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Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data

Supporting the EU-28 Raw Materials and Circular Economy policies through RMIS

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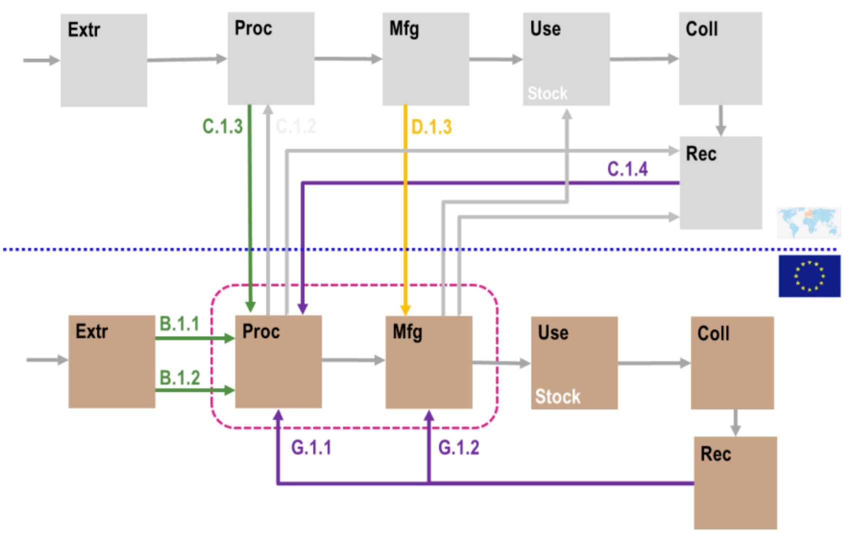

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Contents

Abstract

Relevant and reliable recycling data and indicators are vital to key EU policies related to raw materials, waste management, and circular economy, in order to better understand the present and monitor the progresses towards the future.

In the 2016 Raw Materials Scoreboard and in the context of the 2017 list of critical raw materials (CRM) for the EU, the selected recycling indicator is the end-of-life recycling input rate (EOL-RIR). EOL-RIR reflects the total material input into the production system that comes from recycling of post-consumer scrap and is regarded as a robust measure of recycling’s contribution to meeting materials demand in the EU (input perspective). EOL-RIR meets in fact the so-called "RACER criteria", i.e. it is considered Relevant, Accepted, Credible, Easy and Robust. The same indicator (EOL-RIR) is also adopted in the Circular Economy monitoring framework.

With the above in mind, the objective of this report is threefold: (1) consolidate the methodology to calculate EOL-RIR (Principal recycling indicator), update relevant data, and fill data gaps, (2) identify a meaningful complementary recycling indicator, namely the end-of-life recycling rate (EOL-RR), focused on how efficient recycling industries and recycling routes in the EU are (output perspective), and (3) explore a methodology for estimating recycling potentials (future orientated perspective).

Building on a previous JRC report[1], the key methodological issues related to the principal indicator EOL-RIR are described. Further guidance is provided, in particular, on how to handle multiple data sources in order to: (a) progressively switch from global to regional (EU-28) flows, (b) optimise the use of EU Material System Analysis (MSA) data, (c) ensure the highest level of comparability while mixing EU MSA, Global UNEP/IRP, and industry data. The most updated EOL-RIR figures for 78 raw materials are shown.

Methodological details for the complementary recycling indicator (EOL-RR) are provided and results are shown for selected materials. EOL-RR captures the amount of secondary materials recovered and functionally recycled at end-of-life compared to the overall waste quantities generated, (output-related indicator). It therefore provides complementary information about the performance of the collection and recycling sector and is thus useful from a recyclers’ perspective. Results show that although EOL-RR is relatively high for several materials, which is synonymous with high efficiency of the EU recycling industries, recycling's contribution to overall demand (EOL-RIR) can be much lower, which can be explained as fast growing demand and/or expanding in-use stocks. A set of recycling indicators, rather than just one single indicator, is therefore needed.

The estimate of recycling potentials (Additional recycling indicators) has shown to be an interesting exercise, with promising perspectives as a field of future investigation. The EOL-RIR (potential) can be estimated using the same system boundaries as the EOL-RIR, by considering the amount of material recoverable from non-dissipative end-use applications, under the assumption that the current demand, quantity of products collected for treatment, and import and export flows remain unchanged (‘snapshot in time’). The methodology is illustrated with few examples (Indium and Tungsten).

A general conclusion is that recycling indicators need to be assessed by taking into account materials individually and using material system analyses (MSA)-derived data. Further expansion of raw materials coverage in MSA studies is needed and an update of the 2015 MSA study is advisable, as it used 2012 data, which is partly outdated. The EU Raw Materials Information System (RMIS) can play a key role for better collection, storage, and harmonisation of material flow related data in the EU.

[1] Blengini et al. Assessment of the Methodology for Establishing the EU List of Critical Raw Materials, Publications Office of the European Union, Luxemburg, 2017, 978-92-79-69611-4, doi:10.2760/130462, JRC106997

1 Introduction

1.1 Background

Recycling contributes to the security of supply of raw materials and helps improve the circularity of materials in the EU economy. It is seen as a risk-reducing factor in the EU Criticality Assessment (EC, 2011, 2014, 2017; Blengini *et al.*, 2017) and in criticality frameworks used elsewhere (Dewulf *et al.*, 2016). Recycling is also regarded as a tool for improving sustainability due to the potentially lower environmental impacts of secondary materials provision when compared to primary raw materials production.

Recycling is also expected to contribute to boosting EU competitiveness as set out in the European Commission's Circular Economy Action Plan (EC, 2015). However, as highlighted in the Raw Materials Scoreboard (Vidal-Legaz *et al.*, 2016) and in the Circular Economy (CE) monitoring framework (Mathieux *et al.*, 2017; EC, 2018), the contribution of recycling to overall material inputs is currently low in the EU.

The main factors that currently limit the contribution of recycling to meet demand for raw materials in the EU (Vidal-Legaz *et al.*, 2016) can be summarised / interpreted as: (1) recycling of many materials from end-of-life products and waste streams is currently not economically feasible; (2) there is a lack of suitable technologies available for recycling; (3) some materials are embodied in products stocked in use for long time periods (e.g. buildings or wind turbines); (4) demand for many materials is growing. A set of recycling indicators, rather than just one single indicator, is likely needed.

Recycling rates can be estimated at different points in the recycling chain and, more in general, in the materials flow cycle and in the context of a circular economy. Selected recycling rates can therefore inform raw materials and circular economy policies in a complementary manner, providing a better understanding of (1) the current situation and (2) monitoring progresses towards desired ends.

The end-of-life recycling input rate (**EOL-RIR**) reflects the total material input into the production system that comes from recycling of post-consumer scrap (**input perspective**). EOL-RIR is currently used in the EU Raw materials scoreboard and in the CE Monitoring Framework, as well as in the context of the list of Critical Raw Materials (CRMs) for the EU. The end-of-life recycling rate (**EOL-RR**) is the share of a material in waste flows that is actually recycled (**output perspective**). EOL-RR is used in Monitoring CE and as a complementary indicator in the 2018 Raw materials scoreboard.

At the global level, research shows that EOL-RRs are relatively low for many metals (only for 18 metals is the EOL-RR above 50%) (Graedel *et al.*, 2011; UNEP, 2011). Because of increases in material use over time and long in-use life-time for some products, many EOL-RIR values are sensibly lower than the correspondent EOL-RRs.

If data quality and availability is certainly a limiting factor at global level (UNEP, 2011), calculating regional (EU-28 specific) recycling indicators, which is fundamental to better support EU policies, is even more challenging. In fact, beyond the limited availability of EU-specific data on recycling, the recent JRC work (Blengini *et al.*, 2017; Mathieux *et al.*, 2017) and literature (Ciacci *et al.*, 2017; Passarini *et al.*, 2018; Soulier *et al.*, 2018; Tercero Espinoza and Soulier, 2018) have highlighted the need for and the methodological challenges of incorporating trade flows in the calculations. There are in fact sensible differences among recycling at global vs EU levels, for several raw materials, and with reference to different stages in the supply chain. Moreover, when analysing at regional level, trade flows at several stages can change the picture to a large extent. Trade flows need therefore to be incorporated in the calculations in a meaningful, consistent and reasonably workable manner.

It is crucial to identify the most appropriate recycling indicators and underlying data. In such a context, the **Raw Materials Information System (RMIS)** plays a key role in setting the conditions and progressively improve the quality and availability of the data.

1.2 Goal and structure of this report

The main objective of this report is to consolidate the methodology and identify the best available data that lead to meaningful **recycling indicators** in support of:

- the list of Critical Raw Materials (CRMs) for the EU[2];
- Monitoring the EU raw materials sector (RM scoreboard[3]);
- Monitoring Circular Economy[4].

For the three above policy tools and related frameworks, the **Principal recycling indicator** adopted by the EC is the so-called *End-of-life Recycling Input Rate* (**EOL-RIR**), which is defined as the ratio of secondary raw materials obtained through recycling of products, which reached end-of-life, divided by the overall quantity of raw materials fed into the economy[5].

(1) The first specific objective of this report is to consolidate the methodology and identify the best available data to calculate the **Principal recycling indicator (EOL-RIR)** for a wide range of raw materials (78 candidate CRMs) and with reference to the EU.

A preference is given to using EU regional flows in the calculations, paying attention to the level of comparability when using multiple sources (global vs EU), in view of an advisable expansion of EU Materials System Analysis data availability in the coming years.

A cascade approach is adopted:

- Material System Analysis (MSA) data (BIO by Deloitte, 2015; Passarini *et al.*, 2018) are used as a first choice;
- UNEP / IRP (UNEP, 2011) data are used when MSA data are not available;
- Industry data are used when none of the above are available.

The methodology, some calculation examples and the first results related to the Principal recycling indicator (EOL-RIR) are discussed in chapter 2 and in the Annexes.

(2) A second specific objective is to identify a meaningful **Complementary recycling indicator**, which can be used in combination with the principal one (EOL-RIR) and provide details on how efficient recycling industries and recycling routes in the EU are.

In fact, the principal indicator (EOL-RIR), which certainly depends on how effective are collection and recycling in the EU, is also heavily influenced by other flows such as, for instance, growing demand and long-term in-use stocks.

In such a context, even an excellent performance in terms of collection and recycling of products at end-of-life might turn in a less brilliant performance, when looking at the contribution to satisfy raw materials demand. A possible explanation could be that e.g. demand is growing fast or e.g. materials will still be in use for the next few decades, and are therefore not available for recycling at the time of determination.

The selected Complementary recycling indicator, adopted in the RM scoreboard (2018 edition) and in CE monitoring (Mathieux *et al.*, 2017), is the so-called *End-of-life Recycling Rate* (**EOL-RR**), which is defined as the ratio of secondary raw materials

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[2] COM/2017/0490 final
[3] http://rmis.jrc.ec.europa.eu/?page=scoreboard
[4] COM/2018/029 final
[5] See also Eurostat: http://ec.europa.eu/eurostat/web/products-datasets/product?code=cei_srm010

obtained through recycling of products that reached end-of-life, divided by the raw materials content of products that have reached end-of-life in the year of determination.

The methodology, some calculation examples and the first results related to the Complementary recycling indicator (EOL-RR) are discussed in chapter 3.

(3) A third specific objective of this report is to explore some possible forward-looking **Additional recycling indicators**, which could inform about the potential expansion of recycling in the coming years, as well as the potential in terms of covering demand of raw materials in the EU.

Two recycling rates are used, **EOL-RR(potential)** and **EOL-RIR(potential)**, which can be regarded as the forward-looking version of the Principal (EOL-RIR) and Complementary (EOL-RR) indicators, under given assumptions and simplifications.

This last group of recycling indicators, currently not in use in any of the three above EU policy tools, is more speculative, as all the flows used to calculate both the Principal and the Additional recycling indicators are mostly based on the current flows (i.e. import and export flows), which are likely to change in the future, for a range of reasons.

The methodology, some calculation examples and the first results related to the Additional recycling indicators, EOL-RR(potential) and EOL-RIR(potential), are discussed in chapter 4.

2 The Principal recycling indicator (EOL-RIR) in the EU-28

Regional materials flows for the European Union (EU-28) that are needed to calculate the *End-of-life Recycling Input Rate* (EOL-RIR) are increasingly available through the European Commission's (EC) Raw Material System Analysis (MSA) (BIO by Deloitte, 2015; Passarini *et al.*, 2018) and the Raw Materials Information System (RMIS)[6].

The MSA study offers in good detail the input and output flows, and stocks of materials throughout the EU economy. One of the interesting aspects of the MSA data compared to global flow analysis is the inclusion of import and export flows to each of the stages of the life cycle of a material. Including such flows helps understand the stage and the form raw materials enter the EU. One of the findings well-illustrated in the MSA diagrams is that for many materials the extraction and processing stages are mainly located outside Europe. As consequence, many raw materials enter the EU as intermediates at the manufacture and as end-products at the use stages. For example, over 70% of Beryllium enters as end product at the use stage while the remaining 30% enters as intermediate at the manufacture stage.

