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RESEARCH ARTICLE

Reassessing tin circularity and criticality

Jessie E. Bradley[1] | Willem L. Auping[1] | René Kleijn[3] | Jan H. Kwakkel[1] | Benjamin Sprecher[2]

[1]TU Delft, Faculty of Technology, Policy and Management, Delft, The Netherlands

[2]TU Delft, Faculty of Industrial Design Engineering, Delft, The Netherlands

[3]Leiden University, Institute of Environmental Sciencec, Leiden, The Netherlands

Correspondence
Jessie E. Bradley, TU Delft, Delft, The Netherlands.
Email: J.E.Bradley@tudelft.nl

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Abstract

Tin is an important metal for society with a high risk of supply disruptions. It is, therefore, classified as a critical material in many parts of the world. An exception is the European Union, for which tin was classified as a non-critical material in 2023. However, there are many discrepancies in the literature regarding the definitions and values of the indicators used to determine tin criticality in general, and recycling indicators in particular. Values for end-of-life recycling rate (EoL RR) range between 20% and 75%, and values for end-of-life recycling input rate (EoL RIR) range between 11% and 32%. In this paper, we critically assess the circularity and criticality indicator values for tin and calculate new values using material flow analysis. The new values for tin recycling indicators are lower than those used in most previous research, with a global EoL RR of 16% and an EoL RIR of 11% in 2017. Based on the updated recycling values, combined with a highly concentrated supply, high import reliance, and difficult substitution, we argue that the European Union should classify tin as a critical material. This reclassification can lead to more policy attention for tin, which can help reduce the impact of future supply disruptions and increase the resilience of the European and global tin supply chains.

KEYWORDS
circular economy, critical materials, European union, industrial ecology, material flow analysis, recycling

1 | INTRODUCTION

Tin is a metal with high economic importance (European Commission [EC], 2023b; Schulz et al., 2017). Tin is sometimes referred to as a "spice element" because it is a small part of many products but essential for the quality (International Tin Association [ITA], 2021c). Tin is mainly used in solder that connects electronic components, which makes it important for many new technologies, including 5G, electric vehicles (EVs), and renewable energy technologies (ITA, 2021b).

The tin supply chain also has a high risk of supply disruptions, where supply becomes unable to meet demand (Schulz et al., 2017). Such a disruption was illustrated during the Covid-19 pandemic when the tin price surged to an all-time high. This price increase was caused by a simultaneous increase in demand due to increased electronics use and a decrease in supply due to disrupted mining (Research & Markets, 2022).

Metals that have both high economic importance and a high risk of supply disruptions (supply risk) are often referred to as critical materials (Graedel & Reck, 2016). Labeling a material as critical can help put it higher on the political agenda. Tin is considered critical by the United States, Canada, and the United Kingdom (Graedel et al., 2022; Lusty et al., 2022). However, the European Commission (EC) did not classify tin as critical in their most recent assessment, partially due to a relatively high estimate for tin recycling (EC, 2023b).

Material criticality is often based on indicators that can be estimated through material flow analysis (MFA). MFA is an analytical method that quantifies material stocks and flows within a system (Baccini & Brunner, 2012). Flows can be determined based on a single year or for a range of past years (cumulative MFA), which also allows determination of stocks (Izard & Müller, 2010). In addition, stocks and flows can be determined between countries (geographical MFA) or between components and products (sectoral MFA). The indicator values obtained from MFAs are useful for both criticality and circularity assessment, as well as for identifying areas for supply chain improvement.

Geographical MFAs help determine indicator values for factors such as supply concentration, import dependence, and reserve depletion time. Previous geographical tin assessments have indicated high supply concentration (Li et al., 2021), high import dependence for the European Union (EU) and the United States (Graedel et al., 2022), and a relatively high risk in terms of depletion time (Althaf & Babbitt, 2021). Li et al. (2021) indicated that global tin reserves have continuously declined over the past two decades. However, estimates by the International Tin Association (ITA) imply the opposite (International Tin Research Institute, 2016; ITA, 2020).

Sectoral MFAs help determine indicator values for factors such as lifetime, losses, and recycling. Previous sectoral tin assessments have indicated a relatively low average lifetime and high losses compared to other non-ferrous metals (Charpentier Poncelet et al., 2022). Over the years, a large amount of tin has been lost and, in 2005, landfills contained twice as much tin as reserves. A large amount of tin has also been lost in the steel recycling loop, where it is a contaminant that reduces steel toughness (Izard & Müller, 2010; Panasiuk et al., 2022). Most end-of-life (EoL) tin recycling occurs in alloy form, with a negligible amount of EoL pure tin recycling (Izard & Müller, 2010).

There is a large discrepancy between the reported values for tin recycling. Two important indicators are the EoL recycling rate (EoL RR) and the EoL recycling input rate (EoL RIR). The EoL RR represents the recycled fraction of total post-consumption waste. For tin, reported values range between 20% (Izard & Müller, 2010) and 75% (Graedel et al., 2011; United Nations Environment Programme [UNEP], 2011). The EoL RIR represents the share of total production that comes from recycled post-consumption waste. Reported tin values range between 11% (EC, 2014) and 32% (EC, 2017). This discrepancy warrants a critical inspection of how these values are obtained.

A previous study of recycling indicators used in European criticality and circularity assessments highlighted the importance of context when using and interpreting indicators (Tercero Espinoza, 2021). Context refers to both indicator type and scope. Regarding type, EoL RIR may be an appropriate indicator for criticality assessment as it indicates independence from primary sources. However, EoL RR is a better indicator for circularity assessment, as it is more directly linked to waste management efficiency. Regarding scope, geographical boundaries can greatly impact recycling indicators. For example, setting different boundaries around the EU led to copper EoL RRs as different as 28% and 61% (Passarini et al., 2018). Studies such as UNEP (2011) and EC (2020), in which recycling values are obtained for many metals, often use a mix of recycling indicator types and scopes. However, using different definitions for different metals reduces transparency, impedes comparison, and can lead to misinterpretation (Tercero Espinoza, 2021).

The two knowledge gaps addressed in this paper are (i) an explanation for the wide range of tin recycling indicator values, and (ii) a detailed overview of the tin supply chain. First, previous MFAs and reported recycling indicator values often contradict, including those used in the EC (2023b) criticality assessment. Tercero Espinoza (2021) addressed issues conceptually, but we found no detailed assessment of actual recycling values for tin. Second, since the previous MFAs (Izard & Müller, 2010; Li et al., 2021), new developments have occurred that have not been analyzed yet, especially when it comes to tin flows beyond unwrought flows, and the recycling of both pure and alloyed tin.

In this paper we assess and update tin's circularity and criticality indicator values. We obtain new values based on geographical and sectoral MFAs of the tin supply chain in 2017 and a cumulative sectoral MFA from 1927 to 2017. We pay specific attention to tin recycling, clear up some discrepancies in the literature, and provide new tin estimates for different recycling definitions. Finally, we use the new estimates to reassess tin criticality in the EU.

2 | METHODS

This research consists of an examination of criticality and circularity indicators and three types of MFA. First, we examine the status of tin criticality and circularity indicators in the literature, with a focus on recycling indicators (Section 2.1) and an overview of other indicators (Section 2.2). Second, we perform three MFAs of the global tin supply chain (Section 2.3). Based on these MFAs, we obtain new indicator values and reassess tin criticality for the EU. Details of the assessments can be found in the two supporting information documents, a PDF file (Supporting Information S1) and an excel file (Supporting Information S2).

