Measuring the Environmental Sustainability of a Circular Economy

Author(s):
Haupt, Mélanie; Hellweg, Stefanie

Publication Date:
2019-09

Permanent Link:
https://doi.org/10.3929/ethz-b-000364533 →

Originally published in:
Environmental and Sustainability Indicators 1-2, http://doi.org/10.1016/j.indic.2019.100005 →

Environmental and Sustainability Indicators 1-2 (2019) 100005

Contents lists available at ScienceDirect

Environmental and Sustainability Indicators

journal homepage: www.journals.elsevier.com/environmental-and-sustainability-indicators/

Measuring the environmental sustainability of a circular economy

Melanie Haupt *, Stefanie Hellweg

Chair for Ecological Systems Design, Institute of Environmental Engineering, ETH Zurich, Switzerland

ARTICLE INFO

Keywords:
Circular economy
Environmental sustainability
Environmental indicator
Monitoring
Value retention processes
Recycling

ABSTRACT

"What gets measured gets managed" - this quote by Peter Ducker reveals a pitfall for the targeted transition towards a more sustainable, circular economy. Today, mass-based indicators, such as recycling rates, are used to assess the circularity of individual products, firms and of entire countries. These indicators, however, fail to cover the environmental perspective – one of the most mentioned reasons to move from a linear to a circular economy. Here, we propose a complementary environmental-impact based indicator that measures the environmental value retained through reuse, remanufacturing, repairing or recycling. The indicator extends the focus from end-of-life to the entire life cycle and includes substitution of primary materials. Furthermore, it allows for monitoring the transition towards a circular economy from an environmental and possibly economic and social perspective. We provide three examples that highlight the application of the indicator and also reveal that common beliefs about the environmental performance of the circular economy are sometimes misleading and counter-productive.

1. Introduction

The concept of a Circular economy (CE) is receiving increased attention as an alternative to the take-make-dispose-system that exists today (Stahel, 2016). The Ellen MacArthur Foundation describes the circular economy as an *'industrial system that is restorative or regenerative by intention and design'* (Ellen MacArthur Foundation, 2013) while the European Action Plan states that circular economy is an economy '*where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized'* (EC, 2015). While many definitions of CE exist (Kirchherr et al., 2017; CIRAIG, 2015), at the core of most of them lie "value retention processes", i.e. mechanisms to retain value in our economy through reuse, repair, refurbishment, remanufacturing, redistribution and recycling (Nasr et al., 2018). The vision of a CE is appealing and has raised widespread awareness and willingness to act among governments and industries and was also found to support the implementation of the Sustainable Development Goals (Schroeder et al., 2019). However, concrete examples of groundbreaking CE solutions that make a change in practice have so far been scarce. One of the reasons for this is a lack of quantitative indicators that tell us what is relevant from a resource and environmental perspective and which "value retention process" is the best option in a given situation. Decisions about circular solutions, however, are instead often based simply on beliefs or on metrics that do not explicitly assess environmental performance.

Monitoring both material consumption and environmental impacts as well as defining targets are key for the successful implementation of a CE. Ideally, monitoring results and targets are not just relevant to policy makers, but also inspire action in industry and throughout the wider public. A prerequisite is having harmonized, measurable, relevant and diagnostic indicators (Oswald, 2013). These should assess not only circularity, but also environmental performance since circularity is not necessarily equivalent to environmental sustainability (although often assumed to be). For example, the energy demand for recycling can increase drastically at very high recycling rates and may offset the environmental gains obtained through the recovery of secondary material (Haupt et al., 2018). The use of different resources also has different environmental impacts and changes in consumption patterns may lead to higher or lower overall impacts depending on the material shift (van der Voet et al., 2005). Therefore, environmental indicators and targets are needed to ensure that the economy does not only become circular, but also sustainable.

Recent review studies have provided a good overview and different taxonomies for indicators on CE. An analysis of Parchomenko et al. (2019) differentiated between three groups of CE indicators, i.e. the resource efficiency cluster, the materials stocks and flows cluster and the product-centric cluster. Among all these groups, frequently assessed CE elements include waste disposal, primary vs. secondary use of resources and resource and recycling efficiencies while only a few CE metrics assessed the maintenance of value, value change and longevity. Elia et al.

---

* Corresponding author. John-von-Neumann Weg 9, 8093, Zürich, Switzerland.
E-mail address: haupt@ifu.baug.ethz.ch (M. Haupt).

https://doi.org/10.1016/j.indic.2019.100005
Received 7 August 2019; Received in revised form 9 September 2019; Accepted 9 September 2019
Available online 11 September 2019

(2017) described requirements that need to be measurable by CE indicators and mapped environmental assessments accordingly, highlighting material and substance flow analysis as well as life cycle assessment as the two most promising assessment methodologies covering four out of five CE dimensions. Moraga et al. (2019) described three different scopes of indicators: indicators on physical properties from technical cycles with/without life cycle thinking and indicators measuring effects from technical cycles regarding environmental, economic and/or social concerns. However, today most circular economy strategies from countries, industries and research include only mass-based targets for the recycling and re-use of materials to increase the waste management's contribution to a circular economy. There are limited quantitative targets for the environmental performance and only a few indicators which are able to include value retention processes and end-of-life treatments (Moraga et al., 2019).

Material flow data, widely used in traditional and new indicators, provide a useful baseline to compare the circularity of products, firms and countries (Jacobi et al., 2018; Haas et al., 2015; Elia et al., 2017). Subsets of material flow data may also provide useful indicators on flows of specific substances or elements, levels of reuse and recycling, methods of waste disposal, and recycling indicators (EASAC, 2016). Material-flow based indicators, such as recycling rates, however, are often not well-defined and can describe various performance measures, e.g. collection rates (mass ratio of collected material to material initially consumed), intermediate recycling rates (mass ratio of sorted material to material initially consumed), and final recycling rates (mass ratio of mass in secondary products to material initially consumed) (Haupt et al., 2017). These rates are limited to collection or recycling and do not take into account any other value retention processes or environmental impacts (Fig. 1).

