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Defining regional recycling indicators for metals

An extension of global recycling indicators to regional systems with open boundaries

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Abstract

Recycling indicators are useful for characterizing anthropogenic metal cycles. While there are suitable and generally accepted recycling indicators at the global level, they are not necessarily useful for regional cycles (where the region of interest can be a part of country, an entire country or a group of countries), which are open and interact with other regions such that cross-border flows need to be considered. Herein, we examine the applicability of available (global) recycling indicators to the regional level and, where appropriate, propose modified versions that are both conceptually compatible with the corresponding global indicators and readily accessible through data collected and estimates generated in regional material flow analysis work.

Keywords

Recycling rates, foreign trade.

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1 Introduction

Simple indicators are very useful for capturing and highlighting certain aspects of complex systems. In the case of anthropogenic metal cycles, recycling indicators are a widespread means of global assessment and are used as guidelines or targets in sustainability-related plans and regulations, albeit at the level of product or waste types (e.g., packaging waste, waste electrical and electronic equipment (WEEE), end-of-life vehicles). At the level of individual metals, recycling rates are useful for assessing environmental impacts, e.g. in life cycle assessment (LCA), in assessing resource efficiency, as well as in determining criticality of raw materials (e.g., European Commission, 2011, 2014)

Recycling indicators are usually produced from estimation of the pertinent material flows either for one year (e.g., Ruhrberg, 2006) or for a sequence of years (e.g., Glöser et al., 2013) at the global level. Estimates of these flows are now increasingly available from dynamic models, many of them not global but regional in scope (e.g., Buchner et al., 2015; Chen and Graedel, 2012; Chen et al., 2010). While there are accepted definitions of recycling rates at the global level, these are not necessarily transferable to the regional level because there is a certain amount of material crossing the regional system boundaries at different stages of the cycle (e.g. imports/exports of metal or finished products). This complication is absent in the definition of global recycling rates as the system boundaries there encompass the entire planet.

Herein, we examine the applicability of the global definitions of recycling rates to the regional case and propose selected regional indicators where the global definition is inapplicable.

2 Definition of recycling rates

The International Resource Panel of the United Nations Environmental Programme (UNEP) published an extensive review of the global state of recycling (Graedel et al., 2011; UNEP, 2011) using three key recycling indicators:

1. Old scrap ratio (OSR),
2. Recycled content (used equivalently to the recycled input rate, RIR),
3. End-of-life recycling rate ($EoL\ RR$).

In addition to these, (4) the end-of-life collection rate ($EoL\ CR$), (5) the end-of-life processing rate ($EoL\ PR$), (6) overall recycling efficiency rate ($ORER$) are suggested e.g. by Eurometaux and Eurofer (2012) as pertinent recycling indicators. These definitions have in common that they are based on global flows as illustrated in Figure 1 (top). However, the definition of recycling indicators for regions (parts of countries, countries or groups of countries) needs to take into account flows both entering and exiting the region from the rest of the world.

2.1 Old scrap ratio (OSR)

The old scrap ratio aims to quantify the share of old (or end-of-life, EoL) scrap in the overall recycling flow (Eurometaux and Eurofer, 2012; Graedel et al., 2011), and can be calculated by

$$OSR_{global} = \frac{i}{i + k} \tag{2.1}$$

in the global case, where i is the flow of collected and separated old scrap and k the flow of collected and separated new scrap (see Figure 1). Therefore, the “overall recycling flow” is defined as the sum of new and old scrap collected and separated for recycling.

By direct analogy, the regional OSR should reflect the share of old scrap collected and separated for recycling within a region, compared to the sum of new and old scrap collected and separated for recycling. Since collection and separation are the focus of this indicator, it appears immaterial whether the metal recovery step is meant to occur within the region or elsewhere. Therefore, we propose using Equation (2.1) for the regional case without any changes, and, in particular, without considering scrap imports/exports but interpreting the resulting value of the OSR with caution as significant *unreported/illegal* net scrap imports/exports (compared to the magnitude of i and/or k) can affect it.