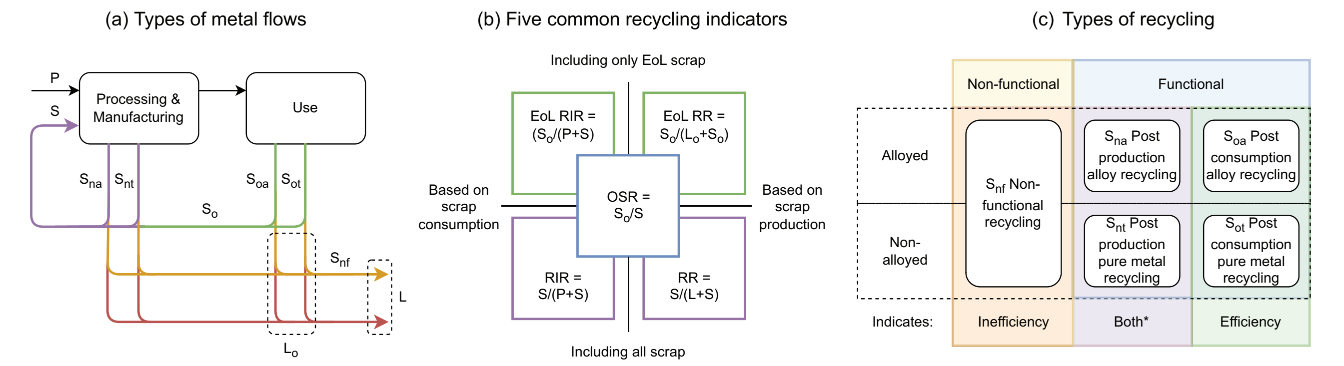


FIGURE 1 (a) Different types of metal flows. L, losses; P, primary production; S, secondary production. Most subscripts are explained in (c). o, old scrap. Non-functional recycling is included as part of losses. (b) Five common recycling indicators based on the flows in (a). EoL RIR, end-of-life recycling input rate; EoL RR, end-of-life recycle rate; OSR, old scrap ratio; RIR, recycling input rate (also referred to as recycled content [RC], although the definitions are not always the same); RR, recycling rate (also referred to as overall recycling efficiency rate [ORER]). (c) Different types of recycling. *Post-production recycling indicates both manufacturing inefficiency and new scrap recycling efficiency. Note: With the term consumption, we mean use, not destruction.

2.1 | Recycling indicators

There are many different types of metal flows (Figure 1a) that lead to a wide variety of recycling indicators (Figure 1b). These indicators can be categorized based on whether they refer to scrap production (recycling rate; RR) or scrap consumption (recycling *input* rate; RIR) and whether they include only EoL scrap (also known as post-consumption or old scrap) or all scrap (also including post-production or new scrap). A fifth indicator, the old scrap ratio (OSR), indicates how much of the total scrap is old scrap (Tercero Espinoza & Soulier, 2017; UNEP, 2011).

In addition to input versus output and old scrap versus new scrap, recycling indicators can refer to only pure metal recycling (e.g., pure tin) or include recycling in alloy form (e.g., bronze) (ITA, 2021a). Metals can also be recycled in a non-functional manner, where one metal becomes an impurity in the cycle of another metal and is no longer available to its own cycle (UNEP, 2011). For example, when tinplate is recycled, tin often ends up in the steel cycle and is lost to the tin cycle (Izard & Müller, 2010). This so-called non-functional recycling is undesired, but can still be included in some recycling values. To further increase complexity, recycling indicators can also differ per temporal, sectoral, and geographical scope, leading to a wide variety of values for a single commodity (Passarini et al., 2018).

Distinguishing between recycling indicators is relevant, as each indicator communicates something different (Figure 1c). For example, post-production recycling indicates both recycling efficiency and manufacturing inefficiency. If manufacturing resulted in less waste, there would be less need for this type of recycling and the RIR would be lower. In contrast, EoL recycling only indicates recycling efficiency. In addition, EoL recycling contributes more to supply security (Helbig et al., 2021). Therefore, it is useful to have EoL indicators that exclude post-production recycling.

In this research, we gather tin recycling values from the literature and industry, and categorize them under the reported or assumed definition and scope. We then assess these values and identify potential errors and reasons for discrepancies. The full analysis can be found in Supporting Information S1 (chapter 1).

2.2 | Other criticality and circularity indicators

In addition to recycling indicators, there are many other criticality and/or circularity indicators. Criticality indicators are often divided into supply risk (SR) indicators and economic importance (EI; sometimes also referred to as vulnerability to supply disruption) indicators (EC, 2023b; Schrijvers et al., 2020). An environmental (and social) impact dimension is sometimes added (Graedel & Reck, 2016). Circularity indicators can focus on individual aspects of circularity (reduce, reuse, and recycle) separately, or they can be more comprehensive (Corona et al., 2019; Pauliuk, 2018). In this research, we focus on individual aspects of circularity and on supply risk indicators.

Although supply risk is meant to indicate the risk of a supply–demand imbalance, most supply risk indicators focus on the supply side. The most common supply risk indicators (Helbig et al., 2021) can be divided over the following supply related categories: scarcity, by-product dependence, import dependence, dependence on primary production (which includes recycling indicators), concentration, political instability, regulations, and other. Demand related categories include demand growth and lack of substitution options.

In European criticality assessment (EC, 2023b), supply risk (Equation 1) is based on indicators for import dependence (import reliance; IR), dependence on primary production (1 – EoL RIR), lack of substitution options (substitution index; SI), and market concentration. For market concentration, the EC (2023b) used the Herfindahl–Hirschman index (HHI) augmented with indicators for socio-political stability (world governance index; WGI)

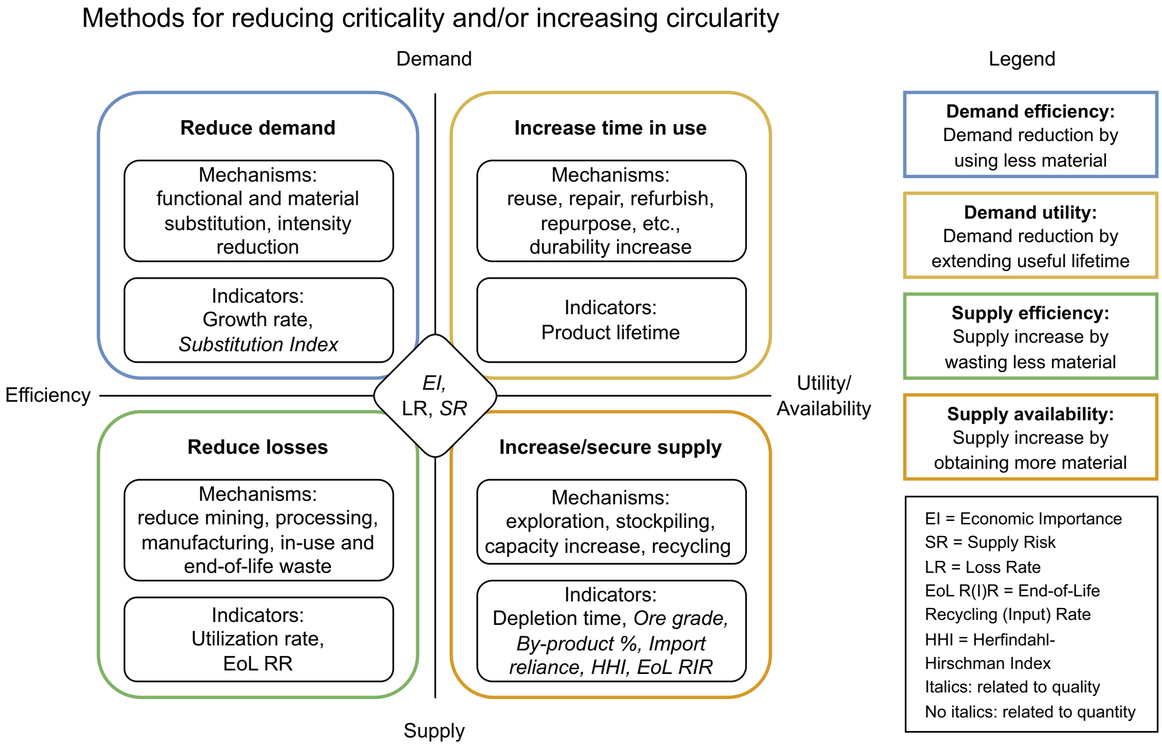


FIGURE 2 Methods and mechanisms for reducing material criticality, and in many cases also for increasing circularity, and indicators reflecting their performance. The indicators in the middle are aggregate indicators related to multiple fields; loss rate (LR) is based on both time in use and losses, supply risk (SR) is based on both demand reduction potential and maintaining/obtaining enough supply, and economic importance (EI) relates to the importance of improving all fields. For references, see Table 1.