To facilitate the comparison of waste management systems of member states, the European Commission has recently harmonized the national performance measures as the mass of inputs into final recycling processes divided by the mass of material consumed in a country (i.e. intermediate recycling rates in Fig. 1). While this is an improvement compared to tracking solely the collection rates, only final recycling rates consider both material quality and quantity losses in the entire recycling chain (Haupt et al., 2017). Final recycling rates are able to holistically assess the resource efficiency by taking into account consumers' collection behavior, material purity, and the efficiency of the recycling process. In view of the large trade flows of low-quality recycling materials from industrialized countries to countries with deficient recycling-infrastructure (Brooks et al., 2018), consideration of such final recycling rates would also provide an incentive for countries to take responsibility of their waste materials beyond national boundaries.

The traditional material flow analysis-derived indicators presented above only partly cover the material cycle. Therefore, to measure the transition towards a sustainable circular economy and to monitor the shift in economic systems, the view needs to be extended to the entire life cycle (Elia et al., 2017; Moraga et al., 2019). Indicator frameworks that include the material production phase, product use phase, and end-of-life phase have been proposed (e.g. Ellen MacArthur Foundation (2015) and European Commission (2018)). For example, the input from virgin and recycled materials used in production is analyzed and the duration of the use phase is quantified (Ellen MacArthur Foundation, 2015). While these indicator frameworks comprehensively assess influencing factors and material flows in/around a circular economy, they lack environmental performance indicators. An exception is a Chinese framework (Geng et al., 2012) that, by taking into account some emissions, partly incorporates the environmental dimension of the circular economy. This framework, however, lacks a life cycle perspective because, for example, material production is not environmentally assessed. Carbon reduction

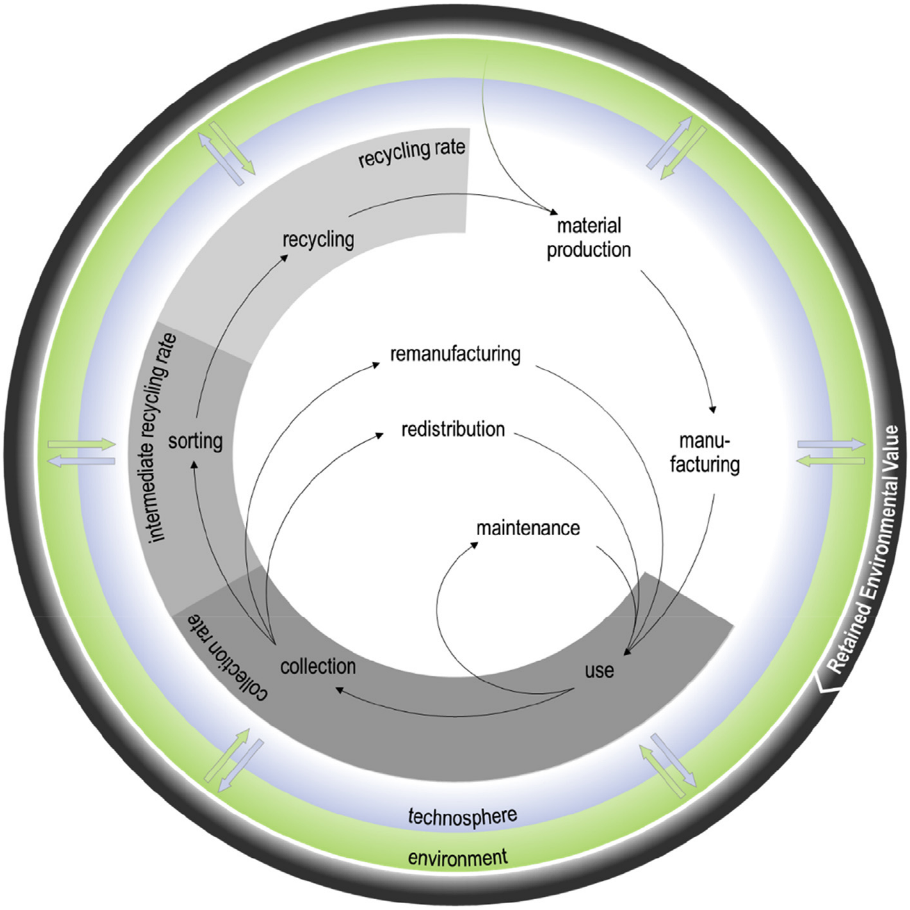

Fig. 1. Schematic representation of a production system. In grey, the collection rate (comparing consumed to collected mass), the intermediate recycling rate (comparing used to sorted mass), and the recycling rate (comparing used mass to secondary material) are indicated. Besides recycling, some value retention processes are shown (remanufacturing, redistribution and maintenance). For simplicity, the value retention processes reuse and repair as well as losses from all processes are omitted in the graph but taken into account below. The exchanges with the environment are indicated to highlight the environmental impact of all processes. Losses to the environment can occur in all processes, but are not shown in the figure. The Retained Environmental Value (REV) is further indicated, covering both the technosphere and the environment and modelling all value retention processes.

and other ecological indicators are part of the low carbon economy development project in China (in place since 2010) and are therefore not included among the indicators for a circular economy (Geng et al., 2012). However, an emergy-based indicator was proposed by Chinese researchers to take up- and downstream impacts of consumption into account (Geng et al., 2013).

