Scope Definition on End-of-Life Chain Performance Assessment: Recycling Rate and French E-Waste Chain Case Study

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Abstract

Efficiency indicators have been frequently used to assess end-of-life chain performance. While legislations give a standard definition, sometimes stakeholders redefine them to fit their own scopes and objectives. It is therefore necessary to fully understand the indicators calculation scope in order to accurately interpret the results during a decision-making process. This work discusses the influence of scope definition when establishing performance rates using the French e-waste chain and recycling rate as an example. Complementary recycling rates to the one established by WEEE Directive are proposed.

Keywords:

End-of-Life Chain, E-Waste, Performance Indicators, Recycling Rate

1 INTRODUCTION

The rise of the world population and the individual search for better living conditions or more comfort go hand in hand with an increase of energy and raw material consumption. As consumption continues to grow, annual waste production increases [1,2] and its composition is also more complex as the years pass by. E-waste for example, also known as Waste Electrical and Electronic Equipment or WEEE, is a particularly complex waste due to its material composition [3]. While it contains some high value materials, it also includes some toxic ones, which can cause environmental and health issues if not properly treated. E-waste complexity and low density of high value materials induce high End-of-Life (EoL) treatment costs, which may result in recycled materials being more expensive than raw ones [4]. This added to the fact that e-waste collection rate remains low [5], results in e-waste EoL treatment not taking off.

As demand for primary resources is not sustainable in the long term [6,7], following the status quo is not an answer to resource depletion. Therefore, it is essential to find solutions to maintain equivalent living standards while decoupling resource use and demand [8]. The circular economy[1] offers a partial answer to this problem [9] and material recycling lies at its heart.

As the paradigm shift to a sustainable economy is primarily motivated by economic considerations [10,11], authorities are willing to help with the transition. In this regard, the European Union has chosen to establish an Extended Producer Responsibility (EPR) system. The first version of the WEEE Directive was published in 2002 [12]. One of the main objectives of the Directive was the creation of take-back schemes within Member States to improve the e-waste EoL chain management. They aim to increase the performance of all stages within the chain (*i.e.* from collection to recycling) and also to ensure the proper disposal of what could not be recovered. This system is outlined on Figure 1, listing all the stakeholders involved.

To tackle material efficiency objectives, a second directive was published on August 2012 [13]. It includes the concept of monitoring EoL chain performances. As waste management tools, EoL chain efficiency indicators can help to assess waste treatment scenarios in order to develop new and more sustainable strategies [14]. They are also means for translating information, or allowing non-technical specialists the use of complex datasets [15]. It is also possible to quantify and monitor the potential impacts of a selected waste stream, as well as the benefits of a specific EoL scenario [16]. In this context, several studies focusing on the development and/or use of indicators for analyzing EoL chain performance have been published [17–21]. There is no consensus among the

[1] Global economic model that decouples economic growth and development from the consumption of finite resources. It is restorative by design, and aims to keep products, components and materials at their highest utility and value, at all times [43].