and trade restrictions (t) (Equation 2). This indicator was calculated for both global sourcing (GS) and European (EU) sourcing. On its own, the HHI is sometimes represented by a fraction (Althaf & Babbitt, 2021) and sometimes by a value between 0 and 10,000. Values between 1500 and 2500 (or 0.15 and 0.25) indicate moderate concentration and those greater than 2500 (or 0.25) indicate high concentration (United States Department of Justice, 2018).

$$\mathrm{SR} = \left[\left(\mathrm{HHI}_{\mathrm{WGI},t}\right)_{\mathrm{GS}} \cdot \frac{\mathrm{IR}}{2} + \left(\mathrm{HHI}_{\mathrm{WGI},t}\right)_{\mathrm{EU}} \cdot \left(1 - \frac{\mathrm{IR}}{2}\right) \right] \cdot \left(1 - \mathrm{EoL}_{\mathrm{RIR}}\right) \cdot \mathrm{SI}_{\mathrm{SR}} \tag{1}$$

$$\mathrm{HHI}_{\mathrm{WGI},t} = \sum_{i=1}^{N} \left(\left(\frac{\mathrm{Production}_i}{\mathrm{Total\ production}} \right)^2 \cdot \mathrm{WGI}_i \cdot t_i \right) \tag{2}$$

The indicators included in our research are shown in Table 1. This table includes all EC (2023b) indicators, at least one indicator per category based on Helbig et al. (2021), and additional circularity indicators related to lifetime and losses. For lifetime, we use the simple indicator of product lifetime, which represents the average time between tin entering and exiting use (Izard & Müller, 2010). This time represents both the initial lifetime of products and the additional time in use due to circularity strategies such as reusing, repairing, and refurbishing.

To better represent material losses, we introduce the novel indicator utilization rate (UR), which indicates the share of total primary and secondary sourcing that actually enters use. This indicator mainly represents pre-use efficiency, while EoL RR represents post-use efficiency. We also include the loss rate (LR) which combines pre-use losses, product lifetime, and post-use losses (Charpentier Poncelet et al., 2022). This indicator represents the rate at which metals become unavailable for further use in kg/year/kg extracted. Most indicator values are obtained through the MFAs; however, demand growth rate and substitution index are based on the ITA (personal communication, 2022) and the EC (2023b), respectively.

We categorize the indicators based on methods for increasing circularity and/or reducing criticality (Figure 2). These methods are divided based on whether they impact demand or supply, and whether they say something about efficiency or availability/utility. Efficiency refers to reducing demand or losses. Availability/utility refers to increasing supply or time in use. In addition, some indicators reflect quantity (actual demand or

TABLE 1 The assessed criticality and circularity indicators. Data shows whether an indicator can be obtained through geographical MFA, sectoral MFA, or other means. Additional indicators are included in Supporting Information S1 (chapter 2).

Category	Indicator	Type	Data	Formula/description	Source
Supply availability indicators					
Scarcity	Reserve depletion time	Quantity	Geographical	Reserves/extraction[a]	Helbig et al. (2021)
	Resource depletion time	Quantity	Geographical	Resources/extraction[a]	
	Ore grade	Quality	Geographical	Metal mass/ore mass	
By-product dependence	By-product percentage	Quality	Geographical	Production as a by-product/total production	Helbig et al. (2021)
Import dependence	Import reliance	Quality	Geographical	Consumption from import/total consumption	EC (2023b)
Concentration[b]	HHI mining	Quality	Geographical	See Equation (2)	EC (2023b)
	HHI refining	Quality	Geographical		
	HHI reserves	Quality	Geographical		Helbig et al. (2021)
	HHI resources	Quality	Geographical		
Political instability	WGI	Quality	Geographical	See EC (2023b)	EC (2023b)
Regulations	Trade restrictions	Quality	Geographical	See EC (2023b)	EC (2023b)
Other	Stockpile	Quantity	Geographical	-	Helbig et al. (2021)
Dependence on primary production	EoL RIR	Both	Sectoral	See Figure 1	EC (2023b)
Supply efficiency indicators					
Losses	EoL RR	Quantity	Sectoral	See Figure 1	Helbig et al. (2021)
	Utilization rate	Quantity	Sectoral	Consumption/(extraction + secondary input)	This research
Demand utility indicators					
Lifetime	Product lifetime[c]	Quantity	Sectoral	The time between entering and exiting use	Izard and Müller (2010)
Demand efficiency indicators					
Demand growth	Growth rate	Quantity	Other	Demand/previous year demand	Helbig et al. (2021)
Lack of substitutes	Substitution index	Quality	Other	See EC (2023b)	EC (2023b)
Aggregate indicators					
Circularity	Loss rate	Quantity	Sectoral	See Charpentier Poncelet et al. (2022)	Charpentier Poncelet et al. (2022)
Risk	Supply risk	Both	Combined	See Equation (1)	EC (2023b)
Vulnerability	Economic importance	Quality	Combined	See EC (2023b)	EC (2023b)

[a]Resources or reserves over consumption when applied to EU28.
[b]HHI values are not augmented by WGI and t, unless they are referred to as $HHI_{WGI,t}$.
[c]Not to be confused with the definition of lifetime used by Charpentier Poncelet et al. (2022).

supply), and others reflect quality (stability and/or flexibility of demand or supply). Some indicators (aggregate indicators) are related to multiple categories.

2.3 | Material flow analysis

In this research, we perform three types of global tin MFA: a geographical MFA for 2017, a sectoral MFA for 2017, and a cumulative sectoral MFA from 1927 to 2017. We collect data from the literature and communication with the ITA. For the geographical MFA, we only consider unwrought tin flows. This MFA includes mining and refining per country and trade and consumption per continent. Details on the calculations and data sources are included in Supporting Information S1 (chapter 3.1) and Supporting Information S2 (sheets 1 – 4).