2015 MSA study and 2018 MSA Study expansion

In 2012, the European Commission launched the *Study on Data Needs or a Full Raw Materials Flow Analysis* with the objective to support the EC in identifying the information and data needs for a complete raw material flow analysis at the European level. The study focused on information collection for 20 materials or groups of materials from a range of publicly available data bases. In 2015, The study was followed up by the project called *Study on data for a Raw Material System Analysis (MSA) (*BIO by Deloitte, 2015*)*. The MSA study aimed to provide a complete overview of existing data sources adapted to material system analysis in Europe, a detailed methodology on establishing MSA in Europe, a complete material system analysis for 28 materials, and recommendations for their maintenance and update. Both projects used the concept of Material System Analysis defined by OECD "*as a material specific flow accounts. MSA focuses on selected raw materials or semi-finished goods at various levels of detail and application (e.g. cement, paper, iron and steel, copper, plastics, timber, water) and considers life-cycle-wide inputs and outputs*".

In 2017 the JRC, in coordination with DG GROW, launched a second MSA Study targeting three base metals: Copper, Aluminium and Iron Ore. This study was completed in 2018 (Passarini *et al.*, 2018).

MSA data (EU-28 regional data) are currently available for 31 raw materials.

As MSA data availability is clearly insufficient to cover all the raw materials of interest, a cascade approach is adopted:

1. MSA data are used as a first choice (EU-28 regional data);
2. UNEP / IRP data are used when MSA data are not available (global data);
3. Industry data are used when none of the above is available (EU-28 regional data or global data).

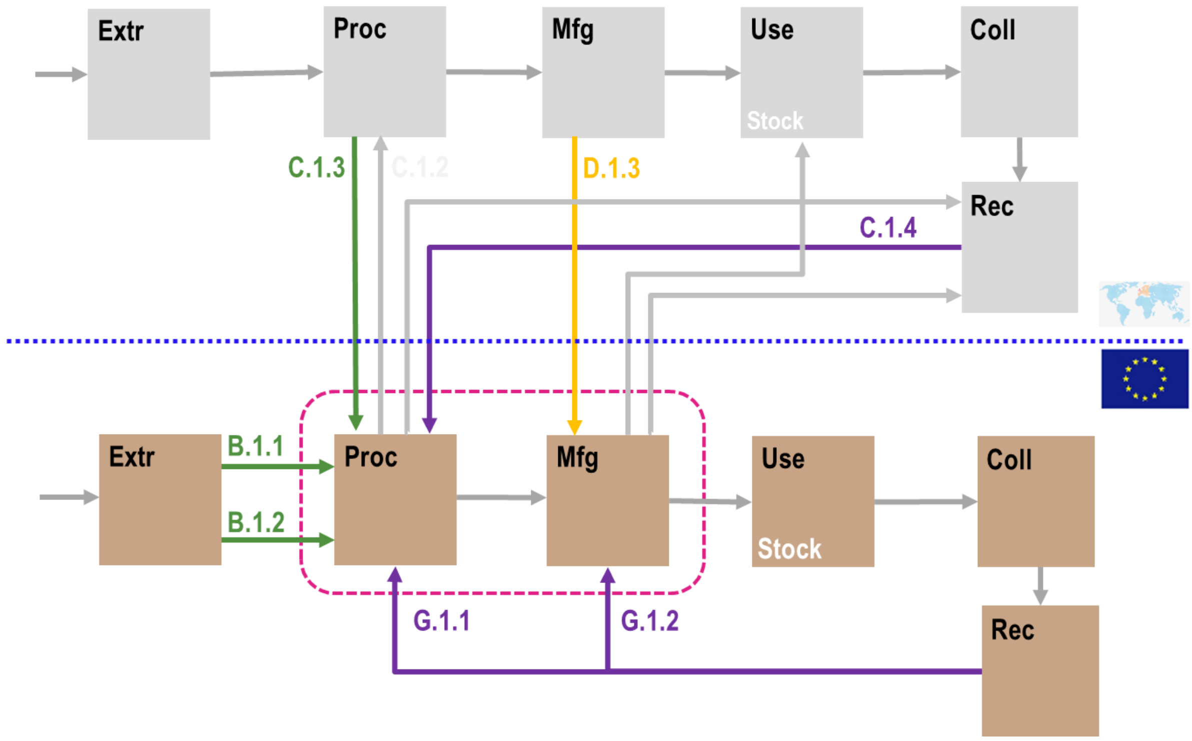
2.1 Calculating EOL-RIR with MSA data

Figure 1 illustrates the flows of the material inputs and outputs taken into account for the calculation of the 'end of life recycling input rate (EOL-RIR)'. The system boundaries defined to calculate the EOL-RIR include the 'processing' and the 'manufacture' stages of a material in Europe. Flows in green refer to primary production, the flow in yellow

[6] http://rmis.jrc.ec.europa.eu/

represents an import of primary material and flows in purple illustrate secondary materials from old scrap.

Figure 1 System boundaries and material flows included in the calculation of the EOL-RIR[7].



Extr: Extraction; Proc: Processing; Mfg: Manufacturing; Coll: Collection; Rec: Recycling

Based on the material flows described in Figure 1, the equation below is adopted:

$$\mathrm{EOL-RIR\ (current)} = \frac{\mathrm{G.1.1+G.1.2}}{\mathrm{B.1.1+B.1.2+C.1.3+D.1.3+C.1.4+G.1.1+G.1.2}} \qquad \text{(eq 1)}$$

The EU 'secondary production (old scrap)' flows are:

- **G.1.1** Production of secondary material from post-consumer functional recycling in EU sent to processing in EU
- **G.1.2** Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU

'Primary production' flows are:

- **B.1.1.** Production of primary material as main product in EU sent to processing in EU
- **B.1.2.** Production of primary material as by product in EU sent to manufacturing in EU

'Imports flows' are:

- **C.1.3** Imports to EU of primary material
- **C.1.4** Imports to EU of secondary material
- **D.1.3** Imports to EU of processed material

Two calculation examples are provided in the boxes below.

[7] Source: EC Critical Raw Materials Background Report (Blengini *et al.*, 2017).

Box 1 Example of the calculation of EOL-RIR for tungsten.

The EOL-RIR for tungsten is calculated using data from the MSA study (BIO by Deloitte, 2015). The material flows used for the calculations are those shown in Figure 1 and the equation above.

Flows of tungsten in the EU	Quantity (tonnes)
B.1.1 Production of primary material as main product in EU sent to processing in EU	869
B.1.2 Production of primary material as by product in EU sent to processing in EU	0
C.1.3 Imports to EU of primary material	2,583
C.1.4 Imports to EU of secondary material	73
D.1.3 Imports to EU of processed material	10,883
G.1.1 Production of secondary material from post consumer functional recycling in EU sent to processing in EU	2,627
G.1.2 Production of secondary material from post consumer functional recycling in EU sent to manufacture in EU	7,603

Using the values above, the EOL-RIR for tungsten is estimated to be:

$$\mathrm{EOL-RIR_W} = \frac{2{,}627 + 7{,}603}{869 + 2{,}583 + 10{,}883 + 73 + 2{,}627 + 7{,}603}$$

$$\mathrm{EOL-RIR_W} = \frac{10{,}231}{24{,}638} = 0.4152$$

The EOL-RIR calculated above means that the recycling of tungsten from EOL products at present provides about 42% of its total demand in the EU.

Box 2 Example of the calculation of EOL-RIR for indium.

Analogously to tungsten, the EOL-RIR for indium is calculated using data from the MSA study (BIO by Deloitte, 2015) considering the material flows in Figure 1 in the equation above.

Flows of indium in the EU	Quantity (tonnes)
B.1.1 Production of primary material as main product in EU sent to processing in EU	0
B.1.2 Production of primary material as by product in EU sent to processing in EU	99
C.1.3 Imports to EU of primary material	17
C.1.4 Imports to EU of secondary material	8.3
D.1.3 Imports to EU of processed material	61
G.1.1 Production of secondary material from post consumer functional recycling in EU sent to processing in EU	0.2
G.1.2 Production of secondary material from post consumer functional recycling in EU sent to manufacture in EU	0

Using the values above, the EOL-RIR for indium is estimated to be:

$$\mathrm{EOL-RIR_{In}} = \frac{0.2}{99 + 17 + 61 + 8.3 + 0.2}$$

$$\mathrm{EOL-RIR_{In}} = \frac{0.2}{185.5} = 0.0011$$

As illustrated in the result above, the contribution of the recycling of indium from EOL products to its total demand in the EU is currently negligible.

As highlighted in the introduction, trade flows at several stages can change the picture, sometimes to a large extent.

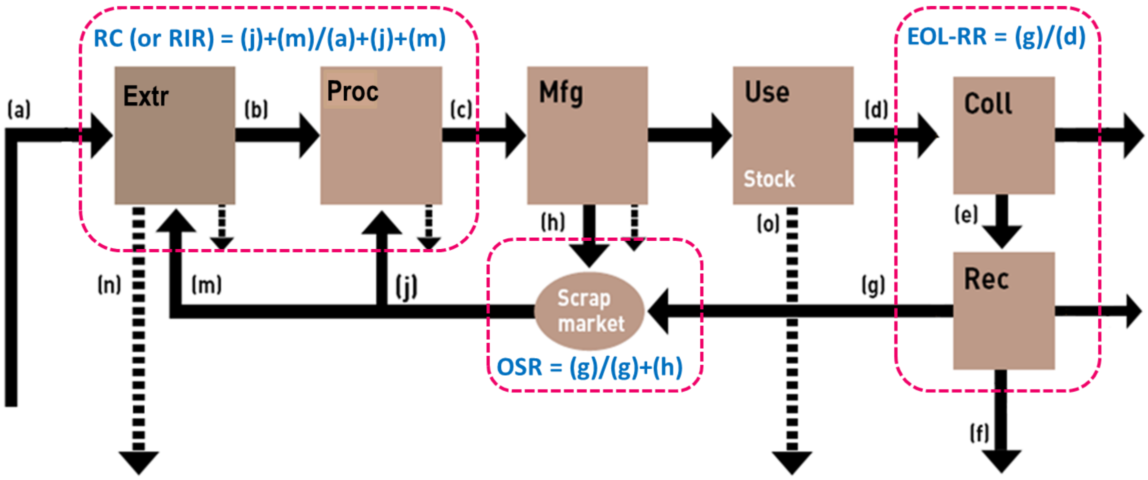
For this reason, four alternative system boundaries for calculating EOL-RIR with MSA data were also discussed (see Annex 2). The accounting for trade flows used for the examples of Tungsten and Indium (regarded as option C) is that selected in the context of the revision of the EC criticality assessment methodology. The remaining three alternatives (Options A, B and D), as well as some calculations and comparisons, are shown in Annex 2.

2.2 Calculating EOL-RIR with UNEP/IRP data

In the report 'recycling rates of metals – a status report' by UNEP, recycling is expressed by three main metrics: old scrap ratio (OSR), recycled content (RC), and end of life recycling rate (EOL-RR) (UNEP, 2011). The OSR describes the fraction of old scrap to the overall scrap market, which includes new scrap from manufacturing. The RC is the fraction of secondary metal (old and new scrap) in the total metal input to the total metal production. RC is sometimes also referred to as recycling input rate (RIR). The EOL-RR refers to the amount of old scrap in the product reaching their EOL. It refers to functional recycling only that is "the portion of EOL recycling in which the metal in a discarded product is separated and sorted to obtain secondary materials".

Figure 2 illustrates the life cycle stages of one exemplary metal. The boxes represent the main stages while the black arrows the flow of metal entering and leaving each stage. Dash arrows indicate losses of the exemplary metal. The system boundaries used to define each of the recycling metrics proposed by UNEP are represented by dashes (pink). The diverse equations to calculate recycling indicators are included inside each of the three system boundaries defined.

Figure 2 System boundaries and flows to estimate diverse recycling indicators for a metal life cycle. Modified from (UNEP, 2011).