Given that circular economy should also target a reduced environmental impact, the need for an impact-based indicator becomes obvious (e.g. Pauliuk (2018) and Haupt et al. (2017, 2018a)). Life cycle impact indicators for monitoring a circular economy include the emergy indicator for China (Geng et al., 2013), the indicator dashboard outlined in Pauliuk (2018), and the circular economy performance indicators proposed by Huysman et al. (2017) and Huysveld et al. (2019). While Pauliuk (2018) refers more generally to previously established methods, such as greenhouse accounting as one indicator of life cycle assessment, Huysman et al. (2017) calculates the ratio of the actual obtained environmental benefit (i.e. of the currently applied waste treatment option) over the ideal environmental benefit according to the resource quality of the respective flow. For this, knowledge on the best treatment option needs to be available. The ideal treatment for a waste stream, however, is subject to change based on technological developments and markets for secondary materials. The indicator is, therefore, not suitable for a continuous monitoring, as the baseline would change over time. The indicator by Huysveld et al. (2019) comprises the full life cycle impacts, but is limited to recycling and presupposes knowledge on a products entire life cycle (cascading use including final disposal). The retention of "value" in the system, i.e. omitting the final disposal, however, is of key importance in CE (Nasr et al., 2018) and mentioned as fifth principal of CE in BSI, 2017 8001:2017 (i.e. "keep materials at their highest value and function"). Most previous indicators neglect the maintenance or change of value in the system (Parchomenko et al., 2019) with a few exceptions that measure financial value retention (Di Maio et al., 2017; Linder et al., 2017). Therefore, we aim at providing an indicator to measure the value retention in the system in environmental terms, considering i) the life cycle impacts of an individual product or material, ii) all value retention processes and iii) the use-phase and potentially changed use-phase impacts.

2. Methods

2.1. Indicator for retained environmental value of circular solutions

The environmental value of a product or material is at the core of the new methodology proposed below. To measure the environmental value retention, the environmental value of a good or product is described here as the environmental impact used in its production (material production and manufacturing in Fig. 1). This represents the previous efforts put into a product and represents a benchmark of what can be maintained in the system by value retention processes and recycling.

We therefore suggest using the retained environmental value (REV) as an impact-based measure for circular economy. This measures the share of the environmental impact (EI) from the production of a material or product that is retained in products and materials recovered from reuse, remanufacturing, or recycling, i.e. the REV (Eq. (1)) quantifies the share of the original environmental impact that can be retained in the technosphere through value retention processes. Since the substitution of primary material plays an important role in terms of environmental impacts of recycling systems (Haupt et al., 2018a; Rigamonti et al., 2018), the REV indicator also accounts for the displaced products or materials. While some value retention processes (i.e. reuse, repair, refurbishment, remanufacturing, and redistribution) maintain a product's value in the system, only the material's value is recovered in recycling processes. This is taken into account by choosing the point of substitution based on the value (i.e. material or product) retained. Hereby, the type and amount of displaced primary material is identified considering functional equivalence, available amounts and market preferences (Vadenbo et al., 2017). More specifically, the REV compares the impact of the displaced product or material (EI_{disp}) following any value retention process (after deduction of the impact for recycling, remanufacturing, etc. (EI_{vrp})) to the impact of the original product ($EI_{original}$). Differences in environmental impacts during the use-phase can be included in the comparison to account for changed efficiencies of a retained and an alternative primary product ($EI_{surplus}$). The surplus environmental impact is assumed to cover the whole life cycle of the displaced product. If a product consists of more than one material, environmental impacts of the different materials are added up (*i* = *materials in original product, j*=*materials in alternative product*). As an example, in glass recycling the REV describes the impact that would be necessary to produce a new glass bottle minus the impacts associated with the recycling divided by the impact of the production of the original glass bottle.

$$REV = \frac{\sum_{j=1}^{n}\left(EI_{disp,j} - EI_{vrp,j}\right) - EI_{surplus}}{\sum_{i=1}^{n}\left(EI_{original,i}\right)} \qquad 1$$

An REV of 0% means that no net environmental value is retained in the product and 100% means that the full original environmental value is contained in the material available for further use, i.e. the higher the REV, the better. The possible range of REV depends on the application. For comparisons of closed-loop reuse, remanufacturing and recycling processes, values of up to 100% can be reached. The difference to 100% denotes the losses and the efforts spent for the value retention processes. Open-loop recycling processes often have REVs much smaller than 100% but can yield REV values over 100% if recovered materials substitute other materials with a higher environmental value. Negative values of REV occur if the use-phase emissions of the retained products are higher than the emissions of the displaced product (i.e. for high *EI_surplus)*. An example of this would be when the energy efficiency of an immature technology improves over time, so that the energy efficiency of the retained product is lower than that of a new product. Hence, the REV quantifies on an absolute scale in which situations a circular process is not sustainable (i.e. negative values). However, it can also be used to compare various circular processes for the same material. In this case, the best option is the one with the highest REV. Finally, REV can be monitored over time to assess progress in terms of the environmental sustainability of circular economy solutions. Fig. 1 shows, in addition to the mass-based indicators, the extended perspective of the REV, in which the material production and the manufacturing of goods as well as the interactions with the environment are taken into account. The inclusion of the primary production allows for quantifying the retained value compared to the initial value. Compared to mass-based indicators, the REV considers all technical inputs (e.g. energy and ancillaries) along the supply chain as well as the exchanges with the environment, i.e. natural resource use and emissions and the resulting impacts.