It appears impractical to define the OSR otherwise, either at an earlier or at a later point in the cycle. A definition earlier in the cycle, i.e. to quantify the amount of old vs. new scrap collected for recycling

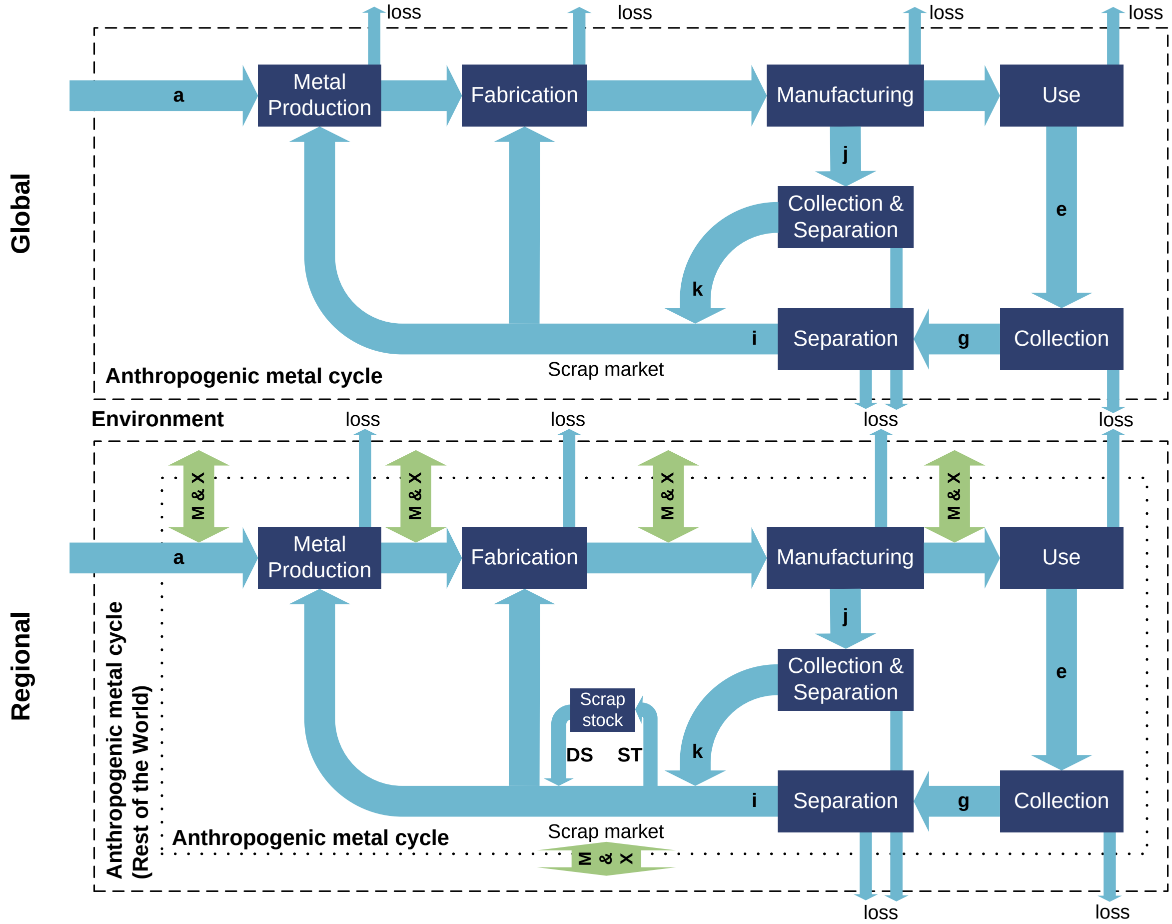

Figure 1: Global (top) and regional (bottom) flows used in the definition of recycling rates. The lettering follows that proposed by Eurometaux and Eurofer (2012) based on Reck et al. (2008), and is compatible with (but not identical to) those used by UNEP (2011) and Graedel et al. (2011). Only letters needed for estimating recycling rates have been depicted.

but before pre-treatment ($g/(g+j)$) would be conceptually incompatible with the global definition. A definition later in the cycle, i.e. one focusing on the amounts of metal recycled in the region of interest suffers from the uncertainty in the origin (EoL/old scrap vs. manufacturing/new scrap) of scrap traded across the regional system boundaries. Moreover, metallurgical losses are generally very small compared to collection and separation losses, such that the OSR as defined in Equation 2.1 appears to better characterize the regional recycling system than a figure including net imports or ignoring net exports of scrap, both new and old.