(a): primary metal input; (b): refined metal; (c): intermediate products (e.g. alloys, semis); (d): EOL products (metal content); (e): EOL metal collected for recycling; (f): EOL metal separated for non-functional recycling; (g): recycled EOL metal (old scrap); (h): scrap from manufacturing (new scrap); (j) scrap used in fabrication (new and old scraps); (m): scrap used in production (new and old scrap); (n): tailings and slag); (o): in-use dissipation. **Extr:** ***Extraction***; **Proc:** ***Processing;*** **Fab:** ***Fabrication;*** **Mfg:** ***manufacturing;*** **Coll:** ***collection;*** **Rec:** ***recycling***

UNEP definitions of old scrap ration (OSR) and recycled content (RC) can be used to estimate the 'end of life recycling input rate' as defined by the EC criticality methodology. Thus, including only the contribution of old scrap to the total production of a material. 'End of life recycling input rate' values can be deducted from UNEP equations as:

$$OSR = \frac{Input\ of\ secondary\ material\ (only\ old\ scrap)}{Total\ of\ secondary\ material\ (new\ and\ old\ scraps)} = \frac{(g)}{(g)+(h)} \qquad (eq\ a)$$

$$RC = \frac{Input\ of\ secondary\ material\ (new\ and\ old\ scraps)}{Input\ of\ primary\ material + Input\ of\ secondary\ mat.(new\ and\ old\ scraps)} = \frac{(j)+(m)}{(j)+(m)+(a)} \qquad (eq\ b)$$

Given the fact that:

$$Secondary\ material\ (new\ and\ old\ scrap) = (g) + (h) = (j) + (m) \qquad (eq\ c)$$

$$EOL - RIR = OSR \times RC = \frac{Input\ of\ secondary\ material\ (only\ old\ scrap)}{Input\ of\ primary\ mat. + Input\ of\ secondary\ \ mat.(new\ and\ old\ scraps)} \qquad (eq\ d)$$

The UNEP report provides several recycling values for OSR and RC estimates, also many times from different data sources. To estimate the end of life recycling input rate (EOL-RIR) only considering the contribution from old scrap, we first calculate the average values of UNEP's OSR and RC. Then, we use *equation d* to estimate the EOL-RIR.

Some calculations and comparison are shown in Annex 3.

2.3 Calculating EOL-RIR with Industry data

When MSA and UNEP data are not available, JRC recommends using recycling rates from previous EC criticality reports, or data available in scientific and technical publications. For some materials, recycling figures might be available in sectorial reports, or might also be provided by expert judgement. In such cases, a detailed justification about the use of these sources shall be given. Such justification shall include information about the system boundaries and flows accounted for the EOL-RIR calculations; description about to number of end-uses accounted for; and details about whether EOL-RIR refer to the complete recycling stage or partially to pre-processing and end-processing stages.

Materials not covered by the MSA study and/or the UNEP's report are the following:

Biotic materials: natural rubber, pulpwood, and sawn softwood.

Industrial minerals: baryte, bentonite, clays (and kaolin), diatomite, feldspar, gypsum, limestone, perlite, potash, silica sand and talc.

Other materials: hafnium, scandium, tellurium, and vanadium, and several rare earths (lanthanum, cerium, praseodymium, samarium, and gadolinium).

There are several reasons why data for recycling is not readily available. In some cases, the recycling of such materials is not done by selective waste treatment separation and recycling routes. In many cases, materials are not selectively separated for recycling but recycled together with the rest of products where the materials are contained. This is the case for instance for two biotic materials: natural rubber (contained in tyres), and pulpwood (used in paper). Natural rubber is not selectively separated and recycled from end of life tyres, but recycled as composites. Neither pulpwood is selectively extracted from paper and recycled, but instead recycled together with the paper. In all these cases, developing a more detailed analysis of the materials is needed to understand how recycling can be assessed and quantified.

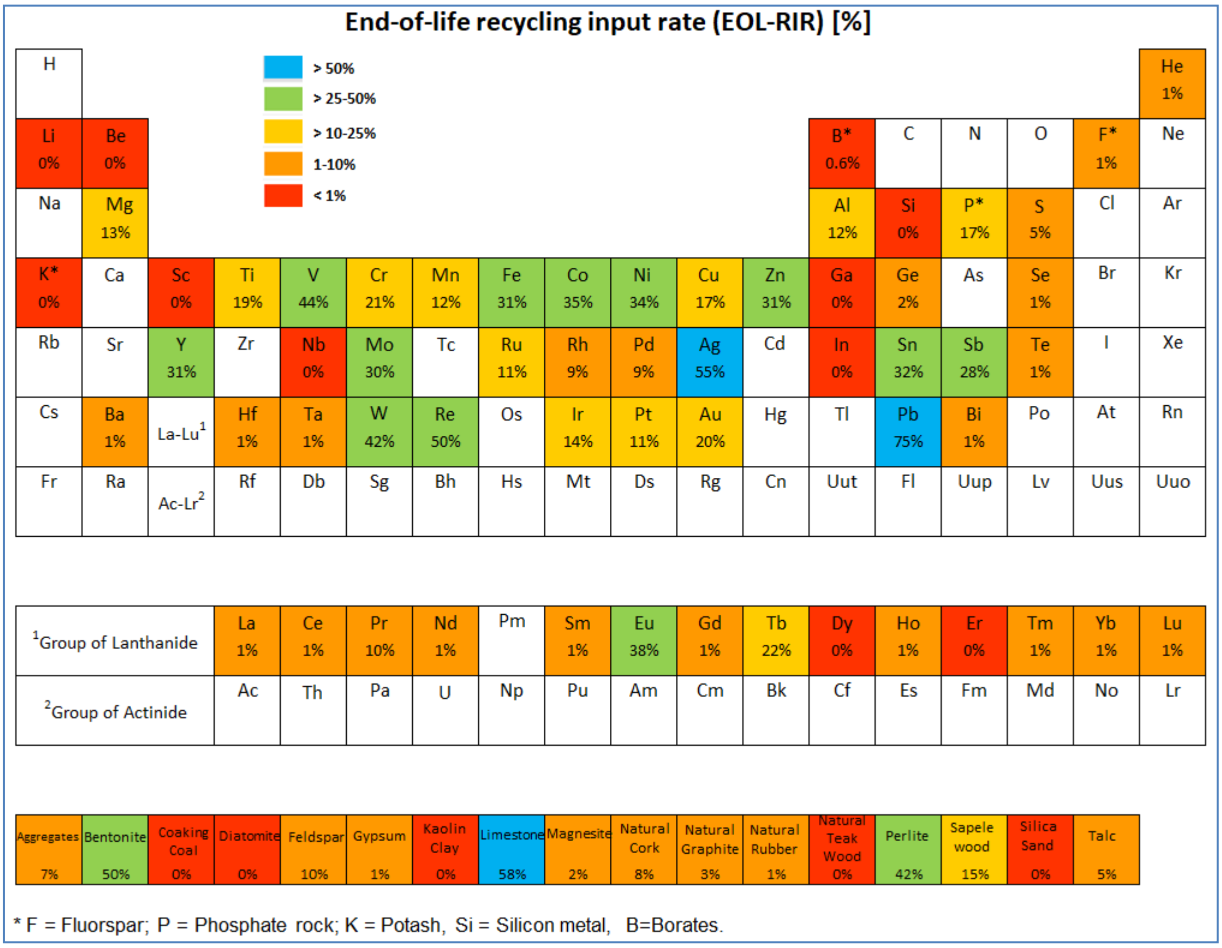
In some cases, there are some limitations set by nature such as physics, chemistry, metallurgy, and thermodynamics for the functional recycling of the materials. Products reaching recyclers must be separated into suitable fractions to obtain optimal ranges for the recovery of the targeted materials. A big variation in the composition and properties of the processed fraction will affect negatively the recovery yield of materials. Some of the recyclates cannot be used for the same functions or applications and are, therefore, used in other functions. In this case, their recycling does not contribute to a potential reduction of their supply, but instead reduces the demand of other raw material in new applications and products.

Some partial calculation examples are shown in Annex 4. Due to data unavailability, the examples neglect the import flows, and the primary production flows are assumed to be equal to the amount of material in end-use applications.

2.4 Results: latest available EOL-RIR figures for the EU-28

Figure 3 provides a summary of current EOL-RIR estimates.

Figure 3 End-of-life recycling input rates (EOL-RIR) for the EU-28 based on the MSA studies (when available) and used to draw the 2017 List of Critical Raw Materials for the EU.



The EOL-RIR varies considerably among different materials. The EOL-RIR is low (in red) for a wide range of materials because (1) their recycling is not economically feasible, (2) there is a lack of suitable technologies available for recycling, (3) because those materials are embodied in products stocked in use for long time periods (i.e., buildings or other infrastructure), or (4) because demand for these materials is growing.

3 The Complementary recycling indicator (EOL-RR)

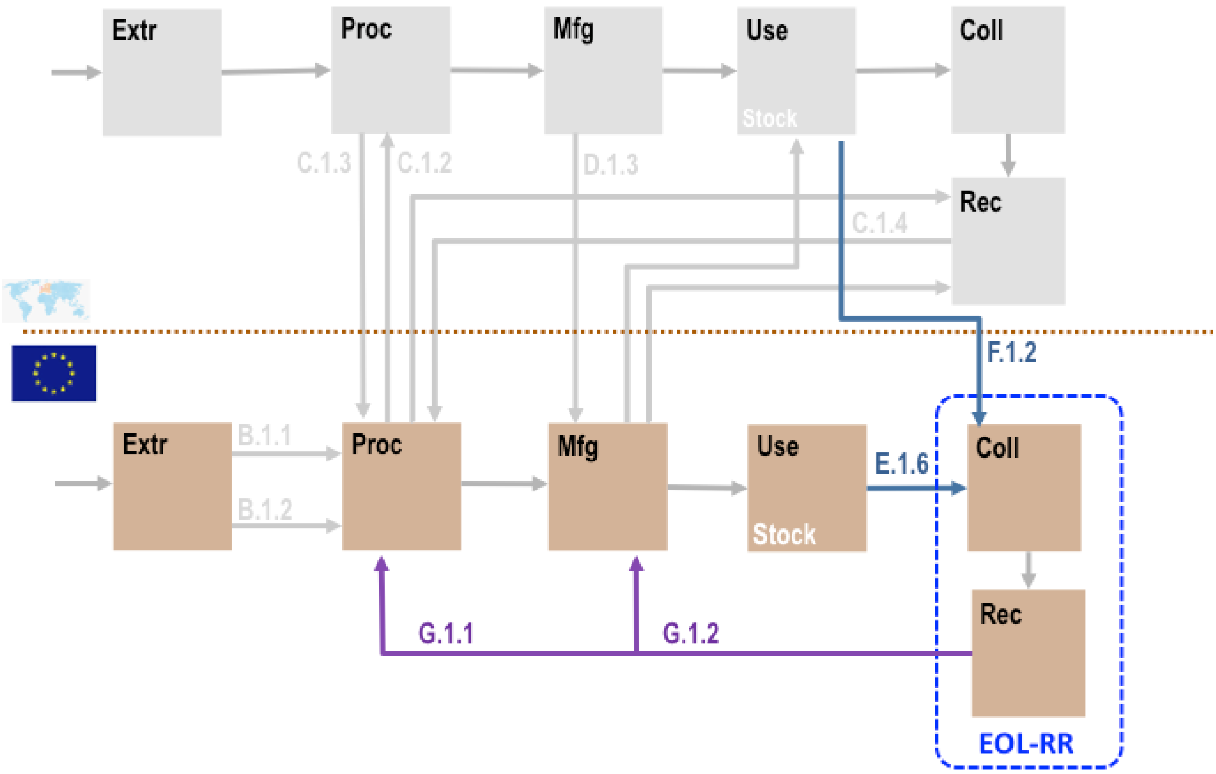
While the EOL-RIR looks at recycled materials as a contribution to the total inputs to the EU economy (input perspective), the EOL-RR captures the amount of (secondary) materials recovered at end-of-life compared to the overall waste quantities generated (output perspective). It provides information about the performance of the collection and recycling to recover materials at end-of-life and it is thus useful from a recyclers' perspective.

The UNEP report 'Recycling rate of metals' provided EOL-RR (current) estimates of metals globally (Graedel *et al.*, 2011; UNEP, 2011).

3.1 Calculating EOL-RR with MSA data

EOL-RR values for the EU-28 can be estimated by using data from the EU critical raw materials assessment (EC, 2017) and the MSA study (BIO by Deloitte, 2015; Passarini *et al.*, 2018). Figure 4 illustrates the system boundaries (in light blue) and material flows (purple and dark blue) taken into account for the calculation of the EOL-RR.

Figure 4 System boundaries and material flows included to estimate the EOL-RR of a raw material.



Extr: Extraction; Proc: Processing; Mfg: Manufacturing; Coll: Collection; Rec: Recycling

The EOL-RR is calculated as following:

$$\mathrm{EOL-RR} = \frac{\text{Secondary production (from old scrap)}}{\text{Material at EOL + Imports of EOL products}} \qquad \text{(eq 2)}$$

The EU 'secondary production (old scrap)' flows are:

- **G.1.1** Production of secondary material from post-consumer functional recycling in EU sent to processing in EU
- **G.1.2** Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU

The 'Material at EOL' flow is:

- **E.1.6.** Products at end of life in EU collected for treatment

The 'Import of EOL products' flow is:

- **F.1.2** Imports to EU of manufactured products at end-of-life

Two calculation examples are provided in the boxes below.

Box 3 Example of the EOL-RR for tungsten.

The EOL-RR for tungsten is calculated using data from the MSA study (BIO by Deloitte, 2015) developed for the year 2012. The material flows needed for the calculations are those shown in Figure 4.