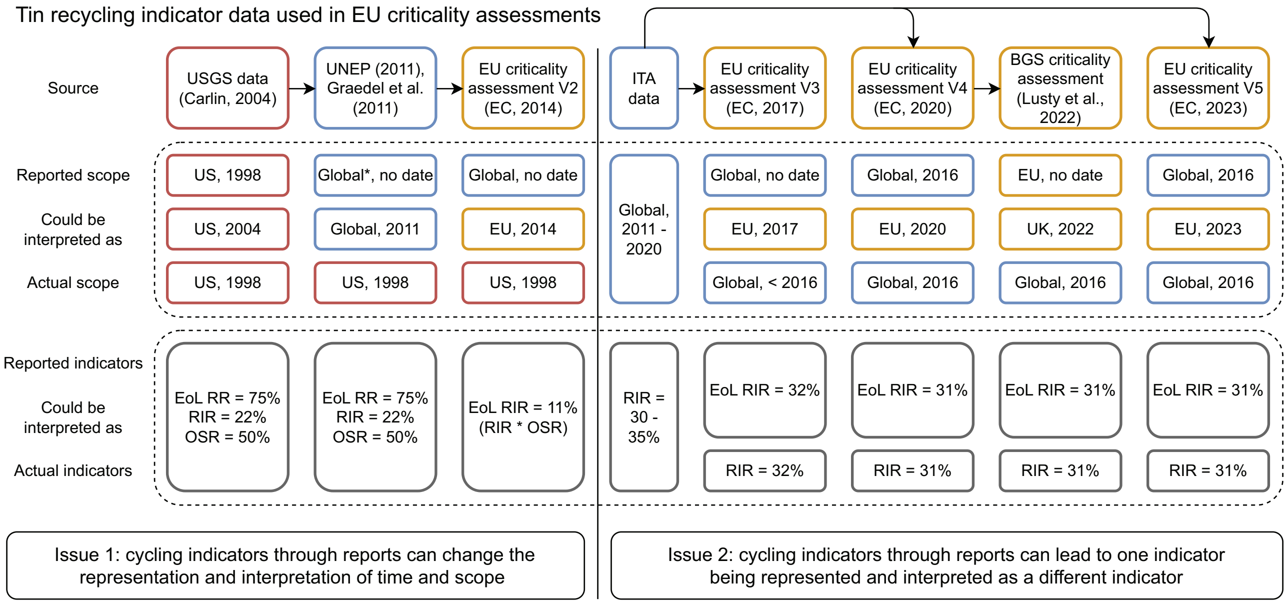


FIGURE 3 Values for tin recycling indicators used in European Union (EU) criticality assessments and the original data they were based on. Tin was not assessed in the first criticality assessment by the EC (EC, 2010). BGS, British Geological Survey; EoL RR, end-of-life recycling rate; (EoL) RIR, (end-of-life) recycling input rate; OSR, old scrap ratio; USGS, United States Geological Survey.

For the sectoral MFAs, we include alloys and recycling flows in addition to unwrought flows. We distinguish between six applications (solder, chemicals, tinplate, batteries, tin copper, and other), and between six end uses (electronics, transportation, packaging, construction, industry, and other). The cumulative sectoral MFA, which includes stocks for 2017, is an update of the analysis by Izard and Müller (2010). Details on the calculations and data sources are included in Supporting Information S1 (chapter 3.2) and Supporting Information S2 (sheets 5 – 15).

We do all analyses for a global scope, but calculate EU28 values where possible. Due to a lack of data availability for the EU, we follow the approach used by the EC (2023b) and use the estimated global indicator values obtained in the MFAs to recalculate criticality for EU28 using Equation (1).

3 | RESULTS

3.1 | Recycling indicator values in the literature

The tin recycling indicator values reported in the literature differ significantly. The full list of values, as well as values for other circularity and criticality indicators, can be found in Supporting Information S1 (chapters 1 and 2). Below, we focus specifically on the values in European criticality assessments, by tracking them to their original source and highlighting issues. Identified issues are summarized in Figure 3.

Frequently cited recycling values come from an International Resource Panel report (UNEP, 2011). These values are used to represent global data, but the tin values are based on a single year (1998) and a single country (the United States) (Carlin, 2004). The EoL RR (75%) is likely too high, due to the inclusion of trade and stock changes, exclusion of dissipative uses, and potential inclusion of non-functional recycling. Graedel et al. (2022) recently reported a much lower global EoL RR (30%) based on Izard and Müller (2010). However, this value is closer to the US value (28%) reported by Izard and Müller (2010) than to their global estimate (20%). The UNEP (2011) RIR and OSR may also not apply to a global scope. The RIR (22%) is lower than global values (30%–35%) reported by the ITA for the past 10 years (ITA, 2021a) and the OSR (50%) is likely too high (ITA, personal communication, 2022).

The EC (2014) multiplied the UNEP (2011) RIR and OSR to estimate the tin EoL RIR in their criticality assessment (Peiro et al., 2018). This highlights the following issue: 1998 US data was assumed to represent more recent global data and was used to calculate tin criticality in the EU in 2014. This large difference in time and scope can go unnoticed if the data is not traced back to its original source.

More recently, the EC (2017, 2020, 2023b) used ITA RIR data to determine EoL RIR. However, they did not multiply this data with an OSR, which led to reporting RIR values as EoL RIR values. This highlights another issue: reusing recycling indicators can lead to one indicator being represented and interpreted as another. Using RIR values to represent EoL RIR becomes increasingly problematic as OSR becomes lower. For an OSR $< 50\%$, the EoL RIR is at most half of what it is represented to be by the EC (2017, 2020, 2023b). This misinterpretation can have important implications