The REV indicator requires data about the life-cycle based environmental impacts of production and recycling processes as well as the use-phase of products. This data and the impact modeling frameworks come from the field of Life Cycle Assessment (LCA). The life cycle inventory and the impact assessment are based on databases covering the upstream supply-chain data. The most consistent and transparent database, ecoinvent (Wernet et al., 2016), was used for this study (version 3.3 cutoff system model). As an indicator, the REV can be set to refer to various, relevant impact or damage categories (e.g. climate change, biodiversity loss, human health effects, cumulative energy or exergy demand). While in some cases one impact category may be sufficient (in case impacts correlate), in other cases a range of impact categories may be used to reveal trade-offs between different environmental impacts (Steinmann et al., 2016). Related to the political targets and its importance for material resources (IRP, 2019), the impact on climate change should be considered but can be supplemented with as many impact categories as necessary. For impacts on climate change, REV targets could further be derived from national climate goals.

2.2. Application examples

The proposed REV indicator is tested in three case studies. For each material and product, different value retention processes or different secondary products are considered. Substitution for all materials and in all scenarios was modeled using the framework provided by Vadenbo et al. (2017). Where not stated otherwise, full substitutability of the primary material or product is assumed.

The assumptions and respective application of the REV as defined in Eq. (1) are described below. The code for the calculation of the REV for all examples, containing also more detailed description of the underlying assumptions, can be downloaded as a jupyter notebook (python code) or as PDF from the journals homepage.

2.2.1. Packaging glass

Packaging glass, collected from households, can be washed and reused, recycled to new packaging glass, or be processed into foam glass, used as an insulation material, or glass sand, used as a sand replacement. The REV is calculated for these four utilization processes. Color-separated green packaging glass was assumed as the input to all scenarios (EI_{prim_glass}). Reuse of glass bottles after a washing process was modeled in scenario 1a. In this scenario, it is assumed that the washed bottle substitutes a new glass bottle, therefore substituting the original material value ($EI_{disp} = EI_{prim\_glass}$). The efforts of the washing process are subtracted from the substituted material (Eq. (2), EI_{REU}). In scenario 1b, secondary packaging glass is assumed to substitute primary packaging glass after a melting process (Eq. (3), EI_{REC_glass}). Scenario 1c describes the recycling of packaging glass to foam glass (Haupt et al., 2018a, EI_{REC_insul}), which is assumed to substitute primary foam glass and extruded polystyrene (XPS) (25% primary foam glass, 75% XPS based on Stettler et al. (2016)) (Eq. (4), EI_{insul_mat}). For scenario 1b and 1c, the material recovery efficiency (i.e. amount of resources after recycling per amount collected) was assumed to be 95% (Haupt et al., 2017) and life cycle impacts for collection, sorting, and recycling were taken from Haupt et al. (2018a, 2018b). In scenario 1d, the crushing of glass to glass sand (EI_{REC_sand}) is modeled (Haupt et al., 2018b), assuming glass sand would replace sand (Eq. (5), EI_{sand}).

$$\boldsymbol{REV}_{REU\ glass\rightarrow glass} = \frac{\boldsymbol{EI}_{prim\_glass} - \boldsymbol{EI}_{REU}}{\boldsymbol{EI}_{prim\_glass}} \qquad 2$$

$$\boldsymbol{REV}_{REC\ glass\rightarrow glass} = \frac{\boldsymbol{EI}_{prim\_glass} - \boldsymbol{EI}_{REC\_glass}}{\boldsymbol{EI}_{prim\_glass}} \qquad 3$$

$$\boldsymbol{REV}_{REC\ glass\rightarrow insulation} = \frac{\boldsymbol{EI}_{insul\_mat} - \boldsymbol{EI}_{REC\_insul}}{\boldsymbol{EI}_{prim\_glass}} \qquad 4$$

$$\boldsymbol{REV}_{REC\ glass\rightarrow glassand} = \frac{\boldsymbol{EI}_{sand} - \boldsymbol{EI}_{REC\_sand}}{\boldsymbol{EI}_{prim\_glass}} \qquad 5$$

2.2.2. Newsprint

Newsprint collected from households is mostly used to produce secondary newsprint in Switzerland (Haupt et al., 2017). Paper fibers, however, are damaged in the recycling process and have limited reuse potential. Closed-loop paper recycling is therefore only possible for a limited number of cycles, and requires the addition of primary fibers to compensate for the share of lost fibers too short for recycling. In comparison to a collection rate, the REV considers the value of the recovered fibers as well as the amount of energy and primary material needed to produce secondary newsprint. Scenario 2a describes the use of paper fibers in the secondary newsprint production (Eq. (6), recycling effort: $EI_{REC\_newsprint}$). Secondary newsprint substitutes primary newsprint ($EI_{disp} = EI_{prim\_newsprint}$) produced from thermo-chemical pulp. The resource recovery efficiency was assumed to be 75% based on the loss of short fibers (Haupt et al., 2017). Scenario 2b describes the recycling of paper fibers to corrugated board ($EI_{REC\_cardboard}$), i.e. to linerboard and fluting medium for the corrugated board production (Eq. (7), $EI_{cardboard}$). The resource recovery efficiency was assumed to be 92% (Haupt et al., 2017). In scenario 2c, the use of paper fibers as cellulose insulation material is modeled (Eq. (8), recycling effort: $EI_{REC\_insulation}$). It is assumed that primary cellulose insulation using thermo-chemical pulp is replaced (EI_{cell_insul}) and that no fibers are lost in the production of insulation material. Life cycle impacts of all recycling processes were taken from Haupt et al. (2018a, 2018b).