It is known—but unfortunately not quantified—that scrap collectors can withhold part of the collected scrap, both new and old, for varying periods of time depending on current metal prices. This stocking/destocking is not reflected in Equation (2.1) for practical/data reasons. Furthermore, it is attractive to assume that the stocking/destocking of scrap depends primarily on current metal prices and not on the origin (old vs. new) of the scrap such that this process does not affect the estimation of the OSR.

Therefore, we propose the use of the OSR with exactly the same definition both at the global and regional levels, accepting the limitation regarding trade of discarded products prior to processing as described above.

2.2 Recycled content (RC) and recycling input rate (RIR)

The definition of and distinction between recycled content (RC) and recycling input rate (RIR) suffers from different interpretations of which flows are to be used as a basis for calculation—the selection being often driven by data availability rather than principle (UNEP, 2011). The terms are sometimes used interchangeably and sometimes not (i.e. RC at the level of metal used to make finished products and RIR at the level of metal production including metal produced on-site by semi-manufacturers). In the following, we explore the possibilities of extending both concepts to the regional level.

2.2.1 From the perspective of metal production: Recycling Input Rate (RIR)

Following the production perspective recommended by Eurometaux and Eurofer (2012), the RIR can be calculated as

$$RIR_{global} = \frac{i+k}{a+i+k} \tag{2.2}$$

at the global level, where a is the flow of primary metal into the anthropogenic cycle and i and k are as defined above (see Figure 1). Note that UNEP (2011) suggests using the term RC but the calculation is done following Equation (2.2). The RIR thus quantifies the share of secondary metal in total input (i.e. the sum of primary plus secondary metal) to metal production.

Adaption of this definition to the regional level requires, in principle, three extensions: one on trade of primary material, one on trade of secondary material, and one on stocking/destocking of scrap.

As Graedel et al. (2011) point out, the calculation of the RIR at the global level is therefore much simpler than that at the regional level. A key difficulty is that the recycled content of imported produced metals is typically not available. Fortunately, taking the metal *produced* in the region of interest as the basis for the regional RIR, this limitation becomes irrelevant. Thus, primary metal would be metal in concentrates, both local and imported and secondary material refers only to imports and exports of scrap. This way, the RIR could be defined as follows at the regional level:

$$RIR = \frac{i + k + \overbrace{(M_W - X_W)}^{\text{net imports of scrap}} + \overbrace{(DS_W - ST_W)}^{\text{net input to metal production from scrap stocks}}}{a + \underbrace{(M_C - X_C)}_{\text{net imports of metal in concentrate}} + i + k + (M_W - X_W) + (DS_W - ST_W)} \tag{2.3}$$

where M_C and X_C are imports and exports of metal in concentrates, respectively, M_W and X_W are imports and exports of scrap (both old and new), and DS_W and ST_W are destocking (taking material out of an existing scrap stock) or stocking of scrap, respectively. While data for M and X are generally available (albeit with varying quality) at the country level and by extension also for groups of countries such as the European Union in the form of foreign trade statistics, the quantities DS_W and ST_W are, while widely acknowledged to be non-zero, very difficult to assess quantitatively in practice. Nevertheless, the definition proposed in Equation (2.3) provides a measure of the use of secondary material for metal production in the region of interest while being a compatible extension of the global RIR definition to the regional case. In fact, Equations (2.2) and (2.3) become identical in the absence of trade and stocking/destocking—the latter being implicitly assumed in the global definition.