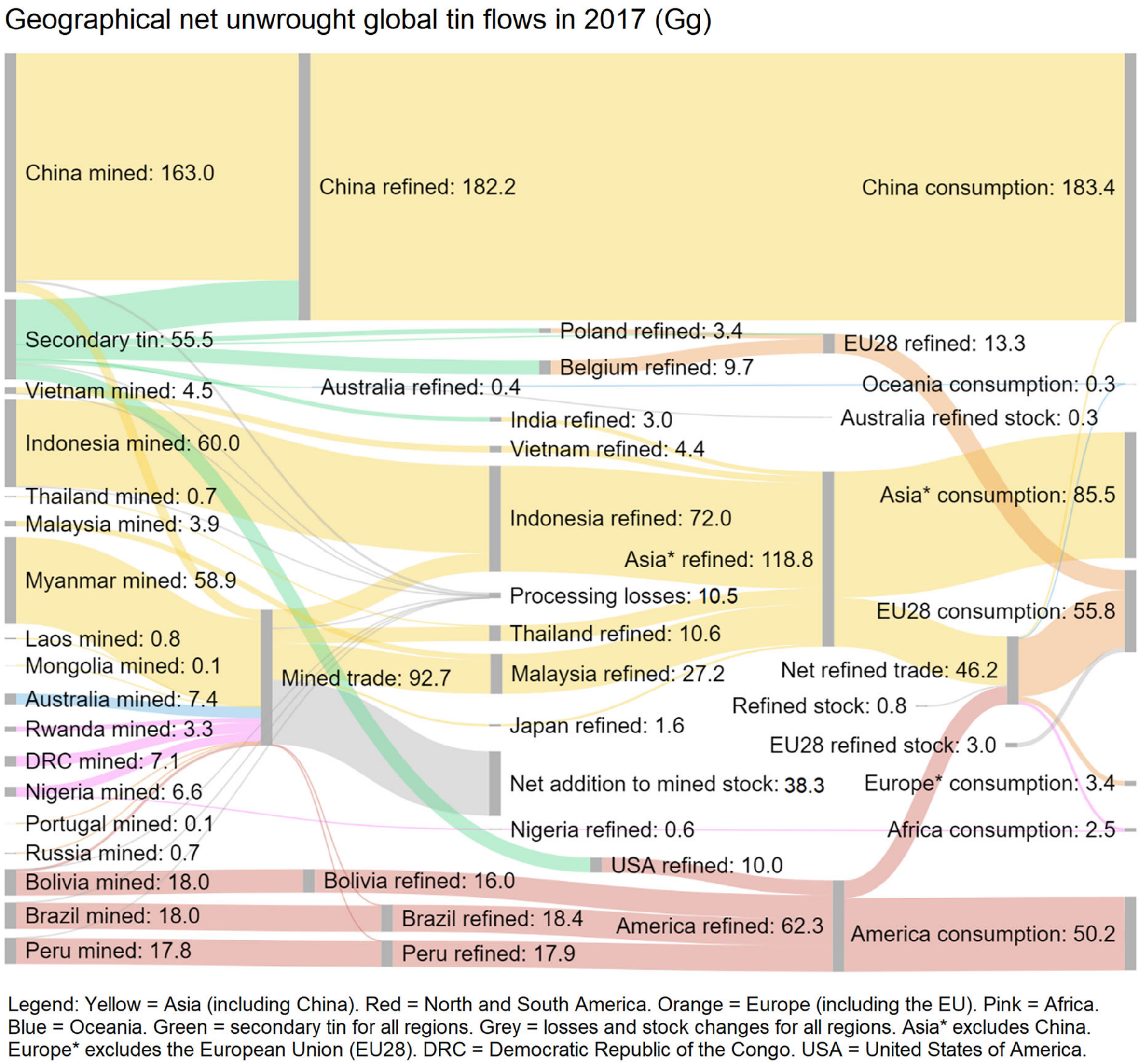


FIGURE 4 Geographical net unwrought global tin flows in 2017 (Gg). For details on the calculations, see Supporting Information S2 (sheets 1 – 4, especially sheet 3).

because EoL RIR is used to determine criticality. This also applies to Lusty et al. (2022), who used the EC (2020) value in their criticality assessment of the United Kingdom.

3.2 | Tin MFA results and updated indicator values

3.2.1 | Geographical MFA 2017

Geographical unwrought global tin flows are shown in Figure 4. In 2017 about 371 Gg of tin was mined, with 79% originating from Asia (44% from China) and 15% from South America (World Bureau of Metal Statistics [WBMS], 2018). Tin is mainly mined from cassiterite ores, with an average global ore grade of about 0.6%–0.7% (ITA, personal communication, 2022) and a very small fraction recovered as a by-product (BP = 3%) (Nassar et al., 2015). The estimated global tin resources and reserves were about 15,400 and 5500 Gg respectively in 2019 (ITA, 2020). We assumed that similar values apply to 2017 and calculated a depletion time of 29 years for resources and 10 years for reserves, considering 30% losses. The HHIs for tin reserves and resources in 2019 are 0.21 and 0.19, respectively. These values indicate moderate concentration.

EU28 has about 7% of global resources and 0% of global reserves. For EU28, we calculated depletion time based on resources-over-consumption instead of resources-over-extraction due to negligible production. Based on consumption of primary tin in 2017 and resources in 2019, we calculated a depletion time of 13 years for resources and 0.05 years for reserves when considering 30% tailings losses and 2.7% production losses. These

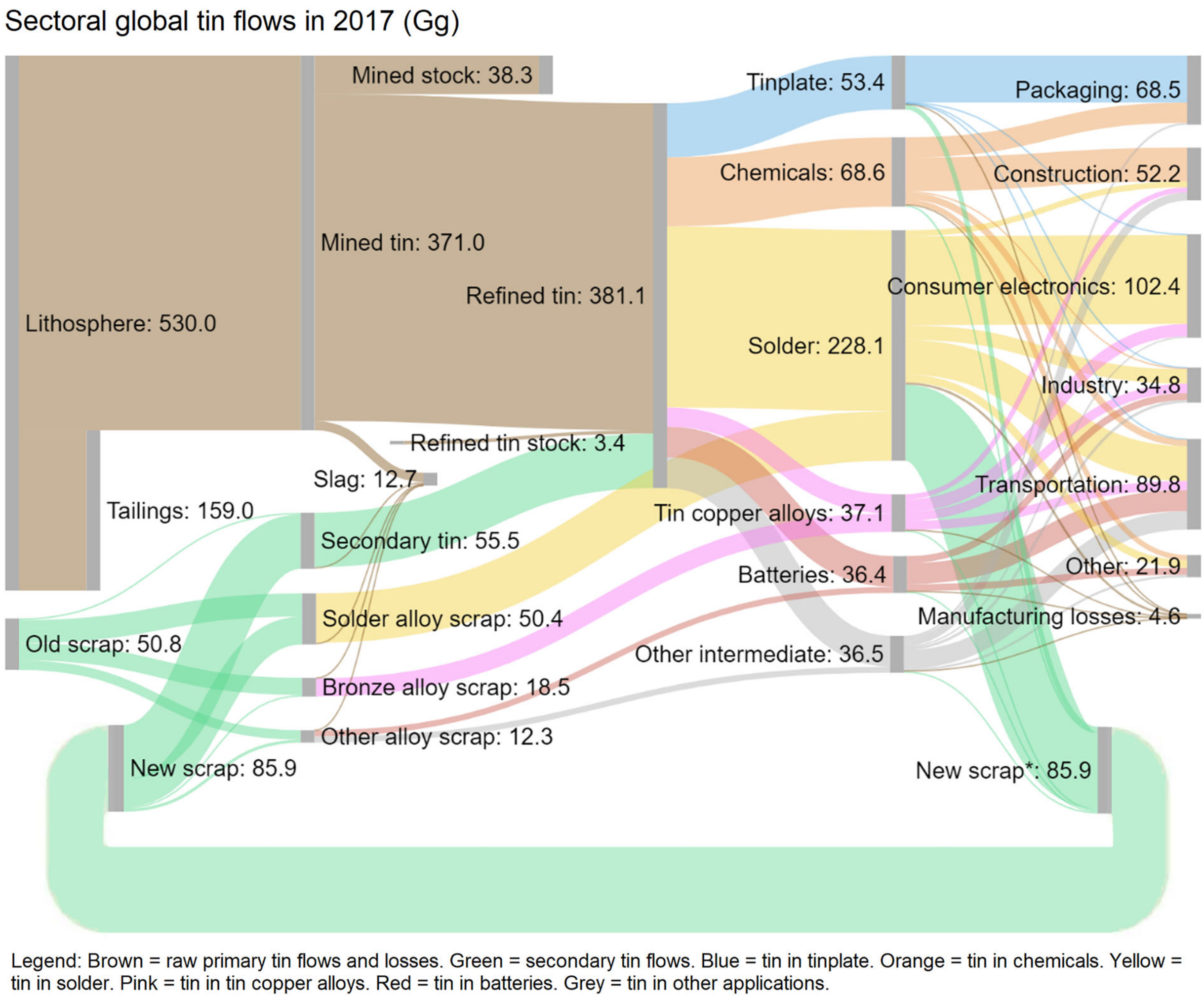


FIGURE 5 Sectoral global tin flows in 2017 (Gg). For details on the calculations, see Supporting Information S2 (sheets 5 – 10, especially sheet 10).

values indicate depletion time if EU28 were forced to rely fully on domestic primary production. In EU28, the average ore grade is about 32 ppm, which makes mining a lot less attractive (ITA personal communication, 2022).

Tin supply is highly concentrated, with a HHI of 0.25 for mining and 0.28 for refining. Both primary (83%) and secondary (57%) production occurred mainly in Asia. EU28 is responsible for about a quarter of global secondary production, and about 24% of EU28 tin consumption can be covered by own secondary production. This secondary production accounts for the total tin production in EU28, which indicates an unwrought tin import reliance of about 76%. In addition, most sources of supply are in areas with a relatively large degree of political instability according to WGI values (EC, 2023b). Some of these areas also have additional trade restrictions for the EU (see Supporting Information S2, sheet 16). Tin is also classified as a "conflict mineral" because part of the supply comes from areas in which conflict benefits from production (Böhme et al., 2014). This further complicates the supply chain and increases risk.