$$\boldsymbol{REV}_{REC\ newsprint\rightarrow newsprint} = \frac{\boldsymbol{EI}_{prim\_newsprint} - \boldsymbol{EI}_{REC\_newsprint}}{\boldsymbol{EI}_{prim\_newsprint}} \qquad 6$$

$$\boldsymbol{REV}_{REC\ newsprint\rightarrow cardboard} = \frac{\boldsymbol{EI}_{cardboard} - \boldsymbol{EI}_{REC\_cardboard}}{\boldsymbol{EI}_{prim\_newsprint}} \qquad 7$$

$$\boldsymbol{REV}_{REC\ newsprint\rightarrow insulation} = \frac{\boldsymbol{EI}_{cell\_insul} - \boldsymbol{EI}_{REC\_insulation}}{\boldsymbol{EI}_{prim\_newsprint}} \qquad 8$$

2.2.3. Cast iron engine

Value retention processes of vehicle motors were investigated as a case study in Nasr et al., (2018), containing data on several value retention processes (Nasr et al., 2018). The simplified composition of the steel motor block, taken from Nasr et al., (2018), consists of steel, cast iron, and aluminum (i = steel, cast iron, aluminum in Eqs. (9)–(11)). The environmental impact of the energy and the materials used in remanufacturing are integrated into the assessment of the REV (based on Nasr et al., 2018; EI_{RMF}). It is assumed that no material removed during the remanufacturing process is recycled (worst-case assumption). The content and calculation of the REV is outlined in more detail in Fig. 2.

In scenario 3a, the remanufactured motor replaces a new equivalent motor. In scenario 3b, a lightweight aluminum motor ($EI_{ALmotor}$, composition from Nasr et al., 2018) was considered as an alternative, which have in the last decade gained market share (Heuss et al., 2012). The change to lightweight motor results in different use-phase impacts: the higher weight of the remanufactured iron motor compared to an aluminum based lightweight motor causes additional fuel use. Per 100 kg weight saving, the fuel consumption is reduced by 0.15–0.7 l/100 km (Wohlecker et al., 2007). An additional 0.43 l/100 km per 100 kg additional weight for 200,000 km leads to an additional environmental impact from the fuel supply chain and combustion emissions (EI_{fuel}). A fuel mix of 40% diesel and 60% low-sulfur petrol was assumed (if the REV is used for monitoring purposes, some of these assumptions would need to be modeled time-specific).

During recycling (scenario 3c), it is assumed that the motor block is dismantled into individual metals, which are then individually recycled (melting processes) (Eq. (11)). The same material was used for the production and substitution of cast metals, although recycled steel is often of lower quality and substitutes cast iron instead of primary steel. Resource recovery efficiency of iron and steel is assumed to be 95% for the dismantling and 88% in recycling and for aluminum 90% for the dismantling and 94% in recycling (recycling yields based on Haupt et al. (2017)).

$$\boldsymbol{REV}_{RMF\ \ FEmotor\rightarrow FEmotor} = \frac{\sum_{i=1}^{n}(\boldsymbol{EI}_{FEmotor,i} - \boldsymbol{EI}_{RMF})}{\sum_{i=1}^{n}(\boldsymbol{EI}_{FEmotor,i})} \qquad 9$$

$$\boldsymbol{REV}_{RMF\ \ FEmotor\rightarrow ALmotor} = \frac{\sum_{i=1}^{n}(\boldsymbol{EI}_{ALmotor,i} - \boldsymbol{EI}_{RMF}) - \boldsymbol{EI}_{fuel}}{\sum_{i=1}^{n}(\boldsymbol{EI}_{FEmotor,i})} \qquad 10$$

$$\boldsymbol{REV}_{REC\ \ FEmotor\rightarrow metals} = \frac{\sum_{i=1}^{n}(\boldsymbol{EI}_{sec.metals} - \boldsymbol{EI}_{REC})}{\sum_{i=1}^{n}(\boldsymbol{EI}_{FEmotor,i})} \qquad 11$$