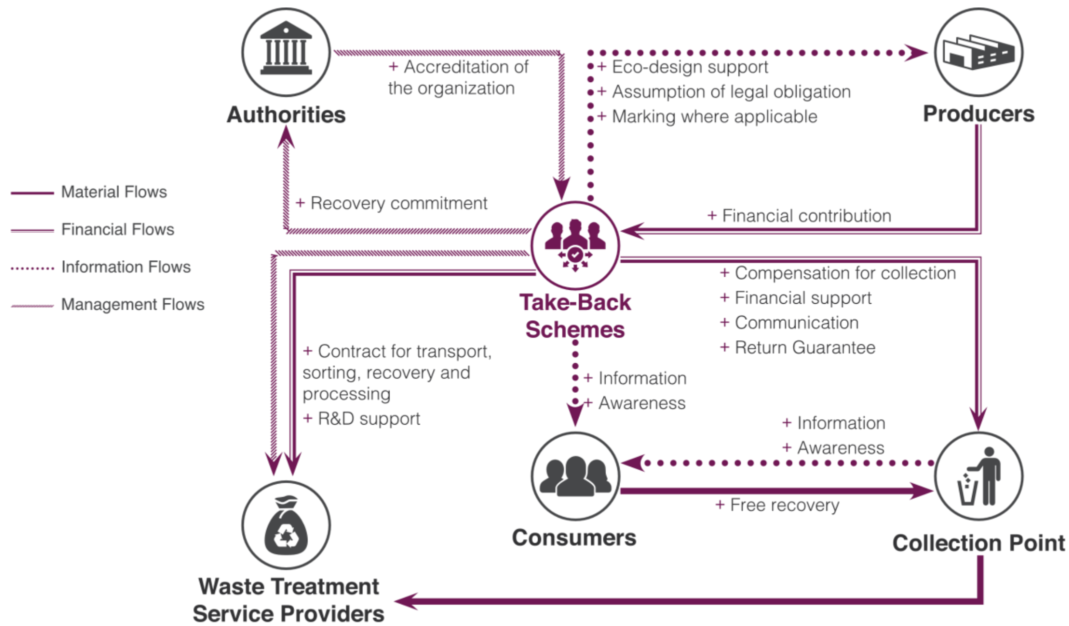

Figure 1. Representation of the take-back schemes system (Adapted from ADEME [44])

practitioners, neither on the limits of the EoL chain, nor on the scope and data to be used to calculate performance rates. While definitions of the EoL treatment options (*i.e.* reuse, recycling, etc.) are clearly detailed in the waste framework directive 2008/98/EC [22], none of the respective rates are properly set. The main problem lies in the fact that the calculation scope is frequently adapted to fit the indicator user needs. In other words, EoL chain stakeholders tend to choose a scope similar to their field of action when assessing performance rates [23]. Hence, communicating the calculation scope used in a study becomes essential as it directly affects the validity of results. Indeed, misinterpreting a calculation scope can lead decision makers (*e.g.* EoL chain stakeholders, environmental agencies, product designers, etc.) to implement wrong strategies.

This work discusses the importance of scope definition on EoL chain performance assessment and proposes different scopes of evaluation. The Recycling Rate indicator (RR) and the French e-waste chain are chosen to illustrate our study. Results will be discussed in sections 2 and 3.

2 E-WASTE REGULATION FRAMEWORK

2.1 European E-Waste Regulation Framework

The development of waste policies in Europe began in the 1970s when the first Waste Framework Directive 75/442/EEC was published [24]. The process went on further and unfolded into several directives specific to each of the main waste streams. In 1990, the European Commission initiated the Priority Waste Streams Program focused on six different streams. WEEE was selected among these main waste streams because of the fast growth of technological innovation, the burden brought to municipal authorities and its complex composition.

In 2002, the European Parliament published the first WEEE specific directive [12]. This directive aims to prevent the generation of e-waste while promoting reuse, recycling, and other forms of recovery as a mean to (i) reduce the amount of e-waste that cannot be recovered, and (ii) to improve circular economy.

To provide further clarification on waste management policy, new regulations were implemented with the European Directive 2008/98/EC [22]. It defines the regulatory framework for the EPR system organization in Europe. Moreover, it specifies that recycling consists of “any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations” [13].

In 2012, the WEEE Directive was revised [13] and introduced several obligations and objectives for the Member States. Among others, they must report to the European Commission the achieved collection, re-use, recycling and recovery rates for all WEEE categories[2] [25].

[2] WEEE are divided into ten categories of equipment as follows: large household appliances; small household appliances; IT and telecommunications equipment; consumer equipment and photovoltaic panels; lighting equipment; electrical and electronic tools; toys, leisure and sports; medical devices; monitoring instruments and control; automatic dispensers. After 2018, the categories will be redefined.