Another factor that can increase supply risk is the limited amount of stockpiling (Sprecher et al., 2015). Tin stockpiles have reduced over the last decades, falling from almost 270 Gg in 1985 to about 30 Gg in 2017 (Elementos, 2019). About 10% of these stocks were in EU28, while EU28 consumption is 15% of global consumption (WBMS, 2018).

3.2.2 | Sectoral MFA 2017

Sectoral global tin flows in 2017 are shown in Figure 5. Most tin was used in solder (47%), followed by chemicals (18%), tinplate (14%), batteries (8%), other (8%), and tin copper (5%) (ITA, 2018). In 2014, the main end use sectors were consumer electronics (31%), transportation (23%), packaging (20%), construction (13%), industry (8%), and other (5%) (Lin, 2015). We assume this still applied in 2017.

For recycling, we estimate an RIR of 29%, an OSR of 37%, and an EoL RR of 16%. These values all include alloy recycling. When alloy recycling is excluded, RIR is 14%, OSR is 3%, and EoL RR is 1%. The RIR and OSR data can be derived from Figure 5. Details of the EoL RR can be found in Supporting Information S1 (chapters 1.3 and 1.4) and Supporting Information S2 (sheet 9). When including non-functional recycling, EoL RR is about 30%, based on 16% functional and 14% non-functional recycling (see Supporting Information S2, sheet 11 for the calculations). An increase in tin can recycling and a reduction in detinning (separating tin from steel) over time have led to increased non-functional recycling.

The OSR of 37% means most tin recycling comes from new scrap. Recycled new scrap is a significant inflow entering the refining and manufacturing stages of the supply chain. However, the new scrap outflow from manufacturing is almost just as large. Therefore, the new scrap flow does not contribute to tin utility (tin actually entering use and fulfilling a useful function), while the old scrap flow does. Tin utilization rate was about 58%, which indicates 42% was either lost during mining, processing or manufacturing, or cycling in the new scrap cycle.

We estimate an EoL RIR of about 11% (<1% when excluding alloys). This value is coincidently the same as the value obtained by the EC (2014), however, it was derived in a different manner, based on a lower OSR and a higher RIR. Eleven percent is a lot lower than the 31% used by the EC (2023b) and this has implications for tin criticality

3.2.3 | Cumulative sectoral MFA 1927–2017

Cumulative sectoral global tin flows between 1927 and 2017 and stocks for 2017 are shown in Figure 6. This figure can be used to determine average values for recycling indicators over this timespan, as well as losses and stock accumulation. About 89% of the tin that has been extracted between 1927 and 2017 has been lost, and for each unit of consumed tin, 88% was lost. For an overview of losses per supply chain stage, see Supporting Information S2 (sheets 11 and 12).

There is almost as much tin in landfills and other waste stocks as in current resources (ITA, 2020). Although we did not distinguish between landfill and a hibernating waste stock, there are stocks in society that contain tin scrap that is stockpiled for future recycling under more favorable conditions. The World Economic Forum (WEF, 2018) indicate that about 67% of the formal Chinese recycling flow of tin in electronics may be sitting in a hibernating stock.

There is also a lot of tin in use, especially in consumer electronics and transportation. In consumer electronics, a second type of hibernating stock can be identified; the one where tin has accumulated in old appliances, such as mobile phones that have not been discarded yet, but no longer have any utility (Speake & Yangke, 2015). This stock can also be a potential source for future recycling. Old vehicles can be another important source of tin in the future, especially since tin in the vehicle stock is expected to grow due to a greater EV share. EVs are estimated to contain about twice as much tin as internal combustion engine vehicles (ITA, personal communication, 2022).

A relatively large amount of tin cycles in the steel loop. Since the analysis by Izard and Müller (2010) even more tin has accumulated here. This accumulation has been impacted by two developments. On the one hand, tin can recycling has increased. EU28 reached a steel packaging RR of 84% in 2019 (Apeal, 2020). On the other hand, the number of detinning facilities has decreased (see Supporting Information S2, sheet 15) due to the reduction of tin intensity in tin cans (Sibley, 2011).

We estimate an average tin product lifetime of about 13 years. This time is relatively short compared to most other non-ferrous metals (Charpentier Poncelet et al., 2022), which means new metal needs to be obtained more often to maintain functionality. By combining product lifetimes and losses at different supply chain stages, we calculated a tin loss rate of 0.11 kg/year/kg extracted. This is higher than the value calculated by Charpentier Poncelet et al. (2022), mainly because our data indicates more mining losses (Supporting Information S1, chapter 2.2).

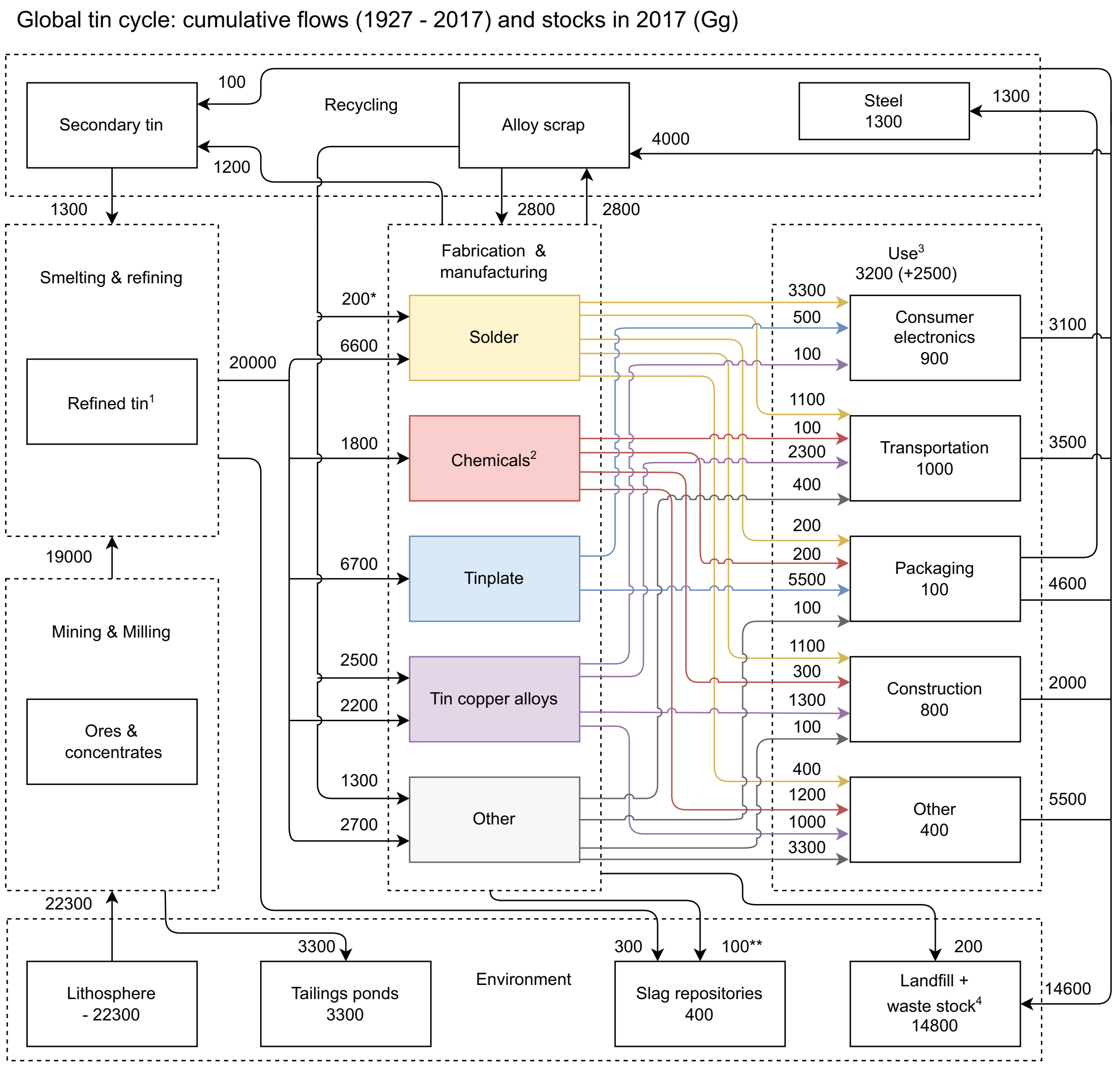
3.3 | Additional indicator values and tin criticality in EU28

Tin has high economic importance (EC, 2023b), growing demand, and difficult substitution. Currently demand grows about 2% per year. However, as tin is an important metal for new technologies, this value is expected to increase to about 4% (ITA, personal communication, 2022). The EC (2023b) reported a substitution index of 0.92. A value closer to 1 indicates more difficult substitution. Tin substitution is most difficult in solder, the largest and fastest growing application (ITA, personal communication, 2022).