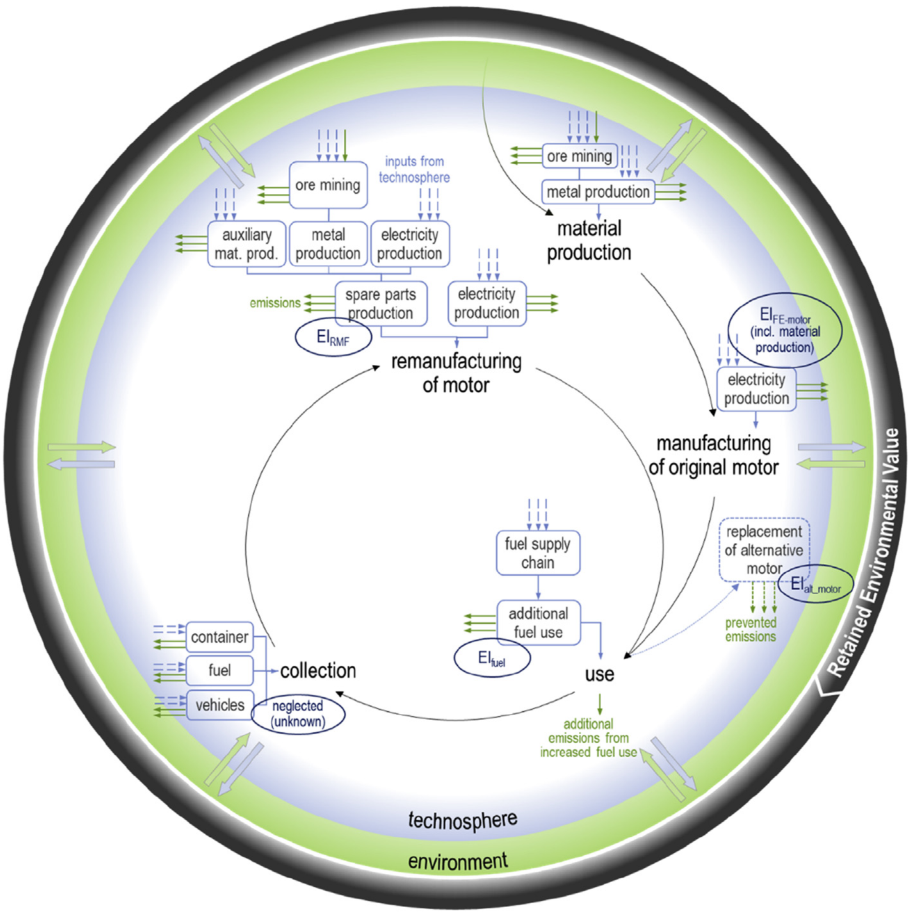

Fig. 2. Schematic representation of the application of the REV on the case of motor-block remanufacturing. $EI_{FE\text{-}motor}$ = environmental impact of primary motor production, EI_{RMF} = environmental impact of remanufacturing, EI_{alt_motor} = environmental impact of the production of an alternative motor (either an iron-based motor block ($EI_{FE\text{-}motor}$) or a lightweight aluminum motor block (EI_{AL_motor})), EI_{fuel} = environmental impact of additional fuel consumption including additional emissions from increased fuel use.

3. Results and discussion

To provide guidance for policymaking and industry, a holistic view on circular economy strategies is needed. The circular economy is often perceived to be environmentally friendly by default and to lead to increased resource efficiency compared to a linear economy. However, the environmental perspective is usually not explicitly assessed, which leads to badly informed and sometimes erroneous decisions. For example, following the hierarchy of value retention processes does not always result in the highest environmental benefit: Closed-loop recycling is not always more beneficial than open-loop recycling, and remanufacturing is not always environmentally preferable to recycling.

Below, the results of the application of the REV indicator on the case studies is described (Fig. 3). The environmental value was defined in these case studies as impacts on climate change based on the related political targets and its importance for material resources (IRP, 2019) as well as in terms of cumulative energy demand. The analyzed impact categories yield numerically different results for the REV but lead to the same ranking among the value retention processes. Furthermore, previous studies on paper and glass have shown that the ranking of different recycling processes according to impacts on climate change correlated well with a ranking based on toxicity impacts (Haupt et al., 2018a).

For the case of packaging glass, the REV of glass washing and reuse clearly surpasses the REV of all recycling options. The REV is, however, higher for the open-loop recycling of glass to foam glass insulation compared to closed-loop recycling to packaging glass. This reflects previous results, stating that recycling glass to foam glass in Switzerland is environmentally preferable to a closed-loop recycling system due to the

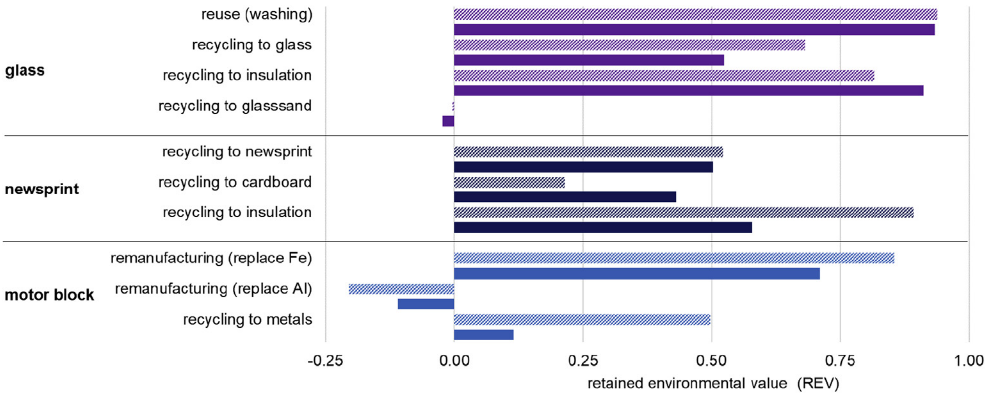

Fig. 3. Retained Environmental Value (REV) of various value retention processes and three different material streams. REV = 100% marks a full retention of the environmental value. The higher the REV, the more favorable the retention process. The REV was calculated for impact on climate change based on the IPCC, 2013 methodology (100 year time horizon, striped) and with regard to the cumulative energy demand (CED, full color). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

replacement of high-impact materials such as XPS insulation (Haupt et al., 2018a). The case study on newsprint highlights similar patterns: in closed-loop newsprint recycling more environmental value is retained than in newsprint-to-cardboard recycling schemes. The highest environmental value, however, can be retained in the system if paper is instead processed to cellulose insulation material that is assumed to substitute primary cellulose insulation. The lower losses in the recycling scheme lead to higher benefits from cellulose substitution than in the other scenarios and therefore to a higher REV.

In the case of the motor block remanufacturing and substitution of a lightweight motor block, the remanufacturing initially has a higher potential for retaining environmental value due to small process efforts needed. The results highlight this environmental benefit of remanufacturing in the first case (replacement of new iron-based motor). If a lightweight motor block is the alternative, the environmental savings in impacts are, however, over-compensated by additional impact through increased fuel use in the use phase of the car: due to the heavier weight of the remanufactured motor in comparison to the new lightweight alternative ($REV = -0.11$ to -0.20). It is, therefore, preferable to remanufacture the iron-based motor only if an iron-based motor will be replaced. When the alternative is an aluminum lightweight motor block, it is better to recycle the iron-based motor and use a more efficient lighter aluminum motor. This example illustrates that when technologies are still undergoing significant development in terms of efficiency gains in the use phase, circular solutions need to be evaluated with care as they may slow-down the phase out of low-efficiency technologies. This calls for remanufacturing processes that help to achieve similar efficiency gains as the evolving base technology. The REV indicator is able to capture all these effects and provides reliable decision support on the best circular solution available.