Flows of tungsten in the EU	Quantity (tonnes)
E.1.6. Products at end of life in EU collected for treatment	16,209
F.1.2 Imports to EU of manufactured products at end-of-life	0
G.1.1 Production of secondary material from post consumer functional recycling in EU sent to processing in EU	2,627
G.1.2 Production of secondary material from post consumer functional recycling in EU sent to manufacture in EU	7,603

Using the values above, the EOL-RR (current) for Tungsten is estimated to be:

$$\mathrm{EOL} - \mathrm{RR_W} = \frac{2{,}627 \ + 7{,}603}{16{,}209}$$

$$\mathrm{EOL} - \mathrm{RR_W} = \frac{10{,}231}{16{,}209} = 0.6312$$

The result above means that the recycling of tungsten from EOL products is 63%. The remaining 37% of tungsten is not recycled.

Box 4 Example of the EOL-RR for indium.

Analogously to tungsten, the EOL-RR for indium is calculated using data from the MSA study (BIO by Deloitte, 2015) developed for the year 2012.

Flows of indium in the EU	Quantity (tonnes)
E.1.6. Products at end of life in EU collected for treatment	60
F.1.2 Imports to EU of manufactured products at end-of-life	3
G.1.1 Production of secondary material from post consumer functional recycling in EU sent to processing in EU	0.2
G.1.2 Production of secondary material from post consumer functional recycling in EU sent to manufacture in EU	0

Using the values above, the EOL-RR (current) for indium is estimated to be:

$$\mathrm{EOL} - \mathrm{RR_{In}} = \frac{0.2}{60 + 3}$$

$$\mathrm{EOL} - \mathrm{RR_{In}} = \frac{0.2}{63} = 0.0032$$

The amount of indium recycled from EOL products at present is negligible (less than 1%).

Box 5 Example of the EOL-RR for Aluminium, Copper and Iron from the 2018 MSA study.

The EOL-RR for Aluminium, Copper and Iron is calculated using data from the 2018 MSA study (Passarini et al, 2018).

Different EOL-RR calculations for **Aluminium**.

EOL-Recycling Rate Formula	%
EOL-RR=(G1.1 + G1.2)/(E1.6+F1.2)	**51%**
EOL-RR=(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	69%
EOL-RR=(G1.1+G1.2)/(E1.6+F1.2-F1.1)	51%

Different EOL-RR calculations for **Copper**

EOL-Recycling Rate Formula	%
EOL-RR=(G1.1 + G1.2)/(E1.6+F1.2)	**28%**
EOL-RR=(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	61%
EOL-RR=(G1.1+G1.2)/(E1.6+F1.2-F1.1)	28%

Different EOL-RR calculations for **Iron**

EOL-Recycling Rate Formula	%
EOL-RR=(G1.1 + G1.2)/(E1.6+F1.2)	**62%**
EOL-RR=(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	75%
EOL-RR=(G1.1+G1.2)/(E1.6+F1.2-F1.1)	62%

Beyond the material flows strictly needed for the calculations of EOL-RR, as in the previous examples, Passarini et al (2018) have also included two additional options that incorporate import / export flows such as:

G.1.3 Secondary material from post-consumer recycling sent out of the EU
F.1.1 Export of products at end-of-life

The results above show that import / export flows can change the picture to a large extent.

3.2 Calculating EOL-RR with UNEP/IRP data

The report ‘recycling rates of metals – a status report’ by UNEP, included end of life recycling rate (EOL-RR) for a number of materials (UNEP, 2011). UNEP defines the EOL-RR as “the portion of EOL recycling in which the metal in a discarded product is separated and sorted to obtain recyclates or secondary materials”. Figure 2 illustrates the system boundaries to account for EOL-RR by dashed (pink). The diverse equations to calculate recycling indicators are included inside each of the three system boundaries defined. The EOL-RR can be calculated by *equation e*:

$$EOL - RR = \frac{Recycled\ EOL\ metal\ (old\ scrap)}{EOL\ products\ (metal\ content)} \qquad (eq\ e)$$

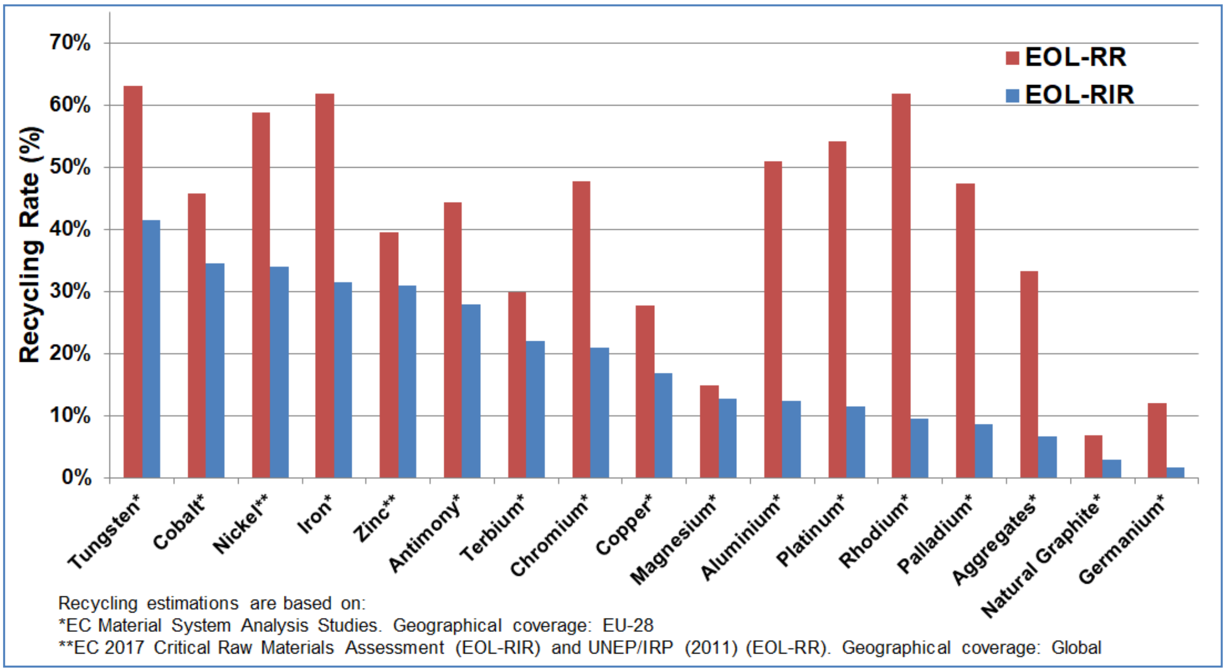
3.3 Results: selected EOL-RR figures for the EU-28

For the EU-28, Figure 5 shows that in spite of the fact that several materials contained in end-of-life products have recycling rates (EOL-RR) above 40 or 50%, recycling's contribution to overall demand for these materials (EOL-RIR) is generally low.

The gap between EOL-RR and EOL-RIR is particularly large for some of the major metals such as iron, aluminium, and nickel, but also for some of the precious metals such as the platinum-group elements. This moreover shows that high efficiency of the EU recycling industries in recovering materials from end-of-life products does not always correspond to a proportional contribution in terms of increased resource security.

It should also be highlighted that many raw materials are contained in long-use societal stocks and that the data presented in Figure 5 do not prejudge future increases in recycling rates.

Figure 5 The current EOL-RR in comparison to EOL-RIR for selected materials[8]



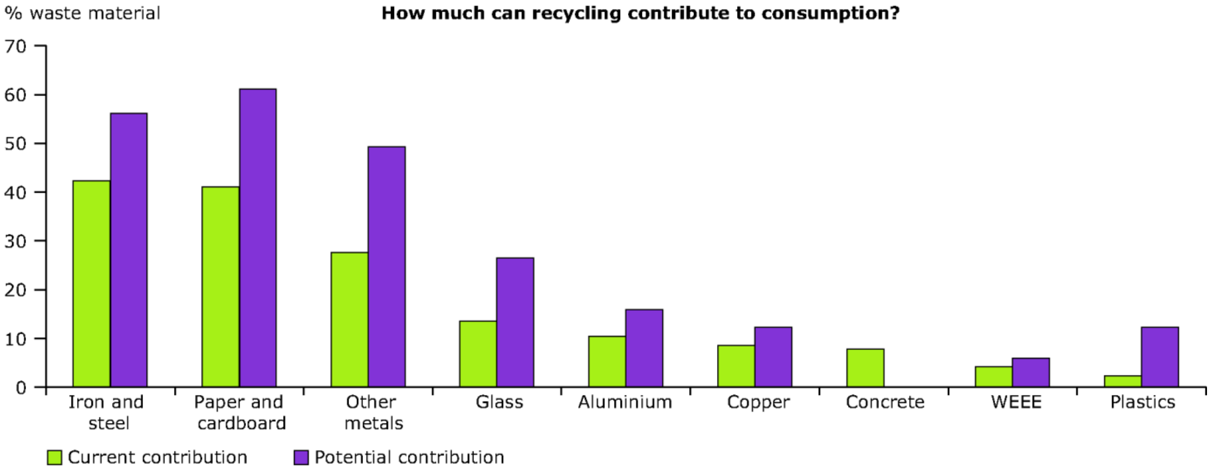
[8] Source: (BIO by Deloitte, 2015; Ciacci, Vassura and Passarini, 2017; EC, 2017).

4 The Additional recycling indicators in the EU-28

While the EOL-RIR and EOL-RR based on current figures are a snapshot in time of the current performance and contribution of recycling (e.g., around years 2012/2013 for the 2015 MSA study), they do not provide an indication of potential recycling increases, under given assumptions.

In 2011, the European Environment Agency (EEA) published a report that includes estimates of current and potential recycling rates for a number of raw materials for 2004 and 2006 (EEA, 2011). Figure 6 shows those recycling estimates for iron and steel, paper and cardboard, other metals, glass, aluminium, copper, concrete, plastics, and waste electrical and electronic products (WEEE).

Figure 6 Recycling's current and potential contribution to meeting EU demand for various materials according to an EEA study[9].



In the EEA study, the current contribution of recycling is defined as the total recycled material compared to the total consumption, while the potential contribution of recycling is estimated as the total waste generated compared to the total consumption (EEA, 2011).

Estimates are calculated using data taken from diverse sources, including Eurostat Prodcom statistics (EUROSTAT, 2016a) and waste generation data from Eurostat waste statistics (EUROSTAT, 2016b). Recycling estimates are extracted from two reports, namely (Villanueva *et al.*, 2010) and (Prognos, 2008). According to the EEA assessment, all materials except concrete show a high potential to improve their current recycling.

In the EEA study, some assumptions used for the calculations are not sufficiently explained. For example, although the current contribution of recycling is defined referring to the total consumption, data is taken from production statistics data. Another aspect that would need further clarification is whether import and export flows to/from the EU are accounted for. Altogether, although the EEA study deserves credit to have provided some initial estimates, it is hard to reproduce and update the figures and, therefore, compare the results with other recycling estimates.

Besides some of these limitations, both recycling indicators aimed to capture the contribution of recycling to the EU supply. Hence, in this report the EEA's current and potential recycling rates are also regarded as the end of life recycling input rates (EOL-RIR).

[9] Source: (EEA, 2011).

4.1 Ambition and limits (recycling potentials)

Against this background, the goal of this section is to discuss a streamlined methodology, based on EC MSA data, to estimate the maximum potential contribution of recycling to the total material input, regarded hereafter as EOL-RIR (potential). The methodology uses the same system boundaries and material flows as the principal and complementary recycling indicators discussed in the previous sections, and developed for the 2017 critical raw materials (CRM) methodology (Blengini *et al.*, 2017; EC, 2017), the EC Raw Materials Scoreboard (Vidal-Legaz *et al.*, 2016), and the EC Circular Economy Monitoring Framework (EC, 2018).

Two recycling rates are discussed: the EOL-RR (potential) and EOL-RIR (potential). These recycling rates can be regarded as the forward-looking version of the Principal (EOL-RIR) and Complementary (EOL-RR) indicators, under given assumptions and simplifications.

This last group of recycling indicators, currently not in use in any of the three above EU policy tools, is more speculative, as all the flows used to calculate them are likely to change in the future, for a range of reasons.

In order to limit the uncertainty of the calculations, the main assumption is that the production of primary raw materials and trade remain unchanged, as well as the quantity of products reaching end-of-life. The only variable is therefore the overall ability of the recycling sector to capture raw materials in end-of-life product flows and recycle them into secondary materials.

