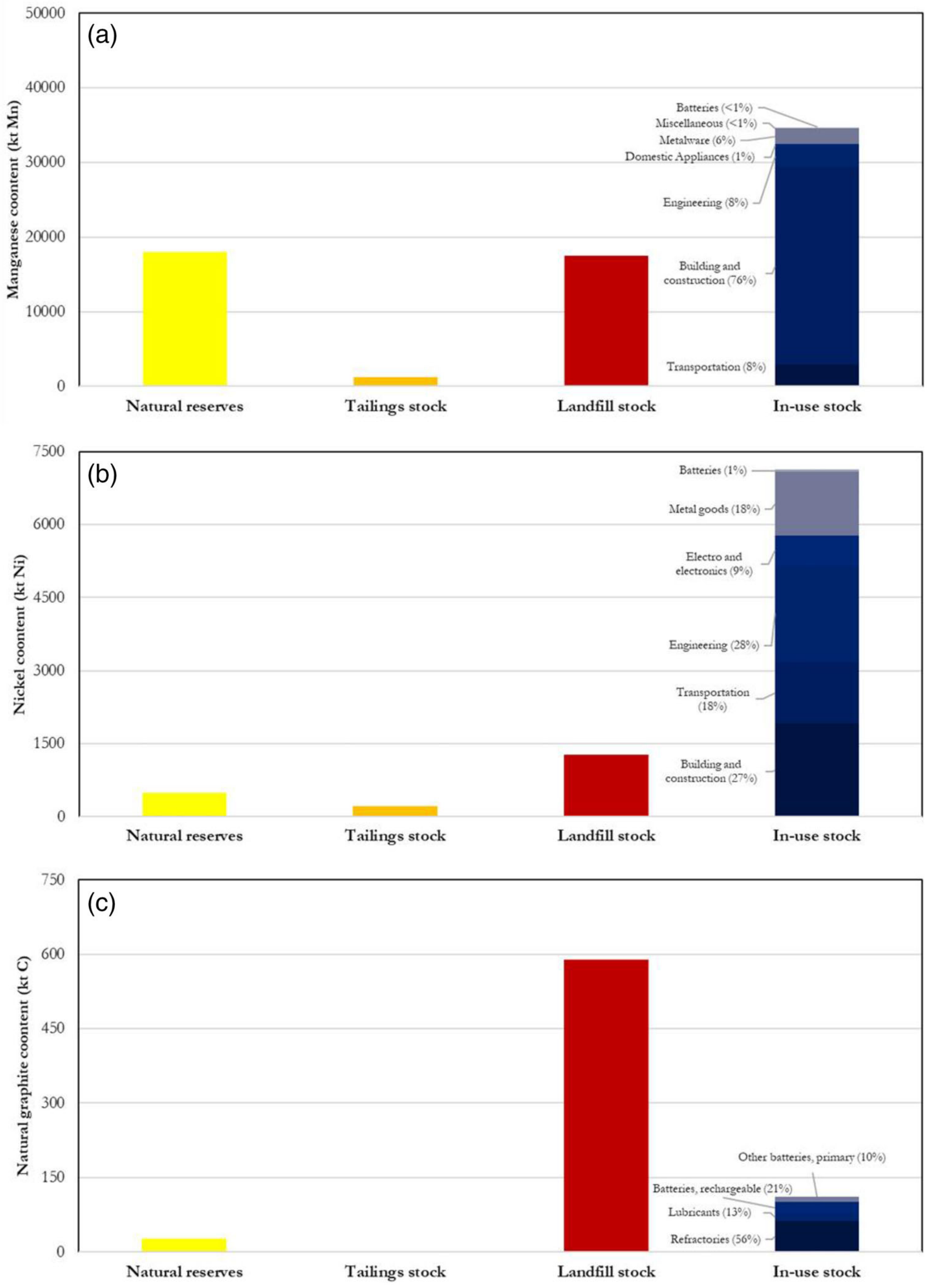

FIGURE 6 Domestic stocks of (a) manganese, (b) nickel, and (c) natural graphite in the EU in 2016: cumulative results for the last 20 years. Percent values in brackets refer to the total in-use stock of each material. Underlying data for Figure 6 are available in Supporting Information S2

as well. Progress in technology and increased production capacity will likely allow for lower-grade ores to be processed including emerging means such as, for instance, phytoaccumulation from mine tailings (Do et al., 2020; Harumain et al., 2017; Nkrumah et al., 2016) or extraction from seafloor nodules (Beaulieu et al., 2017; RPA, 2015; Volkmann et al., 2019) for nickel and manganese. For natural graphite, abundance of primary sources is relatively high and a number of new mine producers are expected to increase, reflecting the natural distribution of this material on the Earth's crust (Olivetti et al., 2017).