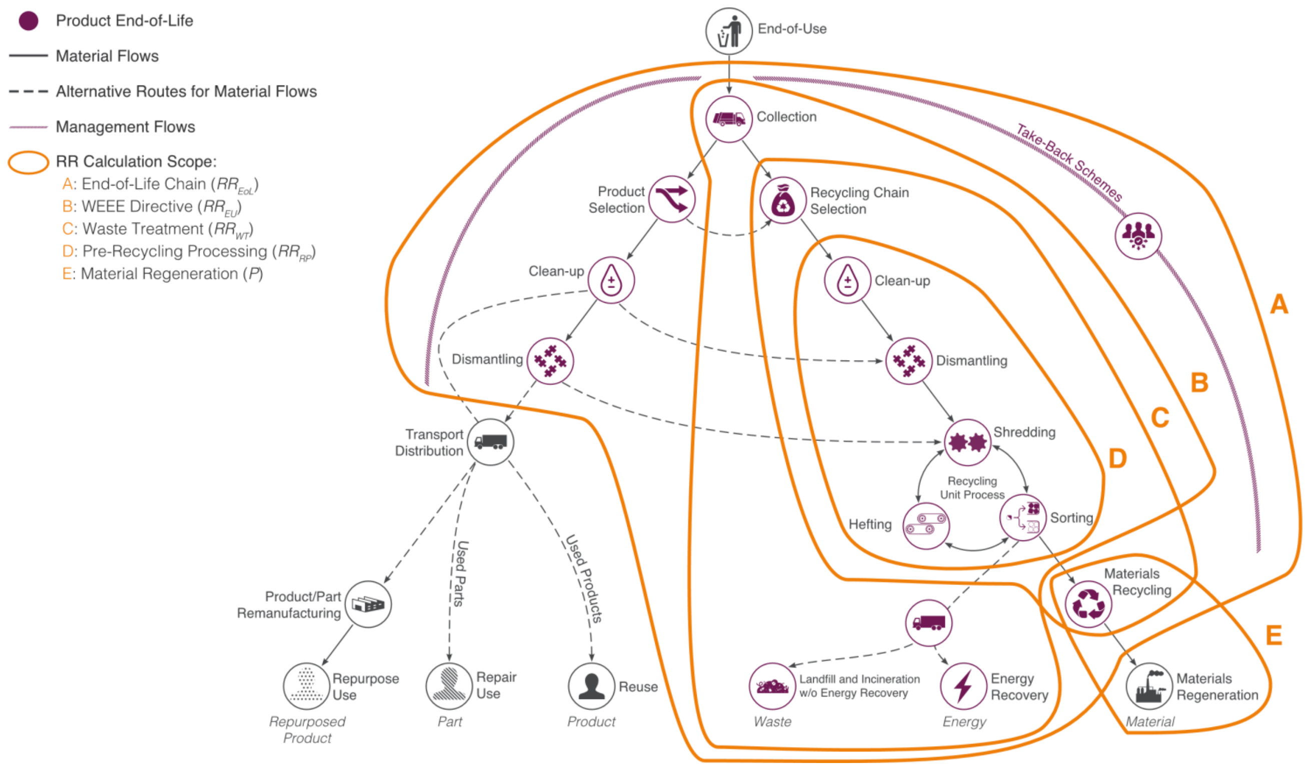

Figure 2. Representation of the e-waste EoL chain and the different scopes for the performance assessment of the EoL chain

2.2 French E-Waste Treatment Chain

The WEEE Directive was transposed into French law (mostly by Decree 2005-829 [26]) to regulate the composition of electrical and electronic equipment and to manage WEEE. It was later complemented by other legislation and by some additions made to the French Environmental Code.

The e-waste EoL chain is sketched on Figure 2, with four scopes of analysis (*A* to *D*). As we can see, each scope has different starting and ending points, and EoL steps also varies from one scope to the other. These scopes will be discussed in Section 3.

The French e-waste EoL chain has been operational since 2005 for professional e-waste, and since 2006 for household [27]. The system involves several stakeholders: producers, distributors, take-back schemes (also known as producer responsibility organizations or compliance schemes), recyclers and local authorities.

In 2015, 43% of the total household e-waste was collected and treated by the take-back schemes (less than 1% was reused, 34% reached the recycling facilities, 3% went to the energy recovery facilities and 5% was disposed) [27]. Regarding recycling, only a part was actually recycled. This is mostly due to the lack of necessary technology and losses during the processes. Recycling is the main treatment organized by the French take-back schemes [3], even though the waste management hierarchy specifies that waste reduction and re-use are better options as they both seek to increase the life-time of products, components and materials [16]. Currently, the performance assessment of the e-waste EoL chain is limited to technical indicators that aim to ensure the system complies with collection and recovery targets set by the legislation [28]. In addition to collection and recovery rates, recycling rates are one of the main indicators for assessing the French e-waste chain.

2.3 Recycling rate Definition from WEEE Directive

The Directive 2012/19/EU established that “the achievement of the recycling target (recycling rate) shall be calculated, for each WEEE category, by dividing the e-waste weight that enters the recycling facilities by the weight of all separately collected e-waste for each category, expressed as a percentage”. The related scope is named *B* on Figure 2. The aforementioned recycling rate is presented in Table 1.