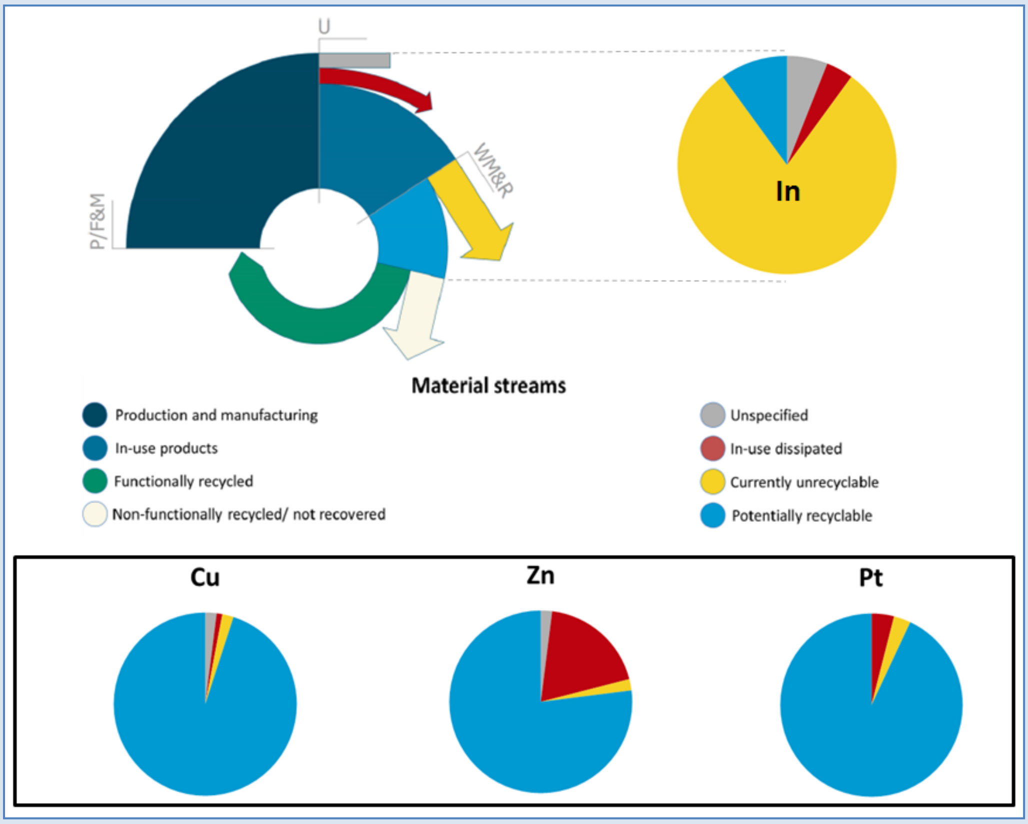
The indicator EOL-RIR(potential) will not therefore estimate how much of future raw materials demand could be covered by recycling, but how much the recycling contribution could have increased, under the assumption and with the data described in the next section.

As previously highlighted, the growing demand of raw materials is one of the main limiting factors to achieve a higher contribution of recycling to meet EU demand. For materials whose anthropogenic cycle is not yet saturated (Ciacci, Vassura and Passarini, 2017), in-use stocks are still building up, in some cases particularly fast, and thus the contribution of recycling to the EU demand will necessarily be limited for the coming years. This is likely to happen to several CRMs, whose massive use started few years ago only.

Box 6 Dissipative material losses as a limit to recycling's contribution to materials demand.

A recent study has investigated and categorized the main causes for dissipation of materials during use, and measured at global level the degree to which they are currently "lost by design". The study illustrates the material streams considered, i.e. (a) In-use dissipation (indicated in red), (b) Currently unrecyclable when discarded (indicated in yellow), or (c) Potentially recyclable when discarded (indicated in blue), and examples of these materials flow shares for a number of materials.

For example, in some common uses materials are lost by intent, e.g. **zinc** in galvanizing and chemical application or **copper** in brake pads (indicated in red). In other uses, no viable recycling approaches might exist at the moment to recover materials, e.g. **indium** in thin-film coatings or **germanium** in polymerization catalysts and fibre optic systems (indicated in yellow). Overall, the study showed that at the global level in-use dissipation affects fewer than a dozen materials (including toxic elements such as mercury and arsenic).



Source: (Ciacci *et al.*, 2015). P/F&M: production/fabrication and manufacturing, U: Use, WM&R: Waste management and recycling.

4.2 Proposed methodology (recycling potentials)

Two additional recycling indicators are proposed: the EOL-RR (potential) and the EOL-RIR (potential). EOL-RR (potential) is presented first, as its calculation is needed for the EOL-RIR (potential)

The EOL-RR (potential) can be defined in several ways. In this report, the EOL-RR (potential) is defined as the 'potentially recyclable' fraction of an exemplary material from the diverse end-use applications. The 'potentially recyclable'[10] fraction of a material is calculated based on the amount of material contained in end-use non-dissipative applications, thus the amount of material that is available for recycling.

$$\mathrm{EOL-RR\ (potential)}_{\mathrm{i,EU}} = \sum_{\mathrm{k=1}}^{\mathrm{n}} \left(\mathrm{M}_{\mathrm{i,EU}} \times \mathrm{PR}_{\mathrm{i,EU}}\right) \qquad \text{(eq 3)}$$

M = Market share of each 'potentially recyclable' end-use application of material 'i' in the EU
i = material under study
EU = European Union EU-28
n = number of 'potentially recyclable' end-use applications
PR = Percentage of material 'i' that remains in 'potentially recyclable' end-use applications 'n'.

Hereafter, the steps needed to estimate the EOL-RR (potential):

Step 1. Identify the 'potentially recyclable' end-use applications.

The 'potentially recyclable' end-use, the applications of a material as suggested by (Ciacci et al., 2015) refer to end-use applications where the amount of the material could be recovered using today's treatment and recycling technologies. This amount could be understood as an upper limit of the recycling of a material given the current recycling technologies. For example, tungsten can be 'potentially recyclable' from mill and cutting tools, mining and construction, catalysts, high speed steels applications, and aeronautics and energy uses. While it remains unrecoverable in pigments, lighting and electronic uses, being these latter end-use applications not considered in the calculations of the 'potentially recyclable' material stream.

In general, the quantity of a material present in end-use applications only in small amounts is not accounted for as 'potentially recyclable' because recycling in those situations might be currently not practical.

Step 2. Estimate the market share of the 'potentially recyclable' end-use applications identified in step 1 ($M_{i,EU}$).

Data of the market share of a material per end-use application are available from different sources. Ciacci et al. 2015 uses the market shares at global level. BIO by Deloitte 2015 and Soleille et al 2016 provide data of the market shares in the EU. In this report, we used data from (Soleille et al. 2016). For example, box 6 includes the market shares of all end-use applications of tungsten including the 'potentially recyclable' end-use applications in the EU.

Step 3. Estimate the amount of the material 'i' 'potentially recyclable' in end-use applications 'n' in the EU ($PR_{i,EU}$).

The amount of a material 'potentially recyclable' is estimated by taking into account the small quantities of material frequently lost and dissipated during use. Material losses are usually accounted for using technical information of specific processes (i.e. abrasion, corrosion), and represent a small percentage compared to the total amount

[10] The 'potential recyclable' quantity of a material refers to the amount of material (measured in mass unit) from non-dissipative uses available for recycling. It is calculated using the 'potentially recyclable' percentage per each end-use application given by (Ciacci *et al.*, 2015; EC, 2017) together with the market share for each of the end-use considered.

of the material in a product. Data to quantify such losses are difficult to find and tend to be highly scattered in literature. The estimates available are frequently material and process specific. For some materials, such losses can be approximated using data from another material. For instance, Ciacci et al 2015 used cobalt as a proxy to estimate the amount of tungsten lost due to the abrasion of cement carbides during use (5%). BIO by Deloitte 2015 also estimated that 5% of tungsten in cement carbides (regarded as other wear tools) was in-use dissipated and lost. Based on such loss estimate, the amount of tungsten 'potentially recyclable' from cement carbides is 95%.

Box 7 Example of the EOL-RR (potential) for tungsten.

The EOL-RR (potential) of tungsten is calculated following the steps described below:

Step 1. The end-use applications of tungsten are first classified into the four material streams (described in columns 3, 4, 5 and 6 of the table below) defined by Ciacci et al. 2015 in order to identify the 'potentially recycled' end-use applications. The classification of end-use applications into material streams is not straightforward and it does not exist a method to do such classification. For tungsten, material stream were deducted based on the description of each end-use application from sources as BIO by Deloitte, 2015 and the USGS minerals yearbook. The percentage for each material stream is taken from the MSA study (BIO by Deloitte, 2015) developed for the year 2012.

Step 2. The market share of the 'potentially recyclable' end-use applications of tungsten are taken from BIO by Deloitte 2015, as these data refers to the EU.

Step 3. The amount of tungsten from the 'potentially recyclable' end-use applications in the EU is calculated using the data contained in the table below:

End use application	Market share in the EU[a]	'Potentially recyclable'[a]	In-use dissipated[a]	Currently unrecyclable[a]	Unspecified
Mining and construction	23	84	16	-	-
High speed steels applications	6	79	21	-	-
Aeronautics and energy uses	5	100	-	-	-
Mill and cutting tools	33	93	7	-	-
Catalysts and pigments	8	0	100	-	-
Lighting and electronic uses	6	100	-	-	-
Other wear tools	19	95	5	-	-
Sum	100	-	-	-	-

[a](BIO by Deloitte, 2015) – All figures are expressed as percentage (%)

Where the EOL-RR (potential) can be calculated as follows:

$$\mathrm{EOL-RR\ (potential)_W} = (0.23 \times 0.84 + 0.06 \times 0.79 + 0.05 \times 1 + 0.33 \times 0.93 + 0.81 \times 0 + 0.06 \times 1 + 0.19 \times 0.95)$$
$$= 0.84$$

The result shows that 84% of tungsten could be 'potentially recyclable'. The remaining 16% of tungsten is in-use dissipated. When compared with the value obtained from the complementary indicator EOL-RR, we can say that the recycling of tungsten could increase 21% (i.e., difference between the EOL-RR and EOL-RR (potential)).

A second example provides an overview of the material streams and metrics considered for indium.

Box 8 Example of the EOL-RR (potential) for indium.

Analogously to tungsten, the steps to calculate the EOL-RR (potential) of indium are:

Step 1. The end-use applications of indium are first classified into the four material streams (described in columns 3, 4, 5 and 6 of the table below) defined by Ciacci et al. 2015. End-use applications where indium is contained in tiny amounts and mixed up with other materials, as for instance in the form of ceramic and alloys, are classified under the 'currently unrecyclable' stream due to the lack of a well-established technology to recycle them. The percentage for each material stream is taken from the MSA study (BIO by Deloitte, 2015) developed for the year 2012 in the EU.

Step 2. The market share of the 'potentially recyclable' end-use applications of indium are taken from BIO by Deloitte 2015, as data are given in the context of the EU.

Step 3. The amount of indium from the 'potentially recyclable' end-use applications in the EU is calculated using the data contained in the table below:

End use application	Market share in the EU [a]	'Potentially recyclable' [a]	In-use dissipated [a]	Currently unrecyclable [a]	Unspecified
Flat panel displays	60	0	-	100	-
Solders	11	100	-	0	-
Photovoltaic cells	9	0	5	95[b]	-
Thermal interface material	7	100	-	0	-
Batteries	5	100	-	0	-
Alloys/compounds	4	100	-	0	-
Semiconductors and LEDs	3	0	-	100	-
Others	1	0	-	0	100
Sum	100	-	-	-	-

[a](BIO by Deloitte, 2015) – All figures are expressed as percentage (%)

Based on these values, the EOL-RR (potential) can be estimated as follows:

$$\mathrm{EOL-RR\ (potential)_{In}} = (0.60 \times 0 + 0.11 \times 1 + 0.09 \times 0 + 0.07 \times 1 + 0.05 \times 1 + 0.04 \times 1 + 0.03 \times 0 + 1 \times 0) = 0.27$$

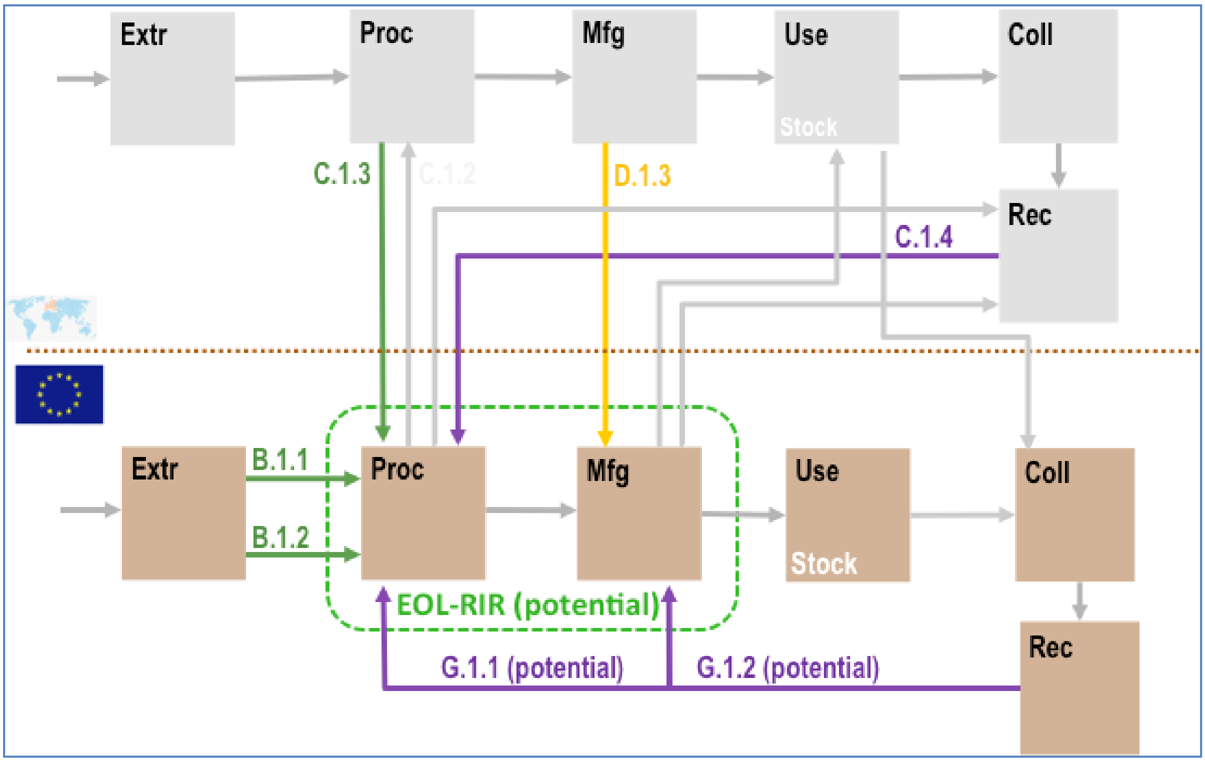
When compared to the value of EOL-RR, the recycling of indium from EOL products could increase up to 27%.