The estimated tin values for criticality and circularity indicators are shown in Table 2. Additional estimates, such as values per application are included in Supporting Information S1 (chapters 1 and 2). The current recycling estimates are lower than what has been reported in previous research. This has various implications, including implications for tin criticality.

When using the new estimates in Equation (1), supply risk becomes high enough to classify tin as critical for the EU. A material is considered critical if both supply risk and economic importance are above their respective thresholds. The recalculated supply risks are 1.3 for mining and 1.1 for processing (see Supporting Information S2, sheet 16), which are both above the threshold of 1 set by the EC (2023b). Combined with an economic importance of 4.5, which is above the threshold of 2.8 (EC, 2023b), tin would be classified as critical for the EU.

Following the EC (2023b), this classification is based on global recycling estimates, as data quality was not high enough for EU specific estimates. EU averages for EoL RIR may be higher than global averages. Therefore, we calculated the maximum EoL RIR required for tin to still be classified as



This figure was updated from Izard and Müller (2010).
*The solder flow is relatively low compared to other alloys, as it was 0 in the analysis by Izard and Müller (2010).
**This value indicates processing losses due to reprocessing of recycled alloys.
1. Refined tin stocks were negligibly small in 2017 and were therefore not included.
2. Chemicals were added as a separate category. Some chemicals dissipate in use. However, for simplification, all losses are sent to landfill.
3. Includes stocks before 1927 (about 700 – 800 Gg) (Izard & Müller, 2010).
4. Landfill and waste stock are included together as no estimation was made of how much scrap has accumulated in hibernating stocks.

FIGURE 6 Cumulative sectoral global tin flows between 1927 and 2017 and stocks in 2017 (Gg). For details on the calculations, see Supporting Information S2 (sheet 11).

critical using the EC (2023b) methodology and data. This is 21%, which is almost twice as much as our estimate of 11%. So, even with a higher EoL RIR, tin should still be classified as critical (see Supporting Information S1, chapter 4 for further details).

4 | DISCUSSION

4.1 | Tin, the overlooked critical metal

Tin should be classified as a critical material for the EU. In this research, current values for circularity and criticality indicators for tin were critically assessed, and updated values were calculated using MFA. Using the new values to recalculate tin criticality in the EU with the EC (2023b)

TABLE 2 Values for tin for the assessed criticality and circularity indicators. If no unit is included, the value is dimensionless. Values apply to the 2017 scope, values in brackets apply to the 1927—2017 scope. The values in this table are estimated averages that can differ significantly per sector and region (see Supporting Information S1 chapters 1 and 2).

Category	Indicator	Global value	EU28 value	Source
Supply availability indicators				
Scarcity	Reserve depletion time	10 years	0.05 years[a]	Own calculations
	Resource depletion time	29 years	13 years[a]	
	Ore grade	0.6%–0.7%	0.003%	ITA + own calculation
By-product dependence	By-product percentage	3%	-	Nassar et al. (2015)
Import dependence	Import reliance	-	0.76	Own calculations
Concentration	HHI mining	0.25	-	Own calculations
	HHI refining	0.28	-	
	HHI reserves	0.21	-	
	HHI resources	0.19	-	
Political instability	HHI_{WGI}	See Supporting Information S2 (sheet 16)		Own calculations
Regulations	$HHI_{WGI,t}$	See Supporting Information S2 (sheet 16)		Own calculations
Other	Stockpile	~30 Gg	~3 Gg	WBMS (2018)
Dependence on primary production	EoL RIR	0.11 (0.15)	-	Own calculations
Supply efficiency indicators				
Losses	EoL RR	0.16 (0.20)	-	Own calculations
	Utilization rate	0.58 (0.74)	-	
Demand utility indicators				
Lifetime	Average product lifetime	13 years	-	Own calculations
Demand efficiency indicators				
Demand growth	Growth rate short term	2%	-	ITA (personal communication, 2022)
	Growth rate long term	4%	-	
Lack of substitutes	Substitution index	0.92[b]	0.92[b]	EC (2023b)
Aggregate indicators				
Circularity	Loss rate	0.11 kg/yr/kg extracted	-	Own calculations
Supply risk[c]	Supply risk extraction	1.3	1.3	Own calculations
	Supply risk processing	1.8	1.1	
Vulnerability	Economic importance	4.5[b]	4.5[b]	EC (2023b)

[a]These values represent resources-over-consumption instead of resources-over-extraction.
[b]We were unable to identify whether this is a global or EU28 value.
[c]The EU28 value for extraction is based on global sourcing following EC (2020). The EU28 processing value is based on combined global and EU sourcing.

methodology results in a critical classification. In line with previous research, we found that tin supply is highly concentrated, there is a high import reliance, and substitution is difficult (EC, 2023b; Li et al., 2021). However, our recycling indicator values are lower than those in previous research (EC, 2023b; Graedel et al., 2022; Izard & Müller, 2010; UNEP, 2011). Especially the change in EoL RIR from 31% (EC, 2023b) to 11%, has a large impact on tin criticality in the EU.

In addition to the indicators included in the EC (2023b) assessment, other demand- and supply-side factors are important when considering tin criticality (Helbig et al., 2021). Demand-side pressure comes from the significant expected demand growth for electronic components for new technologies in general and the energy transition in particular (ITA, 2021b). The relatively short lifetime of tin-containing products also contributes to demand-side pressure, as products need to be replaced more frequently. Supply-side pressure comes from the low depletion time, and limited stockpiling. The low depletion time can increase risk if future exploration and production capacity increases are not sufficient to keep up with growing demand. Low stockpiles can increase risk because there is a limited buffer available if other supply sources are disrupted (Sprecher et al., 2015). We also note that there are social and environmental issues related to tin production that (other than the use of WGI indicators) are outside the scope of this work, but nevertheless important (Arto, 2009).

Despite using global recycling data, we argue that tin is even more critical in the EU than in the rest of the world. First, there is only a small amount of mining and practically no primary production in the EU. Second, the relatively low average EU ore grade makes obtaining own primary supply more difficult. Limited reserves and resources also mean a relatively fast depletion time if the EU were able to build enough primary production capacity for self-sufficiency. Third, it is impossible to fully cover expected demand growth with secondary supply, even if recycling in the EU is significantly higher than our estimates (Tercero Espinoza, 2021). Finally, Europe has a relatively large share of applications that require virgin tin (e.g., chemicals and tinplate) (ITA, personal communication, 2022). These applications are more vulnerable to supply disruptions because most EoL tin recycling is in alloyed form. Most pure tin recycling in the EU also comes from new scrap, which means the import reliance for pure tin that actually ends up in use is close to 100%.