The scope defined by the Directive is focused on the treatment performance of the e-waste collected by the take-back schemes. However, this method does not take into account the flows diverging from e-waste take-back schemes nor the losses occurring during recycling [29]. Moreover, the Directive sets recycling targets based on the overall weight of collected materials. It enables assessment of the benefits achieved through recycling for the different materials: ferrous and nonferrous metals, plastics, critical materials, etc. [20].

In France, all categories meet the recycling and recovery targets set by the Directive 2012 [13] and the French regulation [26] According to the last report published by the French Environment and Energy Management Agency (ADEME), the recycling and recovery rate for all categories reached 82% in 2015 [27].

Table 1. Recycling Rate according to the WEEE Directive [13]

Indicator RR		Recycling Rate WEEE Directive
Equation		$$RR_{EU} = \frac{1}{W_C}\sum_{i=1}^{n} W_i$$
	RR_{EU}	Recycling rate from WEEE Directive.
	n	Number of output fractions* from the pre-recycling processing sent to material recycling
	W_i	Weight of materials in the i^{th} output fraction sent to material recycling
	W_C	Weight of e-waste collected by the take-back schemes
Numerator		Total weight of e-waste sent to material recycling
Denominator		Total weight of e-waste collected by the take-back schemes
Scope	Start	E-waste collection
	End	Sorted fractions after e-waste shredding and sorting

* The term *output fractions* refers to the different output flux generated during the material sorting process (*e.g.* metallic fractions, plastic fractions, etc.).

3 AUXILIARY RR SCOPES PROPOSITION

Based on a literature review, this paper presents four proposals of recycling rate indicators (the last is taken from the literature), in addition to the indicator proposed by the Directive, to calculate the performance of e-waste EoL chain, looking at different scopes of assessment (cf. Figure 2, *A*, *C*, *D* and *E*). In order to better compare the new scopes of calculation to the previous one (cf. § 2.3), the auxiliary scopes will be based on the Directive indicator; in other words, the output fractions W_i will be used as a reference point.

3.1 End-of-Life Chain Recycling Rate

Even though recycling rates have been defined in many ways and for many life-cycle stages, this term remains somewhat non-specific [18]. According to the Eurostat database [30], e-waste recycling rate is the collection rate multiplied by the rate of recycling at the treatment facility. It is assumed that all the collected e-waste is in fact sent to treatment/recycling facilities.

For Nelen *et al.*, recycling performance must be calculated as the ratio of the amount of materials effectively recycled (excluding process losses) to the weight of the waste entering the recycling process [21].

Haupt *et al.* define recycling rate as the ratio of recycled materials to waste generated; they also specify that recycling rate should be calculated according to the type of recycling: open loop (materials are recycled into other types of products; it may result in producing new materials of lesser quality and reduced functionality) or closed loop (components or materials are used again to produce new products of the same type) [18].

Data available to calculate the performance of e-waste treatment must be considered when proposing indicators to assess the EoL chain performance. Some approaches in scientific literature aiming to improve general knowledge of the EoL chain performance, cannot be applied due to a lack of data to calculate the indicators (*e.g.* the specific composition of the input of the recycling process is unknown). In this context, in order to calculate the global recycling performance of the WEEE EoL chain, we suggest an indicator named "End-of-Life Chain Recycling Rate (RR_{EOL})". The corresponding scope is named *A* on Figure 2. This indicator is the weight ratio of materials effectively recycled divided by the total e-waste generated (cf.Table 2).

Table 2. End-of-Life Chain Recycling Rate (RR_{EOL})

Indicator RR_{EOL}		End-of-Life Chain Recycling Rate
Equation		$$RR_{EOL} = \frac{1}{PoM}\sum_{i=1}^{n} W_i \times P_i$$
	n	Number of output fractions from the pre-recycling processing sent to material recycling
	W_i	Weight of materials in the i^{th} output fraction sent to material recycling
	P_i	Material recycling efficiency rate of the recycling facilities treating the i^{th} output fraction
	PoM	Average weight of EEE placed on the market the three previous years*
Numerator		Total weight of materials recycled by the EoL chain (considering the losses in material recycling)
Denominator		Total weight of e-waste generated
Scope	Start	E-waste generation
	End	Recycled materials (output of material recycling)

* PoM calculated as described in WEEE Directive.