However, while reducing losses during extraction and preprocessing operations is certainly desirable and, to some extent, at reach of worldwide technological advancements, margins for achieving substantial improvements appear to be modest for the EU considering its mine production activity. In contrast, average processing performance embeds significant potentials for material recovery, especially for manganese and natural graphite through efficient processing of steel slag and kish (Nakajima et al., 2013; Kalyoncu and Taylor, 2014). If this improvement had been implemented in the past, it can be inferred from our model that the amount of material re-entered in the value chain could have, ideally, approximated the annual domestic supply of manganese to EU manufacturers and about 10% of natural graphite's.

From this perspective, processing (for natural graphite) and manufacture (for manganese and nickel) are the main life cycle phases in the EU value chain that would be potentially affected by supply instability and disruption, but they are also the phases where technological progress and design practices oriented to resource efficiency would likely have the greatest impact since it is where primary and secondary flows usually converge in materials' life cycles.

4.2 | Analysis of performance indicators

TS–RIR indicator attests respectable results for nickel (38% ± 2%) and manganese (25% ± 1%), but limited input of secondary forms to EU manufacture for natural graphite (3% ± 0%). However, only 31% and 22% (i.e., OSR indicator) is actually constituted by old scrap of manganese and nickel, respectively, with the remaining fraction being new scrap. Internal loops of new scrap (i.e., pre-consumer waste collected and recycled at production facility) have generally high recycling efficiency rates thanks to quality levels of trimming waste and scrap from manufacture operations. New scrap generates from process inefficiency so that only old scrap embeds a potential for reducing the dependence on primary sources. The OSR result for natural graphite is certainly positive in this sense (i.e., 90%) although, as said, the absolute material amount supplied from recycling is quite low in comparison.

The enhancement of recycling industry and improvement of process efficiencies at end-of-life are the main areas where supplemental benefits could be very likely achieved if appropriate efforts were implemented. Overall, the amount of old scrap generated at end-of-life would cover theoretically about 60%–70% of flow into use for manganese and nickel and up to more than 90% for natural graphite. This would lead to quite significant improvement from current SSP results and it would likely reduce, but not eliminate, the dependency on (imported) primary material forms. However, process inefficiency and material loss basically halve the amount of manganese and nickel collected for recycling, and they shrink to 10% that of natural graphite. Further leakage of secondary material flows potentially processable in the EU derives from net export to third countries. For instance, a total net export of more than 550 kt of secondary manganese sources from EU to third countries was estimated for 2012—2016. This amount approximately equals 80% of the annual manganese flow from domestic smelters to fabricators of semi-finished products in this region.

The average EoL–RR resulted in 49% (± 8%) for nickel, 51% (± 3%) for manganese, and 8% (± 0%) for natural graphite. Despite annual variations of material flows may affect these estimations (for instance, nickel EoL–RR increases to 53% ± 4% if 2014–2015 outlying values are excluded from calculation), the computed end-of-life recycling performance of manganese and nickel is much higher than that of natural graphite and many other metals in use today (European Commission, 2020; UNEP, 2011). These outcomes also demonstrate that contemporary anthropogenic material cycles are far behind an ideal material circularity even in the case of the most efficiently used metals in our society (Reck & Graedel, 2012).

The EoL–RR indicator depends on the process efficiencies in collection, sorting, separation, and recycling. Collection efficiencies are commonly greater than 80% for manganese and nickel in building and construction, engineering, and transportation as well as for natural graphite in refractories. Thus, it can be inferred that the majority of material generated at end-of-life actually enters dedicated management schemes from which, however, sorting and separation inefficiencies limit the overall recycling rate (i.e., RPER results). Insufficient separation leads to non-functional recycling (i.e., a material is recycled to another material's cycle) or downcycling. This is particularly evident for natural graphite: recycling of refractories is limited but growing, although secondary material is then generally downcycled into dissipative uses like friction materials (Kalyoncu et al., 2014). If collection, sorting, and separation efficiencies had approached achieving ideal efficiency, about 300 kt of manganese, 125 kt of nickel, and 24 kt of natural graphite could have been supplementally recovered at end-of-life in 2016.

For manganese and nickel, issues related to material recovery from major metals-based alloys often prevent our capability to separate and recycle individual metals (Ohno et al., 2016). Because iron is a central element in the value chain of many materials, several studies discussed the possibility of preserving functional recyclability of alloying elements like manganese and nickel within the steel cycle (Reijnders, 2016). Close-loop recycling of steel products can promote functional use of alloying materials, with feedback loops of nickel-bearing alloys occurring in the aerospace industry being exemplary in this respect (Eckelman et al., 2014). However, the potential for functional recycling depends on the capacity to sort and separate material scrap and avoid mixing with alloys of different composition during, for instance, steel scrap remelting in electric arc furnaces, in which nickel and manganese tend to concentrate in the metal phase (Nakajima et al., 2013).