Although the assessment of value changes was found highly relevant by Parchomenko et al. (2019) it is absent in most previously published indicators. The definition of the environmental value as the life cycle impacts is of key importance, as all life cycle stages are considered. Compared to other indicators, the REV takes material consumption and the emissions (air, water, soil) in all life cycle stages into account. The parametrization of the REV indicator requires an in-depth systems understanding, in particular for realistic modeling of substituted products and impacts. The inclusion of substitution is necessary to quantify the retained environmental value and was based on the reporting framework of Vadenbo et al. (2017). The reporting framework includes the technical, institutional and user functional equivalency and market responses. As CE aims at limiting primary resource use, there is a general need to enhance understanding of substitution of primary or secondary resources in the field of circular economy. This aligns well with the needed information to assess the substitution for the REV indicator.

Systems understanding is not only important when assessing circular economy strategies but also key for sustainable development in general: For example, the shifting of waste material for recycling from high-income countries to emerging economies, which is particularly prevalent for plastic waste (Brooks et al., 2018), may result in high local environmental and social impacts far away from the location of the original material use. The implementation of the REV indicator would enforce knowledge creation on international waste trade flows and monitoring of related environmental implications. Such information systems are already in place for hazardous wastes (UNEP, 2014) and will be extended to mixed, unrecyclable and contaminated plastic waste (BRSMEAS, 2019), but they are also essential for other waste materials. Material flow transparency is needed also to assess a final recycling rate (i.e. applying a mass-based perspective), but assessing the environmental performance further requires information on the supply chain of materials, which can be data intensive if applied to entire countries. More transparency with regard to the location of value retention processes would also allow considering regional sensitivities (i.e. energy mix and transport distances). Today, however, recycling processes are rarely questioned and often assumed as "environmentally benign", ignoring the fact that severe impacts may be caused and improvement potentials missed. Therefore, to make sure that the full potential of the circular economy is reached, quantitative assessments of environmental benefits and impacts are required.

The REV indicator can address questions along the whole life cycle: at the design level ("How much value can be retained at a later life-cycle stage?"), when choosing value retention processes ("Should the product undergo maintenance or be remanufactured?") and at the end-of-life ("In which recycling process can most environmental value be recovered?"). Furthermore, a shift towards renewable energy (as essential part of a CE (Ellen MacArthur Foundation, 2013)) can be taken into account by adapting the life cycle impacts of the electricity consumption in the REV calculation.

A sustainable circular economy should not only adopt an environmental perspective, but also consider economic and social performance. With regard to these, several indicators are being discussed (e.g. Di Maio et al. (2017), Horbach et al. (2015) and Linder et al. (2017)). To allow for the analysis of trade-offs between environmental impacts and related costs or social impacts, the REV indicator could also be adapted to cover these pillars of sustainability. For example, the economic value retained in the system could be compared to the financial amount invested on the original production of a product and compared among treatment options (Linder et al., 2017). Similarly, existing quantitative social indicators, e.g. from the emerging field of social life cycle assessment (Andrews et al., 2009), could be applied to consider and compare social impacts as well.

Transitioning towards a sustainable circular economy requires assessment methods that can be applied at all levels: from individual products, to larger systems, to entire economies. The REV indicator can cover all of these levels and help to quantitatively compare circular economy strategies and other resource efficiency measures as well as support material choices. Complementing mass-based indicators, it can also assess the environmental sustainability of cross-material substitutions, i.e. materials replacing other materials in open-loop applications. The application of the REV may provide additional and sometimes unexpected insights, which can help to understand a system better and identify optimal solutions. Complementing final recycling rates, the REV indicator would enable the integration of a life cycle perspective, material quality aspects, and quality-related market mechanisms in policymaking.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

Supported by the Swiss National Science Foundation (SNSF) within the framework of the National Research Programme "Sustainable Economy: resource-friendly, future-oriented, innovative" (NRP 73, http://www.nrp73.ch/en).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2019.100005.

References

Andrews, E.-S., Barthel, L.-P., Beck, T., Benoit, C., Ciroth, A., Cucuzzella, C., Gensch, C.-O., et al., 2009. In: Benoit, Catherine, Mazijn, Bernard (Eds.), Guidelines for Social LCA of Products. UNEP (United Nations Environment Programme).

Brooks, A.L., Wang, S., Jambeck, J.R., 2018. The Chinese import ban and its impact on global plastic waste trade. Science Advances 4, 1–8.

BRSMEAS, 2019. Governments agree landmark decisions to protect people and planet from hazardous chemicals and waste, including plastic waste. http://www.brsmeas.org/?tabid=8005. (Accessed 15 May 2019).

BSI, 2017. Executive Briefing: BS 8001 – a Guide, vol. 6. BSI Group.

CIRAIG, 2015. Circular Economy: A Critical Literature Review of Concepts. Polytechnique Montréal. Montréal, QC, Canada, ISBN 978-2-9815420-0-7.

EASAC, 2016. Indicators for a Circular Economy.

EC, 2015. Closing the Loop - an EU Action Plan for the Circular Economy. European Commission, Brussels, Belgium.

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751.

Ellen MacArthur Foundation, 2013. Towards the Circular Economy: Economic and Business Rationale for Accelerated Transition, vol. 1. Ellen MacArthur Foundation.

Ellen MacArthur Foundation, 2015. Circularity Indicators: an Approach to Measuring Circularity. Ellen MacArthur Foundation, p. 12.