2.2.2 From the perspective of metal use: Recycled content (RC)

Moving the focus from metal production to metal use in a particular region requires consideration of metal imports/exports in addition to traded scrap and ores/concentrates. This introduces the difficulty that the share of recycled material in the traded metal must be estimated. Addition of cross-boundary flows of metal to Equation (2.3) yields:

$$RC = \frac{\overbrace{(\alpha_1 M_M - \alpha_2 X_M)}^{\text{net recycled metal imports}} + i + k + (M_W - X_W) + (DS_W - ST_W)}{a + (M_C - X_C) + \underbrace{(M_M - X_M)}_{\text{net metal imports}} + i + k + (M_W - X_W) + (DS_W - ST_W)} \tag{2.4}$$

where M_M and X_M are imports and exports of metal, respectively, α_1 is the share of recycled material in imported metal and α_2 is the share of recycled material in metal exports. It appears reasonable to use the RIR following Equation (2.3) as an approximation of α_2. An approximation of α_1 may be made based on one of five possibilities:

1. Assume all imported metal is 100% primary, $\alpha_1 = 0$. This is an acceptable choice for metals

known to be of primary origin but yields an estimation of imported secondary metal that is almost certainly too low otherwise (underestimate RC).

2. Assume all imported metal is 100% secondary, $\alpha_1 = 1$. This choice yields an estimation that is almost certainly too high (overestimate RC).

3. Given knowledge of the global RIR, assume this share for all imported metal, $\alpha_1 = RIR_{global}$. This appears to be a reasonable assumption as long as (a) the region of interest does not play a dominant role in the global anthropogenic cycle while (b) strongly differing in its use of secondary material compared to the global average.

4. Treat imported metal as if it had been produced in the region of interest, $\alpha_1 = RIR$ following Equation (2.3). This option appears less attractive than using the global RIR, but can be used without knowledge of the global cycle.

5. Use some other reasonable assumption based on other data or expert judgment. This may be possible or become necessary, e.g. if the region has large net imports from a subset of countries strongly differing from the global average and from the anthropogenic cycle in the region of interest.

2.2.3 Focusing RIR and RC on end-of-life recycling

A special case of the RIR focuses on the share of old scrap in total metal production. At the global level, this indicator can be obtained by

$$EoL\ RIR_{global} = \frac{i}{a+i+k} = RIR_{global} \times OSR_{global} \approx EoL\ RC_{global} \tag{2.5}$$

and characterizes the share of recycled EoL or post-consumer metal in total metal production, which, neglecting metallurgical losses, is approximately equal to the share of EoL material in metal used. While there is no information gain vis-à-vis reporting a RIR together with an OSR, the $EoL\ RIR$ may be useful when reporting on anthropogenic cycles of metals that have a small OSR, e.g. gallium or indium (cf. Licht et al., 2015). Moreover, $EoL\ RIR \neq RIR \times OSR$ and $EoL\ RIR \not\approx EoL\ RC$ at the regional level because of the differences in OSR applicable both to scrap imports as well as metal imports compared to the OSR in the region of interest.

The extensions outlined above for the RIR and RC at the regional level also apply to the $EoL\ RIR$, but with one further complication: Old and new scrap must be treated separately. Therefore, there are additional quantities to estimate, namely: the share of old scrap in imported and exported metal, imported and exported scrap (new and old scrap are generally reported together in trade statistics), and material going into or coming from scrap stocks. It appears impractical to collect estimates of these parameters for only a modest gain in information content. However, we propose that with some simplifying assumptions, these calculations become manageable, provided the global cycle is sufficiently known. We make a proposition for this in the Appendix.

2.3 End-of-life recycling rate ($EoL\ RR$)

The end-of-life recycling rate quantifies the fraction of metal contained in EoL products that is collected, pre-treated, and finally recycled back into the anthropogenic cycle (Eurometaux and Eurofer, 2012). At the global level, this quantity is estimated by

$$EoL\ RR_{global} = \frac{i}{e} \tag{2.6}$$

and implicitly neglects metallurgical losses incurred after pre-treatment, which tend to be low. Nevertheless, a more accurate translation of Equation (2.6) into words would be that the end-of-life recycling rate quantifies the efficiency of collection of end-of-life scrap and its pre-treatment in preparation for secondary metal production.