The EOL-RIR (potential) is calculated by applying the following formula:

$$\mathrm{EOL-RIR\ (potential)} = \frac{\text{`Potentially recycled'}}{\text{Primary production} + \text{`Potentially recycled'} + \text{Imports}} \qquad \text{(eq 4)}$$

Figure 7 highlights the flows of the material inputs and outputs taken into account for the calculation of the EOL-RIR (potential). System boundaries are represented by light green dashed lines while primary and secondary productions as well as import flows are drawn in dark green, purple, and yellow arrows, respectively.

Figure 7 System boundaries and material flows included in the definition of the EOL-RIR (potential) of a raw material.



Extr: Extraction; Proc: Processing; Mfg: Manufacturing; Coll: Collection; Rec: Recycling

Based on the material flows described in Figure 7, equation 4 is further developed to:

$$\mathbf{EOL-RIR\ (potential)} = \frac{\mathbf{G.1.1\ (potential)+G.1.2\ (potential)}}{\mathbf{B.1.1+B.1.2+C.1.3+D.1.3+C.1.4+G.1.1\ (potential)+G.1.2(potential)}} \quad \text{(eq 5)}$$

'Potentially recycled' material flows are:

- **G.1.1 (potential)** Potentially recycled amount of secondary material from post-consumer functional recycling in EU sent to processing in the EU;
- **G.1.2 (potential)** Potentially recycled amount of secondary material from post-consumer functional recycling in EU sent to manufacture in the EU.

'Primary production' flows are:

- **B.1.1.** Production of primary material as main product in EU sent to processing in the EU;
- **B.1.2.** Production of primary material as by product in EU sent to manufacturing in the EU.

'Imports' flows are:

- **C.1.3** Imports to EU of primary material;
- **C.1.4** Imports to EU of secondary material;
- **D.1.3** Imports to EU of processed material.

The 'primary production' and 'import' flows are assumed to remain unchanged.

The steps needed to estimate EOL-RIR (potential) are the following:

Step 1. Estimate the EOL-RR (potential) using equation 3 (see Boxes for examples).

Step 2. Determine the 'potentially recycled' fraction (denoted as G.1.1 potential and G.1.2 potential. in Figure 7) using the EOL-RR (potential) from step 1

The 'potentially recycled' material flows are not readily available and need to be deducted by using the definition of EOL-RR (potential) obtained in step 1 and showed in the equation 6. The EOL-RR (potential) is defined as the amount of material 'potentially recycled' to the amount of material contained in products and end-use applications that have reached their EOL (materials at EOL) plus the amount of imports of EOL products.

$$\mathrm{EOL-RR\ (potential)} = \frac{\text{`Potentially recycled'}}{\text{Materials at EOL + Imports of EOL products}} \qquad \text{(eq. 6)}$$

To calculate the 'potentially recycled' material flow, the materials at EOL and the imports of EOL products flows are assumed to remain unchanged. Equation 7 shows how the 'potentially recycled' flows are deducted:

$$\text{`Potentially recycled'} = \mathrm{EOL-RR\ (potential)} \times (\text{Materials at EOL} + \text{Imports of EOL products}) \qquad \text{(eq. 7)}$$

Step 3. Calculate the EOL-RIR (potential).

Once the 'potentially recycled' material flows are calculated, the EOL-RIR (potential) is deducted following the definition in equation 8:

$$\mathrm{EOL-RIR\ (potential)} = \frac{\text{`Potentially recycled'}}{\text{Primary production + `Potentially recycled' + Imports}} \qquad \text{(eq 8)}$$

Data for the total primary production and import flows are assumed to remain unchanged. Estimates are taken from (BIO by Deloitte, 2015). Some degree of uncertainty certainly exists.

The next section provides calculation examples for two selected materials (tungsten and indium).

4.3 Preliminary results (recycling potentials)

Two examples for tungsten and indium are presented and discussed (see boxes).

The EOL-RIR (potential) is calculated substituting the 'secondary production (old scrap)' by the 'potentially recycled' amount of the material under analysis obtained from EOL-RR (potential). The 'potentially recycled' quantity refers to the amount of materials contained in products that is deemed recoverable with current technologies. The quantity of materials contained in tiny amounts and in-use dissipated are considered as not recoverable, and thus do not represent a possible contributor to the supply of materials.

Data for indium and tungsten are taken from the 2017 list of CRMs for the EU, the MSA study (BIO by Deloitte, 2015) and other sources (Ciacci et al. 2015).

Based on these preliminary results, indium appears to be a material with some margin to improve its current contribution of recycling to its supply (<1%), even though the upper limit is likely 8% of current demand (given the current total material input to EU, the EOL products collected for waste treatment and the import and export amounts).

Tungsten starts from remarkably higher EOL-RIR of 42% and seems to have a margin to increase to 49%. The EOL-RIR of indium is negligible but could increase over 8%.

Box 9 Example of the EOL-RIR (potential) for tungsten

This box illustrates how to calculate the EOL-RIR (potential) for tungsten following the proposed methodology for recycling potentials.

Step 1. The steps needed to calculate the EOL-RR (potential) for tungsten are illustrated in **Box 7**. The EOL-RR (potential) of tungsten is 84%.

Step 2. The 'potentially recycled' amount of tungsten for the given EOL-RR (potential) is calculated using eq. 7. The quantity of tungsten in EOL products, and the imports of tungsten contained in EOL products to the EU are taken from (BIO by Deloitte, 2015).

Flows of tungsten in the EU	Quantity (tonnes)
E.1.6 Products at end of life in EU collected for treatment	16,209
F.1.2 Imports to EU of manufactured products at end-of-life	0

$$\text{`Potentially recycled'} = 0.84 \times (16{,}209 + 0) = 13{,}616 \text{ tonnes}$$

Step 3. The EOL-RIR (potential) of tungsten is calculated using the 'potentially recycled' amount of tungsten obtained in step 2, the total primary material input (B.1.1 and B.1.2), and the import flows (C.1.3, D.1.3 and C.1.4) that are assumed to remain unchanged. Data are taken from (BIO by Deloitte, 2015).

Flows of tungsten in the EU	Quantity (tonnes)
B.1.1 Production of primary material as main product in EU sent to processing in EU	869
B.1.2 Production of primary material as by product in EU sent to processing in EU	0
C.1.3 Imports to EU of primary material	2,583
C.1.4 Imports to EU of secondary material	73
D.1.3 Imports to EU of processed material	10,883

$$\text{EOL} - \text{RIR (potential)} = \frac{13{,}616}{869 + 2{,}583 + 10{,}883 + 73 + 13{,}616} = 0.486$$

The results show that the maximum contribution from recycling EOL products to the EU demand is 49% of the total material input of tungsten.

Box 10 Example of the EOL-RIR (potential) for indium

The EOL-RIR (potential) of indium is calculated analogously as the EOL-RIR (potential) of tungsten following three steps.

Step 1. The steps needed to estimate the EOL-RR (potential) of indium are illustrated in **Box 8.** The EOL-RR (potential) of indium is 27%.

Step 2. The 'potentially recycled' amount of indium for the given EOL-RR (potential) is estimated using eq. 7. The quantity of indium in EOL products, and the imports of indium contained in EOL products to the EU are taken from (BIO by Deloitte, 2015).

Flows of indium in the EU	Quantity (tonnes)
E.1.6 Products at end of life in EU collected for treatment	60
F.1.2 Imports to EU of manufactured products at end-of-life	3

$$\text{`Potentially recycled'} = 0.27 \times 60 + 3 = 17.01 \text{ tonnes}$$

Step 3. The EOL-RIR (potential) of indium is calculated using the 'potentially recycled' amount of indium given by the EOL-RR (potential) in step 2, the total primary material input (B.1.1 and B.1.2), and the import flows (C.1.3, D.1.3 and C.1.4) that are assumed to remain unchanged. Data are taken from (BIO by Deloitte, 2015).

Flows of indium in the EU	Quantity (tonnes)
B.1.1 Production of primary material as main product in EU sent to processing in EU	0
B.1.2 Production of primary material as by product in EU sent to processing in EU	99
C.1.3 Imports to EU of primary material	17
C.1.4 Imports to EU of secondary material	8.3
D.1.3 Imports to EU of processed material	61

$$\text{EOL} - \text{RIR (potential)} = \frac{17.01}{99 + 17 + 61 + 8.3 + 17.01} = 0.0841$$

The result shows that the maximum contribution from recycling EOL products to EU demand can reach up to 8.4% of the total material input of indium.

5 Conclusions

The recycling indicators described in this report support key EU policies on raw materials and circular economy and the related policy tools, in particular: the list of Critical raw materials for the EU, the Raw Materials Scoreboard and the Circular Economy Monitoring Framework.

The methodology and the underlying data have been presented and discussed, with emphasis on the most recent figures and the future perspectives, while keeping in mind that the selected recycling indicators must meet the so-called "RACER criteria", i.e. they need to be Relevant, Accepted, Credible, Easy and Robust.

For what **concerns the methodology**, the JRC contribution can be summarised as it follows:

- The JRC highlighted key methodological issues related to the principal indicator **EOL-RIR**, which is currently used, and it is expected to be used in the future, in all the three above mentioned policy tools.
- The methodology is described and guidance is provided, in particular, on how to handle multiple data sources in order to: (a) progressively switch from global to regional (EU-28) flows, (b) optimise the use of MSA data, (c) ensure the highest possible comparability while mixing MSA, UNEP/IRP and industry data.
- The most updated EOL-RIR figures for 78 raw materials are provided.
- Methodological details and some examples are provided for **EOL-RR**, as a complementary indicator to EOL-RIR (**input perspective**), in order to provide details on the current performance of the recycling industries and related recycling routes (**output perspective**).
- Results for selected raw materials have shown that, although EOL-RR is relatively high for several materials, which is synonymous with high efficiency of the EU recycling industries, recycling's contribution to overall demand (EOL-RIR) can be much lower, which can be explained as fast growing demand and/or expanding in-use stocks. A set of recycling indicators, rather than just one single indicator, is likely needed.
- **Recycling potentials** discussed in this report have shown to be an interesting exercise, with interesting perspectives as a field of future investigation.
- In particular, it was highlighted that (1) the quantity of the materials used in end-uses is hardly fully recycled due to dissipative end-use applications and (2) There is a potential to improve the current contribution from recycling as illustrated in the examples of Indium and Tungsten.
- In any case, from the methodological point of view, a more general conclusion is that recycling indicators of materials need to be **assessed individually**, using material system analyses focused on a single material.

For what **concerns the data**:

- EU-28 regional flows and data are currently available for 28 (MSA 2015) plus 3 (MSA 2018) raw materials.
- The recent JRC work has highlighted that, even though it can be acceptable to use global recycling rates to fill data gaps in e.g. criticality assessments, it would be advisable to progressively replace global with regional (EU-28) data.
- Further expansion of raw materials coverage in MSA studies is needed, and an update of the 2015 MSA study is advisable, as it used 2012 data.
- A key contribution of RMIS in this task is expected for better data availability, harmonisation and coordination.

References

BIO by Deloitte (2015) *Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials*. Prepared for the European Commission, DG GROW.

Blengini, G.A. *et al.* (2017) *Assessment of the Methodology for Establishing the EU List of Critical Raw Materials-Background report*. Luxembourg: Publications Office of the European Union.

Blengini, G.A. *et al.* (2017) *Assessment of the Methodology for Establishing the EU List of Critical Raw Materials - Annexes*. JRC Technical Report EUR 28654 EN. Ispra, Italy: Publications Office of the European Union.

Blengini, G. A. *et al.* (2017) 'EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements', *Resources Policy*, 53. doi: 10.1016/j.resourpol.2017.05.008.