European Commission, 2018. Communication Form the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a Monitoring Framework for the Circular Economy.

Geng, Y., Fu, J., Sarkis, J., Xue, B., 2012. Towards a national circular economy indicator system in China: an evaluation and critical analysis. J. Clean. Prod. 23 (1), 216–224.

Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P., 2013. Measuring China's circular economy. Science 339 (6127), 1526–1527.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. J. Ind. Ecol. 19 (5), 765–777.

Haupt, M., Vadenbo, C., Hellweg, S., 2017. Do we have the right performance indicators for the circular economy?: insight into the Swiss waste management system. J. Ind. Ecol. 21 (3), 615–627.

Haupt, M., Kägi, T., Hellweg, S., 2018a. Modular life cycle assessment of municipal solid waste management. Waste Manag. 79, 815–827.

Haupt, M., Kägi, T., Hellweg, S., 2018b. Life cycle inventories of waste management processes. Data in Brief 19, 1441–1457.

Haupt, M., Waser, E., Würmli, J.-C., Hellweg, S., 2018c. Is there an environmentally optimal separate collection rate? Waste Manag. 77, 220–224.

Heuss, R., Müller, N., van Sintern, W., Starke, A., Tschiesner, A., 2012. Lightweight, Heavy Impact, pp. 1–24.

Horbach, J., Rennings, K., Sommerfeld, K., 2015. Circular economy and employment. In: 3rd IZA Workshop: Labor Market Effects of Environmental Policies.

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., De Meester, S., 2017. Performance indicators for a circular economy: a case study on post-industrial plastic waste. Resour. Conserv. Recycl. 120, 46–54.

Huysveld, S., Hubo, S., Ragaert, K., Dewulf, J., 2019. Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. J. Clean. Prod. 211, 1–13.

IPCC, 2013. Climate Change 2013: The physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jacobi, N., Haas, W., Wiedenhofer, D., Mayer, A., 2018. Providing an economy-wide monitoring framework for the circular economy in Austria: status quo and challenges. Resour. Conserv. Recycl. 137, 156–166. June.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. September.

Linder, M., Sarasini, S., van Loon, P., 2017. A metric for quantifying product-level circularity. J. Ind. Ecol. 21 (3), 545–558.

Maio, F. Di, Rem, P.C., Baldé, K., Polder, M., 2017. Measuring resource efficiency and circular economy: a market value approach. Resour. Conserv. Recycl. 122, 163–171.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: what do they measure? Resour. Conserv. Recycl. 146, 452–461. January.

Nasr, N.Z., Russell, J.D., Kreiss, C., Hilton, B., Hellweg, S., Bringezu, S., von Gries, N., 2018. Redefining Value. The Manufacturing Revolution. Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy. United Nations Environment Programme, Nairobi, Kenya.

Global Resources Outlook, 2019. Natural Resources for the Future We Want. In: Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J., Cabernard, L., Che, N., Chen, D., Droz-Georget, H., Ekins, P., Fischer-Kowalski, M., Flörke, M., Frank, S., Froemelt, A., Geschke, A., Haupt, M., Havlik, P., Hüfner, R., Lenzen, M., Lieber, M., Liu, B., Lu, Y., Lutter, S., Mehr, J., Miatto, A., Newth, D., Oberschelp, C., Obersteiner, M., Pfister, S., Piccoli, E., Schaldach, R., Schüngel, J., Sonderegger, T., Sudheshwar, A., Tanikawa, H., van der Voet, E., Walker, C., West, J., Wang, Z., Zhu, B. (Eds.), A Report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

Oswald, I., 2013. Environmental Metrics for WEEE Collection and Recycling Programs. Universität Augsburg, Institut für Materials Ressource Management (MRM), Lehrstuhl für Ressourcenstrategie.

Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H., 2019. Measuring the circular economy - a multiple correspondence analysis of 63 metrics. J. Clean. Prod. 210, 200–216.

Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129, 81–92. October 2017.

Rigamonti, L., Niero, M., Haupt, M., Grosso, M., Judl, J., 2018. Recycling processes and quality of secondary materials: food for thought for waste-management-oriented life cycle assessment studies. Waste Manag. 17, 261–265.

Schroeder, P., Anggraeni, K., Weber, U., 2019. The relevance of circular economy practices to the sustainable development goals. J. Ind. Ecol. 23 (1), 77–95.

Stahel, W.R., 2016. Circular economy. Nature 531, 435–438.

Steinmann, Z.J.N., Schipper, A.M., Hauck, M., Huijbregts, M.A.J., 2016. How many environmental impact indicators are needed in the evaluation of product life cycles? Environ. Sci. Technol. 50 (7), 3913–3919.

Stettler, C., Rüttimann, S., Kägi, T., 2016. Ökobilanz Verwertungen von Altglas - ökologischer Nutzen der Sammlung von Verpackungsglas. Carbotech AG, Basel, Switzerland.

UNEP, 2014. Basel Convention on the Control of Transboundary Movements of Hazardous Wates and Their Disposal. Secretariat of the Basel Convention, Châtelaine, Switzerland.

Vadenbo, C., Hellweg, S., Astrup, T.F., 2017. Let's Be clear(er) about substitution: a reporting framework to account for product displacement in life cycle assessment. J. Ind. Ecol. 21 (5), 1078–1089.

van der, Voet E., van Oers, L., Nikolic, I., 2005. Dematerialization: not just a matter of weight. J. Ind. Ecol. 8 (4), 121–137.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230.

Wohlecker, R., Johannaber, M., Espig, M., 2007. Determination of Weight Elasticity of Fuel Economy for ICE, Hybrid and Fuel Cell Vehicles(724).