Tin has been overshadowed by “major metals” on the one hand and critical “minor metals” on the other hand, and this is also reflected in the data quality. Most data is available for major metals, such as copper and aluminum, with poorer data for minor metals (Chen & Graedel, 2012). However, increased concern for minor metals with a critical classification, such as indium and rare earth elements, has improved data availability (Tercero Espinoza, 2021). In contrast, tin data has barely improved since the analysis by Izard and Müller (2010). Due to the poor data availability, many assumptions had to be made and there is quite some uncertainty in the results. All assumptions have been documented in Supporting Information S1, which also includes uncertainty ranges for many of the calculated indicators.

Criticality assessment is arguably somewhat arbitrary but nevertheless influential. There are many different methods and indicators for determining criticality and the conclusions regarding which metals are critical can also differ significantly (Schrijvers et al., 2020). For example, different assumptions regarding the relative weighting of supply concentration compared to recycling, led to a critical classification for tin in the UK assessment (Lusty et al., 2022) despite using the same EoL RIR as in the EU assessment (EC, 2023b). A discussion on the usefulness of the criticality concept in general is outside of the scope of this research. However, criticality assessments do influence policy.

The EC (2023b) criticality assessment specifically has influenced the recently proposed Critical Raw Materials Act (EC, 2023a). Therefore, a positive side effect of reclassifying tin as critical for the EU would be increased policy attention, which could help improve data quality, as well as increase the resilience of the EU and global tin supply chains. Tin supply chain resilience can be improved by diversifying supply, exploration, stockpiling, and increasing circularity.

4.2 | Tin circularity (reduction, reuse, and recycling)

Tin circularity can be improved by reducing demand through substitution and intensity reduction. Innovation efforts should especially focus on substitutes for solder, the largest, fastest growing, and most difficult to substitute application (ITA, personal communication, 2022). The tin intensity of tin cans has already decreased considerably over time (Sibley, 2011). This reduction has positively impacted the economics of tin cans, but negatively impacted the economics of detinning and functional recycling (Ciacci et al., 2015; Izard & Müller, 2010). This highlights a trade-off between circularity mechanisms.

Tin circularity can also be improved by reducing losses along the supply chain. We introduced the UR indicator to gain more insight into pre-use tin efficiency. Currently, only about 58% of incoming tin ends up in use. The rest is either lost (28%) or remains in the new scrap cycle (14%). The new scrap cycle reflects production inefficiency that could be addressed by reducing total manufacturing waste, even though this also reduces RIR, which again highlights a trade-off.

“Reduce” is preferred over “recycling” in terms of circularity (Potting et al., 2017; Zhang et al., 2022). Therefore, both intensity reduction and manufacturing waste reduction can be considered beneficial even though they reduce recycling. However, it is also important to consider the system dynamics at play, and in future research it would be interesting to asses potential rebound effects related to these circularity trade-offs, on both the tin and the steel cycles.

Tin circularity can further be improved by increasing the useful time in use through reuse and durability increase. We used average product lifetime to indicate the average time between tin entering and exiting use (Izard & Müller, 2010). We assumed that this indicator includes both initial lifetime and additional time in use due to circularity strategies, but excludes hibernating stocks that do not contribute to utility. We include these stocks as part of the landfill stock. However, hibernating stocks may be quite significant (WEF, 2018) and have the potential to contribute to increased recycling. In that sense, they may behave in a similar manner to stockpiles. A limitation of our research is that we did not explicitly include these hibernating stocks. Indicators exist that take into account hibernating stocks (Moraga et al., 2021), and these could be applied to tin in future research if suitable data becomes available.

A specific focus of our research is recycling. Most tin recycling is post-production recycling, which does not directly increase utility or contribute to supply security (Helbig et al., 2021). Most EoL tin recycling occurs in alloy form, of which about half is recycled in a non-functional manner. The recycling of tin cans is very high. This looks good for tin on the surface, but since it is mostly non-functional, it leads to losses in the tin cycle and contamination of the steel cycle. Graedel et al. (2022) recently expressed increased concern for critical metals with a high alloy share and low functional recycling. This makes it all the more relevant to properly distinguish between different types of recycling.

4.3 | The risks of "recycling" recycling indicators

Recycling indicators impact both circularity and criticality assessments, and the policy decisions based on these assessments. Classifying a material as "critical" highlights economic importance and supply risks and can lead to increased efforts to reduce these risks. Labeling a material as more "circular" can be used by companies and sectors to advertise their "sustainability." Therefore, it is important to carefully consider the validity of indicators used for a specific exercise; how well do they indicate what they are meant to indicate? Below, we discuss the risks related to the problematic reuse of recycling indicators.

Problematic reuse of recycling indicators occurs either by creating or by copying errors. Errors are created when a value that was correct in the context of a previous publication becomes incorrect when it is reused in a new context. Regarding time and scope, an example is the potential interpretation of 1998 EoL RIR data for the United States as global data for 2011 (UNEP, 2011) or EU data for 2014 (EC, 2014). Regarding indicator type, an example is the EC (2017, 2020, 2023b) interpreting RIR data from the ITA as EoL RIR data. Errors are copied when indicators that have been incorrectly calculated, defined, or interpreted in a previous publication are reused, for example, Lusty et al. (2022) copying the EC (2020) EoL RIR data.

There are several reasons for confusion when interpreting recycling indicators. In some cases, recycling indicator values can be kept intentionally vague for the purpose of greenwashing. In other cases, the large variety of indicators and ways in which these can be calculated and defined can lead to accidental errors and misinterpretations. Adding to the risk of confusion, different names are used for the same phenomenon. For example, we use (EoL) RIR to represent the amount of (EoL) secondary production divided by total primary and secondary production (Tercero Espinoza & Soulier, 2018). However, other authors may use different terms such as the "degree of circularity" (Haas et al., 2015). Another term that is often used synonymously to RIR is recycled content (RC) (UNEP, 2011). However, RC and RIR can also differ, especially for a regional scope (Tercero Espinoza & Soulier, 2018). There are many different ways to calculate regional recycling, which can lead to a wide range of values (Passarini et al., 2018). Not all these values are useful for criticality assessment, in which self-sufficiency is more important than actual recycled content.

Tracking and transparency help limit misinterpretation of indicators. Reusing recycling indicators is common in research and often unavoidable due to the lack of data and time to obtain new data. The use of different terminologies may also be unavoidable due to differences in preferences between researchers. However, to avoid errors as much as possible, it is important to carefully consider the context when selecting which recycling indicator to use; to go back in the literature to identify the original time, scope, and definition of a certain value; and to be transparent about what the value means and how it was obtained. In this research, we have tried to be as transparent as possible about our indicators, and we have mentioned multiple times that they apply to a global scope. In future research, tin should be assessed in more detail specifically for the European scope.

Going forward, circularity and criticality assessment may become increasingly dynamic. The methods and indicators used in the current research are all based on a static situation or on the past. However, material criticality and supply chain resilience are dynamic phenomena that can change over time. The indicators used in the current research may no longer be valid in a prospective dynamic setting. An interesting avenue for future research is therefore the exploration of indicator performance, and potential adaptation of indicators, in a dynamic context.

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CONFLICT OF INTEREST STATEMENT

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

Jessie E. Bradley https://orcid.org/0000-0002-1452-5866
Willem L. Auping https://orcid.org/0000-0003-1898-643X
René Kleijn https://orcid.org/0000-0001-5227-5119
Jan H. Kwakkel https://orcid.org/0000-0001-9447-2954
Benjamin Sprecher https://orcid.org/0000-0002-0136-5656

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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