The recycled materials data comes from recycling company feedbacks provide to take-back schemes. The reliability of this data is regularly questioned [32]. It can be calculated per WEEE category or waste stream; this last approach is usually adopted by Member States to implement WEEE treatment, *e.g.* others small appliances. Since the specific composition of the WEEE generated is unknown, it is not possible to obtain a RR_{EOL} per material recycled. Knowledge of the global performance of the WEEE end-of-life chain is useful at a national level mainly to take-back schemes and environmental agencies, and can be used to compare the performance of different countries.

3.2 Waste Treatment Recycling Rate

For some stakeholders, assessing treatment chain efficiency is very important. For example, knowing the treatment efficiency is essential for designers to calculate the recyclability of their products, either as a part of an eco-design strategy or when verifying if they comply with legislation [33–37]. The "Waste Treatment Recycling Rate (RR_{WT})" indicator calculates the aforementioned efficiency. The corresponding scope is named *C* on Figure 2. The details of this indicator are shown in Table 3.

Table 3. Waste Treatment Recycling Rate (RR_{WT})

Indicator RR_{WT}		Waste Treatment Recycling Rate
Equation		$RR_{WT} = \frac{1}{W_T}\sum_{i=1}^{n} W_i \times P_i$
n		Number of output fractions from the pre-recycling processing sent to material recycling
W_i		Weight of materials in the i^{th} output fraction sent to material recycling
P_i		Material recycling efficiency rate of the recycling facilities treating the i^{th} output fraction
W_T		Weight of the total e-waste treated* by the EoL chain
Numerator		Total weight of materials recycled by the EoL chain (considering the losses in material recycling)
Denominator		Total weight of e-waste treated by the EoL chain
Scope	Start	Collected e-waste that is going to be processed by the treatment chain
	End	Recycled materials (output of material recycling)

* The quantity of e-waste treated is not the same as the quantity of e-waste collected as quite often these values differ from one to another.

It is calculated by dividing the total weight of all recycled materials by the total weight of e-waste treated by the chain. This indicator mainly seeks to assess the degree by which e-waste materials are being recovered. Thus, the RR_{WT} scope begins with the e-waste that is going to be treated by the EoL chain. In comparison, the RR_{EU} starts with the collected waste, and the RR_{EOL} with the whole e-waste generated (obtained from the EEE placed on the market. While the RR_{WT} scope ends after the material recycling steps; (like for the RR_{EOL}), whereas RR_{EU} stops just before the recycling process.

3.3 Pre-recycling Pathway Recycling Rate

For recycling companies involved in the e-waste recycling chain, calculation of the RR is based on a gate-to-gate approach. It is an internal performance indicator that helps with quantifying the pre-recycling processing efficiency. It is usually calculated concurrently the purity rate indicator. Both are used by recycling companies to evaluate the financial gains of the recycling pathway. In this context, to calculate the recycling performance of the pre-recycling process, we suggest an indicator named "Pre-recycling Pathway Recycling Rate (RR_{RP})". The corresponding scope is named *D* (cf. Figure 2). This indicator is calculated by dividing the weight of materials sorted from the pre-recycling pathway by the weight of e-waste entering to the recycling plant (Table 4). RR_{RP} is calculated for each material within a waste stream.

Table 4. Pre-Recycling Pathway Recycling Rate (RR_{RP})

Indicator RR_{RP}		Pre-Recycling Pathway Recycling Rate
Equation		$RR_{RP} = \frac{1}{W_{upstream}}\sum_{i=1}^{n} W_i$
n		Number of output fractions from the pre-recycling processing sent to material recovery
W_i		Weight of materials in the i^{th} output fraction sent to material recycling
$W_{upstream}$		Input weight of the e-waste upstream flow at the pre-recycling facility
Numerator		Total weight of materials sorted by the pre-recycling processing pathway
Denominator		Incoming e-waste to the recycling plant
Scope	Start	E-waste supply to the waste treatment plant after clean-up and dismantling
	End	Material recovery after sorting processes

The input weight of e-waste ($W_{upstream}$) used for the calculation of pre-recycling processing recycling rate (RR_{RP}) differs from the one used for the calculation of the

RR_{EU} (according to the WEEE Directive). In the case of RR_{RP}, the $W_{upstream}$ value is limited to a single pre-recycling facility, whereas for the RR_{EU}, the value is given for all the recycling facilities involved in the e-waste recycling chain. When calculating the RR_{RP}, the downstream performance of material recycling and regeneration are not taken into account. That is why any efficiency rate (such as P_i) is used in the equation.