Ciacci, L. *et al.* (2015) 'Lost by Design', *Environmental Science & Technology*, 49(16), pp. 9443–9451. doi: 10.1021/es505515z.

Ciacci, L., Vassura, I. and Passarini, F. (2017) 'Urban Mines of Copper: Size and Potential for Recycling in the EU', *Resources*. Molecular Diversity Preservation International Publishing (MDPI), 6(1), p. 6. doi: 10.3390/resources6010006.

Dewulf, J. J. *et al.* (2016) 'Criticality on the international scene: Quo vadis?', *Resources Policy*, 50, pp. 169–176. doi: 10.1016/j.resourpol.2016.09.008.

EC (2011) *Tackling the challenges in commodity markets and on raw materials*. European Commission.

EC (2014) *Report on Critical Raw Materials for the EU*. Brussels, Belgium: European Commission (EC).

EC (2015) *Closing the loop - An EU action plan for the Circular Economy, COM(2015) 614 final*. Brussels. doi: EUR-Lex - 52015DC0614 - EN - EUR-Lex.

EC (2017) *Communication on the list of critical raw materials 2017*. COM(2017) 490 final. Brussels.

EC (2018) *A monitoring framework for the circular economy*, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committe of the Regions*. doi: COM/2018/029 final.

EEA (2011) *Earnings, jobs and innovation: the role of recycling in a green economy*. Copenhagen: European Environment Agency (EEA) (EEA Report No 8/2011).

EUROSTAT (2016a) *Prodcom - Statistics by Product*.

EUROSTAT (2016b) *Waste statistics*.

Graedel, T. E. *et al.* (2011) 'What Do We Know About Metal Recycling Rates?', *Journal of Industrial Ecology*, 15(3), pp. 355–366. doi: 10.1111/j.1530-9290.2011.00342.x.

Mathieux, F. *et al.* (2017) *Critical raw materials and the circular economy - Background report*. JRC. doi: 10.2760/378123.

Passarini, F., Ciacci L., Nuss P. and Manfredi S. (2018) Material Flow Analysis of Aluminium, Copper, and Iron in the EU-28, EUR 29220 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-85744-7, doi:10.2760/1079, JRC111643.

Prognos (2008) *Resource savings and CO2 reduction potential in waste management in Europe and the possible contribution to CO2 reduction target in 2020*.

Soulier, M. *et al.* (2018) 'Dynamic analysis of European copper flows', *Resources, Conservation and Recycling*. Elsevier B.V., 129, pp. 143–152. doi:

10.1016/j.resconrec.2017.10.013.

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

UNEP (2011) *Recycling Rates of Metals - A Status Report*. Paris: United Nations Environment Programme (UNEP).

Vidal-Legaz, B. *et al.* (2016) *EU Raw Materials Scoreboard*. 1st edn. Edited by L. Heymans and P. Millet. Luxembourg: Publications Office of the European Union.

Villanueva, A. *et al.* (2010) *Study on the Selection of Waste Streams for End-of-waste Assessment- Final Report*. European Commission (EUR - Scientific and Technical Research Reports).

List of abbreviations and definitions

EC	European Commission
EOL	End-Of-Life
IPR	International Resource Panel
RR	Recycling Rate
RIR	Recycling Input Rate
OSR	Old Scrap Ratio
RC	Recycled Content
UNEP	United Nations Environmental Programme

Definition of Basic Recycling Terminology:

Secondary raw materials are defined as '*materials produced from other sources than primary*'.

Recycling rates give *'in time value of the state-of-the-art of the amount of material recovered based on current collection and treatment technology performances'*.

End of life recycling input rate (EOL-RIR) is '*the input of secondary material to the EU from old scrap to the total input of material (primary and secondary)*'. In the EC criticality assessments, recycling rates and EOL-RIR refer only to **functional recycling.**

Functional recycling is '*the portion of EOL recycling in which the material in a discarded product is separated and sorted to obtain recyclates'.* Recyclates obtained by functional recycling are used for the same functions and applications as when obtained from primary sources. As opposed to recyclates generated from **non-functional recycling** which substitute other raw materials, and therefore do not contribute directly to the total supply of the initial raw material.

Recyclability is *'the potential quantity of a material or product available for recovery at a certain period of time'.* For a material 'a', it refers to the theoretical amount of 'a' potentially recovered once products containing 'a' reach their end of life (EOL).

New scrap refers to '*the scrap generated from processing and manufacturing processes'* and it is also sometimes regarded as pre-consumer scrap. It has a known composition, normally high purity, and origin, and can be often recycled within the processing facility.

Old scrap, also regarded as post-consumer scrap, is '*the amount of material contained in products that have reached their end of life (EOL)'*. It is often mixed with other materials such as plastics or alloys, therefore its recycling requires further detailed processing for proper recovery.

Potentially recyclable fractions of a material are calculated based on the amount of material contained in end-use non-dissipative applications, and refers to the amount of material that is available for recycling.

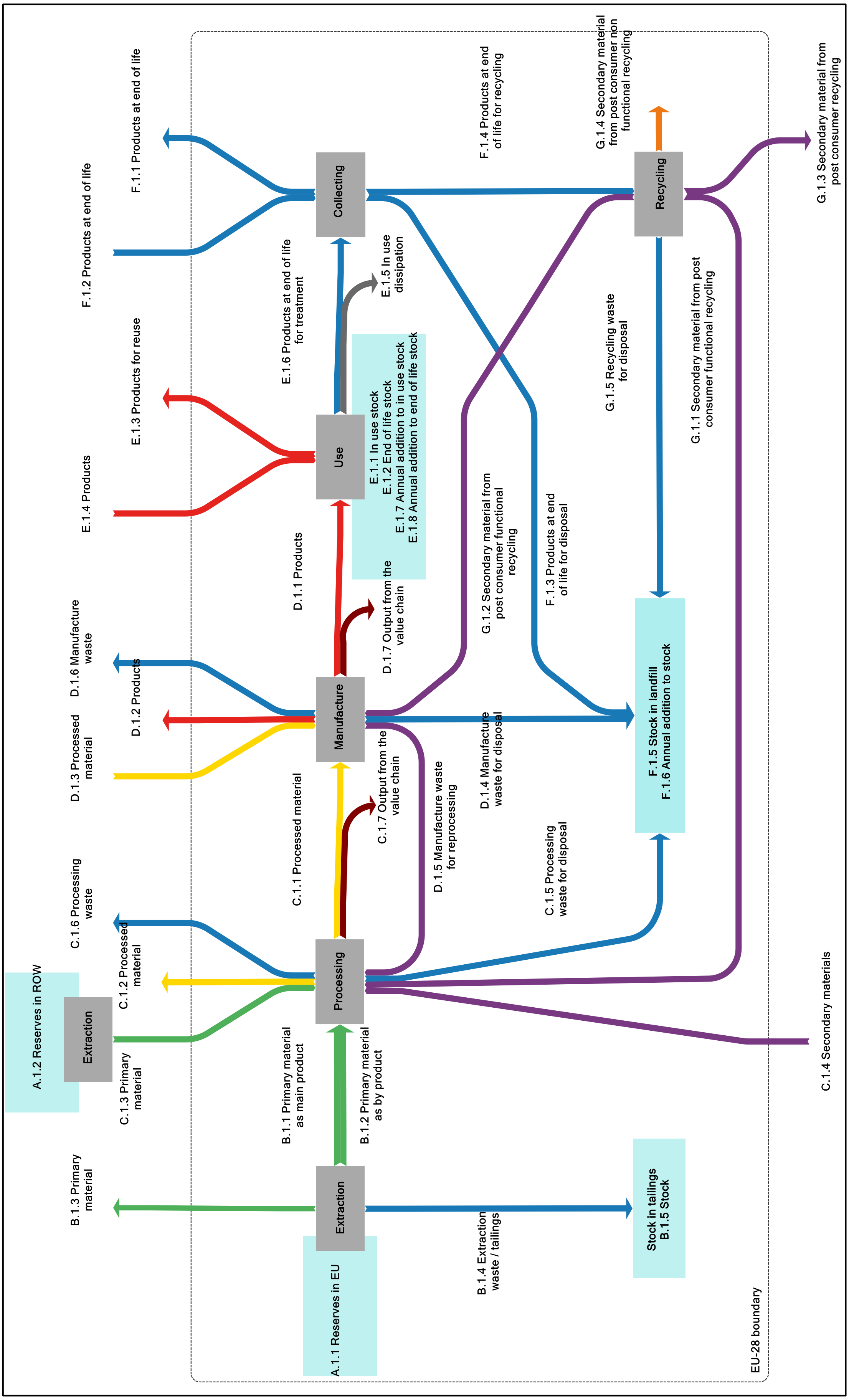
Potentially recycled fractions of a material are the amount of material contained in end-use non-dissipative application that could be potentially recycled.

List of boxes

List of figures

Annexes

Annex 1. MSA study framework and material flows/stocks considered

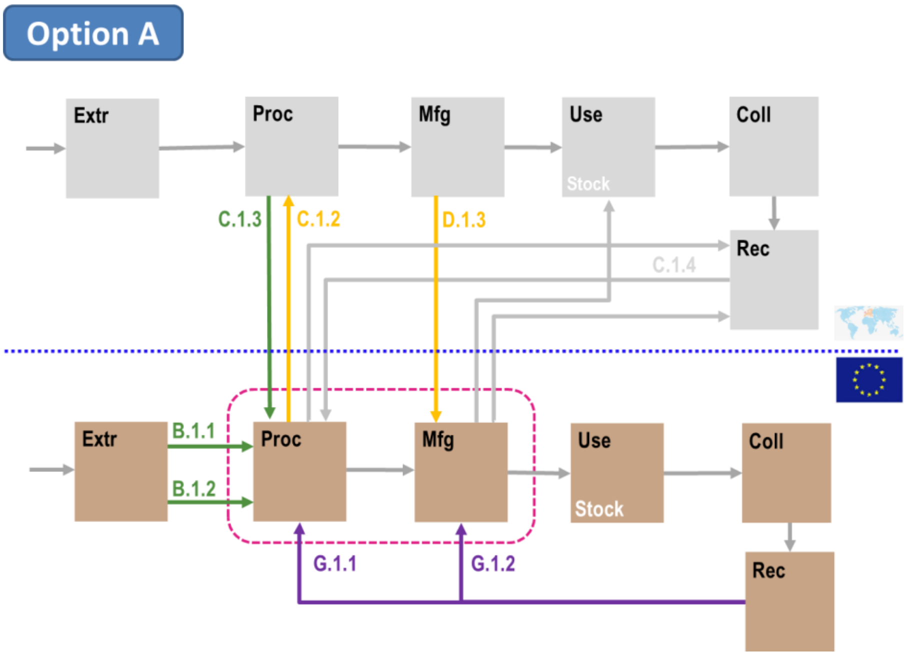


Annex 2. Alternative system boundaries for calculating EOL-RIR with MSA data

Note: Option C is presented in section 2.1.

Streamlined Approach (Option A)

Option A is the streamlined option. It takes into account the 'net import' (i.e. C.1.3 import and C.1.2 export flows) to the processing stage. Imports of secondary materials (C.1.4) are not included in the calculation. When the import of secondary material is high (i.e. Rhodium), a correction must be introduced.



Green: primary material; Yellow: processed material; Purple: secondary material.

$$EOL - RIR_A = \frac{G.1.1 + G.1.2}{B.1.1 + B.1.2 + (C.1.3 - C.1.2) + D.1.3 + G.1.1 + G.1.2}$$

Where the MSA flows accounted for are:

B.1.1. *Production of primary material as main product in EU sent to processing in EU;*

B.1.2. *Production of primary material as by product in EU sent to manufacturing in EU;*

C.1.2 *Exports from EU of processed material;*

C.1.3 *Imports to EU of primary material;*

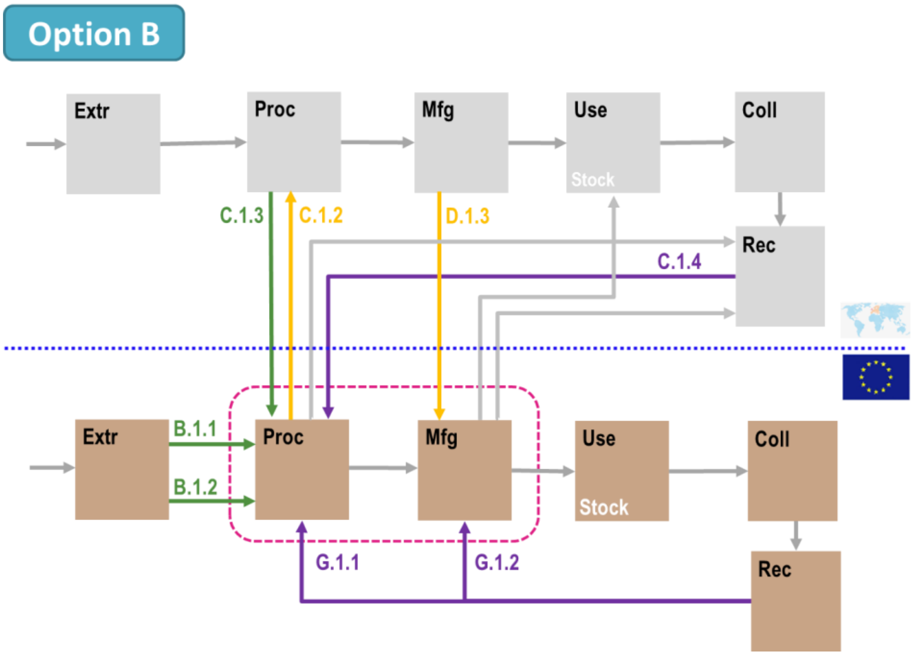
D.1.3 *Imports to EU of processed material;*

G.1.1 *Production of secondary material from post-consumer functional recycling in EU sent to processing in EU;*

G.1.2 *Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU.*

Net Import Approach (Option B)

Option B takes into account the 'net import' (i.e. C.1.3 import and C.1.2 export flows) to the processing stage. Imports of secondary materials (C.1.4) are included in the calculation as imports (only in the denominator). This option is based on the assumption that the raw material that leaves the EU (at the processing stage) is not contributing to EU manufacturing (i.e. no added value and jobs downstream).