Scrap quality control and impurity limitation are hence fundamental to avoid non-functional losses as well as detrimental effects to new product performance such as surface defects and undesired wear of tools caused by excessive nickel contents (Nakajima et al., 2014; Reijnders, 2016). Ultimately, technical and economic feasibility dictate elemental recoverability, which cannot be ensured in applications where manganese and nickel are minor constituents like low alloy steels, plating, and coating (Henckens & Worrel, 2020).

According to Ohno et al. (2014), improving recycling efficiencies involves dedicated actions at policy and industry levels to (i) encourage and support markets for secondary materials, (ii) achieve sufficient knowledge of alloys composition, and (iii) develop suitable technologies for individual alloy type sorting. Some EU initiatives have addressed these aspects through, for instance, integrated product policy, ecodesign directives, extended producer responsibility, and the EU Green New Deal. Further momentum may result from recycling targets for individual materials and labeling schemes (Henckens & Worrel, 2020), should these actions be implemented in the EU and globally. In contrast to short-lived materials like plastics or paper, recycled content requirements are less recommendable for metals since, in theory, an unintended consequence could be artificially high yield losses in manufacturing that aim at increasing the secondary supply in metal production. A better incentive would be to increase the OSR since it would encourage higher recycling efficiencies at end-of-life (UNEP, 2011).

On the other hand, constraints in technology development and the manufacture industry set conditions to fully operational implementation of economically feasible strategies for material recovery and sustainable material supply (Hayes & McCullough, 2018). This varies from material to material. Although the three targeted materials need to face a similar set of issues (such as high import reliance, lack of natural deposits, interconnection with steel cycle, pivotal role in energy storage systems, and limited end-of-life recycling), each material has its own inherent life cycle and no set of indicators can alone represent the complex nature of its manufacturing network (Nassar et al., 2020) that, in the end, determines the level to which these strategies can be successfully implemented.

5 | CONCLUSIONS

The MSA results demonstrated that a consolidated technological and industrial chain exists in the EU for the targeted materials. The analysis showed only marginal relevance of domestic mine extraction and processing compared to material amounts demanded by EU fabricators, manufacturers, and consumers. Processing for natural graphite and manufacture for manganese and nickel are the main life cycle stages in the EU value chain that would potentially benefit from a reliable and stable material supply chain. The results showed that the sectors building and construction, engineering and transportation products for nickel and manganese, and refractories for natural graphite are the most promising candidates for improvements in end-of-life recycling efficiency due to high demand, high in-use stocks, and amount of waste and secondary materials potentially available for recycling at end-of-life. This evidence may support future decision-making on targeted strategies toward raw material recovery.

Descriptive and quantitative modeling approaches like the ones applied in this study constitute an evidence-based approach to the setting of boundary conditions for efficient resource use and contribute to the achievement of a fully stable supply chain. Ultimately, enhancing the resilience of recycling industry in the EU, which is currently far from ideal performance for the targeted materials, requires an improved understanding of the interlinkages between these materials and it introduces a new facet to supply constraints that should be further investigated to achieve full representation of elemental presence in modern society and set leverages for driving viable patterns of material production and consumption. As part of the manuscript series this work belongs to, a related work of the authors has applied a multi-material perspective to investigate flows of cobalt, lithium, manganese, nickel, and natural graphite in LIBs (Matos et al., 2021).

The current MSA framework is the result of a dual effort aimed at introducing a methodology universally applicable to different strategic materials but also versatile and exhaustive enough to capture the inherent characteristics of these materials' life cycles. However, improvements in data availability, accessibility, and harmonization would certainly benefit the setting of framework for material flows and stock analysis like MSA. In particular, the current MSA accounting procedure and visualization scheme is relatively aggregated and may struggle to track material flows and stocks of intermediated forms and products, especially in material cycles with complex industrial chains. We suggest that future revisions of the MSA framework aim at increasing the level of detail of processing and manufacture through the inclusion of, at least, one stage in between, and the addition of the corresponding market stages to increase accuracy and transparency of the analysis.

Lastly, recommendations on periodical updates of MSA results are more debatable as the pattern of material uses evolve and may determine dramatic changes in the current supply network due to geological, technical, political, economic, and social reasons. Although the three raw materials investigated in this study have applications well consolidated and driven by mature technologies, the expansion of emerging specialty uses such as energy storage systems and mobility electrification is expected to become significant in the next years. A careful material-specific evaluation of a periodical MSA update is recommended.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DISCLAIMER

The presented data are also part of a separate technical report (Matos et al., 2020). Views expressed are those of the authors and do not reflect an official position of the European Commission.

DATA AVAILABILITY STATEMENT

Data available in article supporting information and on request.

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SUPPORTING INFORMATION

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