Use of Equation (2.6) at the regional level would measure the efficiency of the region's waste management system in supplying pre-processed scrap of local origin for recycling *anywhere*. Therefore, we are of the opinion that Equation (2.6) should also be applied at the level of regions without modification and that addition of trade flows to this equation would lead to misinterpretations rather than a better assessment of the regional waste management system.

Note that, despite the fact that Equation (2.6) is based on flows prior to formal trading of pre-processed/separated scrap, *unreported/illegal* scrap trade does affect the value of the $EoL\ RR$ if these flows are significant compared to i. This is relevant in particular for metals contained in waste electrical and electronic equipment (WEEE)—an activity widely acknowledged to exist but inherently difficult to quantify. In case of net exporters, e.g. WEEE leaving the EU, the existence of unreported exports leads to a lower value of the $EoL\ RR$. We postulate that this is not a flaw in the indicator since WEEE collected but not processed for recycling in the EU can be seen as a "loss" in the collection process (the collected WEEE is not passed on the following separation process). Therefore, the existence of unreported exports correctly leads to a lower $EoL\ RR$ and points to a potentially fruitful area of improvement.

The way unreported/illegal imports affect the $EoL\ RR$ for net importers of said scrap ultimately depends on the fate of the imported WEEE. If the discarded products (e.g. WEEE) are landfilled, there is no effect on the indicator for the importing region. If the discarded products are immediately recycled, the estimated $EoL\ RR$ will be higher than expected. If the discarded products go back into use (possibly after repair/refurbishment), they will affect the $EoL\ RR$ only after a time delay corresponding to the extended use. In this case, the magnitude of the effect will depend on the relative amount of imported discarded products for further (“second”) use compared to the amount of new products going into use at the same time (assuming similar lifetimes). Therefore, as with any indicator, it is necessary to consider the features of the system being described when interpreting the value of the $EoL\ RR$.

2.4 Other recycling indicators

Other recycling indicators proposed by Eurometaux and Eurofer (2012), namely, the

$$\text{end-of-life collection rate, } EoL\ CR = \frac{g}{e} \tag{2.7}$$

$$\text{end-of-life processing rate, } EoL\ PR = \frac{i}{g} \tag{2.8}$$

$$\text{overall processing rate, } OPR = \frac{i+k}{g+j} \tag{2.9}$$

$$\text{overall recycling efficiency rate, } ORER = \frac{i+k}{e+j} \tag{2.10}$$

all have in common that, when applied to the regional level, they all take as basis domestic scrap, both old and new, either collectable or collected. As was the case for the OSR and $EoL\ RR$, modifying the definitions in Equations (2.7)– (2.10) would not lead to a more accurate representation of the regional waste management and recycling system but to a misrepresentation of their performance and needs for improvement.

3 Conclusion

We examined a series of recognized recycling indicators defined at the global level and explored their usefulness for describing regional metal cycles. The guiding idea was that, as a result of their openness, global definitions of recycling indicators applied to regional anthropogenic cycles without considering flows across the system boundaries could lead to a potentially serious misrepresentation of the efficiency of regional systems under scrutiny.

Upon closer examination, most recycling indicators refer to the collection and pre-processing (dismantling, mechanical separation) of scrap prior to the final metallurgical step. The reason for this is a generally very high efficiency of metal recovery once the scrap has been properly collected and separated. Since *legal* trade in scrap occurs after collection and separation, the global definitions of these indicators are directly applicable to regional anthropogenic cycles. In fact, inclusion of trade would falsify the meaning and the results of these indicators.

Exceptions to this are the recycling input rate, RIR and the recycled content (RC, sometimes used interchangeably), which aim to measure the share of secondary metal produced or used in the region of interest. In this case, both trade of scrap and metal need to be considered. We propose a modification of the equations used to calculate RIR and RC (and the related $EoL\ RIR$ and $EoL\ RC$) together with recommendations on simplifying assumptions that make the increased data requirements manageable. We believe these modified definitions of RIR and RC lead to a more accurate characterization of regional anthropogenic cycles and their availability could add to the information gained from regional MFA studies.