The RR_{RP} is specially adapted for assessing recycling processes in order to determine the most efficient means to recycle a given product. Knowing the e-waste pre-recycling processing performance is very useful for recycling companies. For example, it can help to design a recycling pathway based on this performance [38].

3.4 Material Recovery Efficiency Rate

Recycling companies, such as UMICORE [39], quite frequently have two main activities: the production of secondary raw materials (named as *material recycling* in Figure 2) and the preparation of these materials to be used in the industry (named *material regeneration* in Figure 2). This actors use an additional efficiency rate in order to calculate the recovery performance of the materials obtained from e-waste, here named as "Material Recovery Efficiency Rate (P)". This assessment is important because it allows to link the EoL treatment to the production of new goods using recycled materials.

Table 5. Material Recovery Efficiency Rate (P) [39]

Indicator P		Material Recovery Efficiency Rate
	Equation	$P_i = \frac{W_{RM} - W_{raw}}{W_i}$
	i	i^{th} output fraction from the pre-recycling processing sent to material recycling
	W_{RM}	Weight of materials in output fraction after material recovery
	W_{raw}	Weight of raw materials added during the material recovery processes
	W_i	Weight of materials in the ith output fraction sent to material recycling
	Numerator	Total weight of materials recovered by the regeneration processes
	Denominator	Weight of sorted fractions from pre-recycling processes
Scope	Start	Pre-recycling processes sorted fractions supplying the regeneration plant
	End	Regenerated materials

Since it is rather an efficiency rate than a RR, this indicator is named differently than the three previously proposed. In the same way as the RR_{RP}, the P indicator is calculated internally based on a gate-to-gate approach. The corresponding scope is named E (cf. Figure 2). It is calculated by dividing the amount of materials produced by the regeneration processes (excluding raw materials added during the recovery process), by the weight of the sorted fractions produced by the pre-recycling processes (cf. Table 5).

P_i indicator seeks to quantify the recovery processes efficiency [40,41]. It is usually correlated with a raw material incorporation rate. This indicator helps the regeneration companies by both quantifying the material impurities in sorted fractions and determining the losses associated with the regeneration processes Knowing the e-waste material recovery efficiency is essential for calculating EoL chain performance and e-waste treatment RRs. This information can be used to support policies seeking to optimize the recovery chain.

4 CONCLUSIONS

This work discusses the importance of better understanding and properly defining the scope of analysis when calculating the RR performance. RR is one of the main indicators for assessing the e-waste EoL chain performance. As previously mentioned, the WEEE Directive determines a RR in order to assess the EoL chain which is focused on the performance of take-back schemes. Besides excluding the flows treated outside the official channels, it does not consider the processes losses occurring during e-waste treatment. Those limitations were also discussed by other authors and complementary approaches are suggested in the literature.

In that regard, this article proposes complementary scopes of evaluation that adjust to the needs of different stakeholders. Indeed, as presented in Section 3, the scope of calculation can have many interpretations as it can be modified to suit the needs of the user of the indicator. RR_{EOL} provides a global performance of the e-waste EoL chain and it is useful mainly to take-back schemes and environmental agencies, as well as to compare the performance of different countries. On the other hand, RR_{WT} provides information about the treatment performance of the take-back systems, including process losses, and can be used by designers when developing new products. Finally, RR_{RP} and P are better suited for calculating the pre-recycling, recycling and regeneration performances of companies based on a gate-to-gate approach.

A common reference framework exists, so it is not necessary to draft a common document. However, it seems necessary to create tools to enable all stakeholders to understand each other. To that end, the adoption of these four indicators together with the WEEE Directive should provide useful and clear information to the stakeholders involved in the e-waste chain. Indeed, even if the WEEE Directive suggests a calculation method for e-waste RR, it cannot be the only one as this method implies a multi-actor scope and the collection of data is not always possible. That is why stakeholders currently calculate the RR based on their specific scope. The presented rates respond to this need as they are stakeholder-specific. It is therefore essential to always specify the calculation scope when communicating the results of a performance assessment so it can be understandable. Our argument on RR could be duplicated for other EoL indicators such as energy recovery rate, landfill rate, re-use rate, etc.

It is important to remember that the level of information available should be considered when suggesting new indicators in order to ensure their feasibility.

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