Green: primary material; Yellow: processed material; Purple: secondary material.

$$EOL - RIR_B = \frac{\boldsymbol{G.1.1} + \boldsymbol{G.1.2}}{\boldsymbol{B.1.1} + \boldsymbol{B.1.2} + (\boldsymbol{C.1.3} - \boldsymbol{C.1.2}) + \boldsymbol{D.1.3} + \boldsymbol{C.1.4} + \boldsymbol{G.1.1} + \boldsymbol{G.1.2}}$$

Where the MSA flows accounted for are:

B.1.1. *Production of primary material as main product in EU sent to processing in EU;*

B.1.2. *Production of primary material as by product in EU sent to manufacturing in EU;*

C.1.2 *Exports from EU of processed material;*

C.1.3 *Imports to EU of primary material;*

C.1.4. *Import to the EU of secondary materials;*

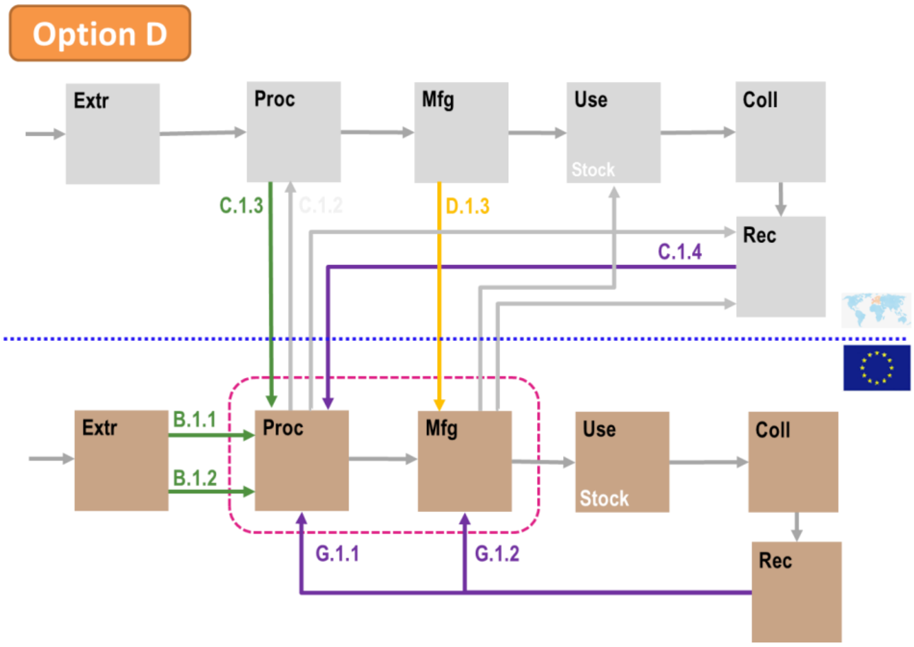
D.1.3 *Imports to EU of processed material;*

G.1.1 *Production of secondary material from post-consumer functional recycling in EU sent to processing in EU;*

G.1.2 *Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU.*

Gross Import + Imported Secondary Materials (Option D)

Option D is similar to option C, but in addition, it considers the imported secondary material flow (C.1.4) as an input of secondary materials, thus it contributes to reduce the risk (C.1.4 is included in the numerator and denominator). The underlying assumption is that the contribution of imported secondary materials is riskless, which is very unlikely. A disadvantage is the low comparability with data given in the UNEP's study on metals, which is the second data source proposed in this revision of the method.



Green: primary material; Yellow: processed material; Purple: secondary material.

$$EOL - RIR_D = \frac{G.1.1 + G.1.2 + C.1.4}{B.1.1 + B.1.2 + C.1.3 + D.1.3 + C.1.4 + G.1.1 + G.1.2}$$

Where the MSA flows accounted for are:

B.1.1. *Production of primary material as main product in EU sent to processing in EU;*

B.1.2. *Production of primary material as by product in EU sent to manufacturing in EU;*

C.1.3 *Imports to EU of primary material;*

C.1.4. *Import to the EU of secondary materials;*

D.1.3 *Imports to EU of processed material;*

G.1.1 *Production of secondary material from post-consumer functional recycling in EU sent to processing in EU;*

G.1.2 *Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU.*

Comparison among End of life recycling input rate (EOL-RIR) used in the 2013 EC criticality study, values obtained using the MSA study (options A to D) and UNEP data

Materials	EC study 2013	MSA study 2015				UNEP report 2011
		Option A	Option B	Option C	Option D	
Aggregates	n.i	7	7	7	7	n.i
Aluminium	35	-	-	-	-	16
Antimony	11	28	28	28	28	7
Barytes	0	-	-	-	-	n.i
Bauxite	0	-	-	-	-	n.i
Bentonite	0	-	-	-	-	n.i
Beryllium	19	0	0	0	0	8
Borate	0	1	1	1	1	n.i
Chromium	13	30	28	21	25	13
Clays	0	-	-	-	-	n.i
Cobalt	16	47	47	35	35	16
Coking coal	0	0	0	0	0	n.i
Copper	20	-	-	-	-	15
Diatomite	0	-	-	-	-	n.i
Feldspar	0	-	-	-	-	n.i
Fluorspar	0	1	1	1	1	n.i
Gallium	0	0	0	0	1	0
Germanium	0	2	2	2	2	9
Gold	25	-	-	-	-	23
Gypsum	1	-	-	-	-	n.i
Hafnium	0	-	-	-	-	n.d.
Indium	0	0	0	0	4	0
Iron	22	-	-	-	-	24
Lead	n.i	-	-	-	-	50
Limestone	0	-	-	-	-	n.i
Lithium	0	0	0	0	0	0
Magnesite	0	2	2	2	2	n.i
Magnesium	14	13	13	13	13	14
Manganese	19	-	-	-	-	19
Molybdenum	17	-	-	-	-	17
Natural Graphite	0	3	3	3	3	n.i
Natural Rubber	0	-	-	-	-	-
Nickel	32	-	-	-	-	26
Niobium	11	0	0	0	0	11
Perlite	0	-	-	-	-	n.i
Phosphate Rock	0	17	17	17	17	n.i
Potash	0	-	-	-	-	n.i
Pulpwood	51	-	-	-	-	n.i
Rhenium	13	-	-	-	-	9
Sawn Softwood	9	-	-	-	-	n.i
Scandium	1	-	-	-	-	n.d.
Selenium	5	-	-	-	-	n.d.

Materials	EC study 2013	MSA study 2015				UNEP report 2011
		Option A	Option B	Option C	Option D	
Silica sand	24					n.i
Silicon	0	0	0	0	0	n.i
Silver	24	-	-	-	-	21
Talc	0	-	-	-	-	n.i
Tantalum	4	-	-	-	-	3
Tellurium	0	-	-	-	-	n.d.
Tin	11	-	-	-	-	11
Titanium	6	-	-	-	-	6
Tungsten	37	42	42	42	42	37
Vanadium	0	-	-	-	-	n.d.
Zinc	8	-	-	-	-	9
PGMs	35	-	-	-	-	-
Platinum		24	18	11	23	23
Palladium		24	15	9	25	40
Rhodium		129	21	9	39	32
Ruthenium		-	-	-	-	11
Iridium		-	-	-	-	14
Osmium		-	-	-	-	
REE (Heavy)	0	-	-	-	-	-
Terbium		28	28	22	22	
Dysprosium		0	0	0	0	
Erbium		0	0	0	0	
Yttrium		43	43	31	31	
REE (Light)	0	-	-	-	-	-
Lanthanum		-	-	-	-	
Cerium		-	-	-	-	
Praseodymium		-	-	-	-	
Neodymium		1	1	1	1	
Samarium		-	-	-	-	
Europium		56	56	38	38	
Gadolinium		-	-	-	-	

n.d: no data available; n.i.: not included

Annex 3. Examples of EOL-RIR with UNEP/IRP data

End of life recycling input rate (EOL-RIR) calculated using UNEP's figures.

Material	OSR_{av} (%)	RC_{av} (%)	EOL-RIR = OSR_{av}(%) x RC_{av}(%)
Aluminium	45	35	16
Antimony	45	16	7
Beryllium	45	18	8
Chromium	66	19	13
Cobalt	50	32	16

Annex 4. Examples of EOL-RR with Industry data

Recyclates or secondary materials obtained from industrial minerals are frequently used for other functions and applications than those for virgin raw materials. In order to understand better the amounts of secondary materials that are effectively back to substitute virgin primary materials and therefore contribute to the total supply, data need to be analysed in further detail. The EU Industrial minerals association (IMA) has published a report[11] that includes recycling rates and information about the end-use of the recyclates obtained from some industrial minerals materials (IMA, 2013). Based on the information published, JRC has distinguished between functional and non-functional recycling. The table below shows the example of bentonite. For bentonite, recycling into new paper grade is accounted for as functional recycling whereas energy recovery by incineration is considered to be non-functional recycling. The IMA report states that about 70% of paper is recycled: 40% into new paper grades; 30% incinerated and 30% landfill.

Bentonite							
	End use (first)		**Recycling**		**End use (second)**		**Recycling rate**
	Type	**%**	**Process**	**Recyclate**	**Type**	**%**	**%**
Functional recycling	Civil engineering	11	Bentonite is used in several civil engineering applications	Construction materials	Concrete bricks and tiles; asphalt; wood, glass, metals, plastics, gypsum; dredging soil, soil and track ballast; other mineral and construction and demolition waste	60	6.6
	Paper	4	Recycling of paper	Recycled paper	New paper grades	40	1.6
	Total functional recycling						**8.2**
Non-functional recycling	Pet litter	29	Incineration together with municipal waste	Fly ash	Several industries as wall board industry	20	5.8
	Foundry Molding Sands	24	Bentonite contain in foundry sand is regenerated after metal casting	Not specified	Construction industry	80	19.2
	Pelletizing of iron ore	21	Bentonite transferred to the slag phase	Not specified	Cement industry	70	14.7
	Paper	4	Incineration together with municipal waste	Fly ash	Several industries as wall board industry	30	1.2
	Others	11	-	-	-	0	0
	Total non-functional recycling						**40.9**
Total recycling (functional and non-functional)							**49.1**

[11] IMA. 2013. Recycling Industrial Minerals. Brussels: Industrial Minerals Association (IMA). http://www.ima-europe.eu/sites/ima-europe.eu/files/publications/IMA%20Recycling%20Sheets%20FULL%20published%20on%2024.10.2013_0.pdf. Accessed February 22, 2016.

The report states that about 70% of paper is recycled: 40% into new paper grades; 30% incinerated and 30% landfill. In the table above, recycling into new paper grade is accounted for as functional recycling; the energy recovery by incineration is considered to be non-functional recycling.

Calcium carbonate (limestone)							
	End use (first)		Recycling		End use (second)		Recycling rate
	Type	%	Process	Recyclate	Type	%	%
Functional recycling	Paper*	40	Recycling of paper	Recycled paper	New paper grades	40	16
	Container glass	15	Recycling of glass	Recycled glass	New glass products	68	10.2
	Total functional recycling						**26.2**
Non-functional recycling	Paper	40	Incineration together with municipal waste	Fly ash	Several industries as wall board industry	30	12
	Plastics	15	-	Construction materials	Several products	17.5*	2.6
	Paints and coatings	15	Bentonite contain in foundry sand is regenerated after metal casting	Aggregates and construction materials	Construction industry	55**	8.2
	Container glass	15	Not detailed	Construction related	Construction industry	7	1.1
	Reagent in flue gas treatment	8	Incineration together with municipal waste	gypsum	Construction industry; underground mining; restoration of open cast mines, quarries and pits	90.5	7.2
	Others	7	-	-	-	0	0
	Total non-functional recycling						**31.1**
Total recycling (functional and non-functional)							**57.3**

*Average value estimated of 15-20% values reported. ** Average value estimated of 50-60% values reported.

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