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A End-of-life recycling input rate ($EoL\ RIR$) at the regional level

Adapting Equation (2.3) to account for old scrap only, we obtain:

$$EoL\ RIR = \frac{i + \overbrace{(\gamma_1 M_W - \gamma_2 X_W)}^{\text{net imports of old scrap}} + \overbrace{(\delta_1 DS_W - \delta_2 ST_W)}^{\text{net destocking of EoL scrap}}}{a + (M_C - X_C) + i + k + (M_W - X_W) + (DS_W - ST_W)} \quad \text{(A.1)}$$

where γ_1 the share of old scrap contained in scrap imports, γ_2 the share of old scrap contained in scrap exports, δ_1 the share of old scrap exiting stocks and δ_2 the share of old scrap entering stocks. The denominator remains unchanged compared to Equation (2.3).

For γ_1, we propose to follow an equivalent logic to that proposed for α_1 in the main text. Furthermore, we propose that γ_2 may be taken to be the OSR for the region of interest, provided no special circumstances are given, such as an inability to process certain types of scrap (usually EoL scrap) in the region of interest or a clear competitive advantage/disadvantage in processing certain types of scrap.

For stocking/destocking, $\delta_1 \approx \delta_2$ appears to be a useful and reasonable simplification (δ in the following). However, it is not immediately clear what the value of δ should be. If the region is scrap rich[1] it will tend to export more scrap than it imports, that is, $(M_W - X_W) < 0$ and δ should resemble the share of old scrap predominant in the region of interest. Conversely, if the region is scrap poor, it will tend to import more scrap than it exports, $(M_W - X_W) < 0$, and stocking/destocking flows will more closely resemble the import flows of scrap. Therefore, we propose the following simplification:

$$\delta = \begin{cases} OSR_{region} & \text{if } (M_W - X_W) < 0 \text{ (region is net exporter of scrap)} \\ OSR_{global} & \text{if } (M_W - X_W) > 0 \text{ (region is net importer of scrap)} \end{cases} \quad \text{(A.2)}$$

Combining all simplifications, we arrive at

$$EoL\ RIR = \frac{i + \overbrace{(OSR_{global}\, M_W - OSR\, X_W)}^{\text{net imports of old scrap}} + \overbrace{\delta(DS_W - ST_W)}^{\text{net destocking of EoL scrap}}}{a + (M_C - X_C) + i + k + (M_W - X_W) + (DS_W - ST_W)} \quad \text{(A.3)}$$

where γ_1 and γ_2 have been substituted by OSR_{global} and OSR for the region of interest, respectively, and δ is estimated by Equation (A.2).

[1] The term "rich" (resp. "poor") here is to be understood relative to the region's ability to recycle said scrap profitably and in its entirety.

B End-of-life recycled content ($EoL\ RC$) at the regional level

We arrive at the definition of $EoL\ RC$ by extending Equation (A.3) to account for metal import/exports and their respective shares of EoL secondary material:

$$EoL\ RC = \frac{\overbrace{(\beta_1 M_M - \beta_2 X_M)}^{\text{net recycled (EoL) metal imports}} + i + \overbrace{(OSR_{global}\, M_W - OSR\, X_W)}^{\text{net imports of old scrap}} + \overbrace{\delta(DS_W - ST_W)}^{\text{net destocking of EoL scrap}}}{a + (M_C - X_C) + (M_M - X_M) + i + k + (M_W - X_W) + (DS_W - ST_W)} \quad \text{(B.1)}$$

where β_1 is the share of recycled material from old scrap contained in metal imports and β_2 the share of recycled metal from old scrap in metal exports. The denominator remains unchanged compared to Equation (2.4).

We propose to choose the value of β_1 following the logic outlined for the estimation of α_1. Furthremore, we postulate that

$$\beta_1 \approx OSR_{global} \quad \text{(B.2)}$$

is a reasonable and practical approximation as long as (a) the region of interest does not play a dominant role in the global anthropogenic cycle while (b) strongly differring in its use of secondary material compared to the global average. Furthermore, we postulate that

$$\beta_2 = OSR_{region} \quad \text{(B.3)}$$

is a reasonable value provided the quality of recycled metal is comparable to that of primary metal.

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