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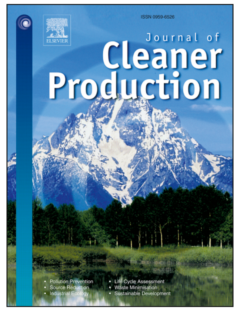

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Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions

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Abstract

Increasing the recycling of plastic waste is a key priority within Europe and its circular economy initiatives. The benefits of recycling however decrease until a cut-off point is reached where recycling becomes environmentally and economically too expensive to achieve a net benefit compared to disposal. To identify this point, suitable indicators with a life cycle perspective are needed. In this study, we analysed the existing Recyclability Benefit Rate and the Recycled Content Benefit Rate indicators, which express the potential environmental benefits from recycling compared to disposal (e.g. incineration) taking into account life cycle thinking. However, improvements of these indicators are still needed. The aim of this research was to advance the existing indicators by introducing improved equations. More specifically, we further developed these indicators in four aspects, i.e. (i) by including the final step (e.g. incineration) in the cascaded use of the material, (ii) by accounting for the same basket of products in the denominator as the one in the nominator of the indicator, (iii) by eliminating confusion about the calculated result when the denominator is negative, and (iv) by introducing a new parameter ‘d’ to account for the lifetime of the product made from recycled material compared to the product made from virgin material. These adjustments clarify and advance the monitoring of the environmental benefits of material cascading. The indicators were applied to a case of mixed and contaminated plastic waste, which showed that recycling is more environmentally beneficial than incineration in this case. The impact of injection moulding of the new product was significant due to its energy consumption, and higher for the recycled material. Future research could focus on an economic cost-benefit analysis to complement this environmental analysis. Additionally, the practical implementation of accounting for the lifetime difference between the recycled and the virgin material needs further research.

Keywords

Circular economy, recycling, open-loop, benefit indicators, plastic waste, material cascading

1. Introduction

Managing plastic waste is a top priority in order to protect our environment from further plastic pollution (Xanthos and Walker, 2017). Besides protecting natural ecosystems from pollution, the proper management of plastic waste is crucial to conserve its resource potential as long as possible. In a circular economy, plastic waste is considered as a resource capable of substituting virgin material. The European Commission identifies plastic waste as a key priority in its ‘Action Plan for the Circular Economy’ (European Commission, 2015).

Several plastic waste treatment options are feasible depending on the quality of the waste. The quality of plastic streams can be reduced, for example, when several types of plastics get mixed and/or contaminated, e.g. during manufacturing of packaging, during waste collection at households. Separating these plastic waste streams can be technically very hard and therefore too expensive (Ghisellini et al., 2016). In case of plastic waste with a reduced quality, open-loop recycling and incineration are generally the only two feasible options (Huysman et al., 2017), besides disposal in a landfill as the last resort. Open-loop recycling is the recycling of a material from one product system into a different product system (ISO, 2006b), usually a low-value application. Quality loss in the recycled material compared to the virgin material is called downcycling. On the contrary, in closed-loop recycling the quality of the virgin material is generally better conserved in the recycled material, which can be used in the same type of product as before (Huysman et al., 2017). Incineration of plastic waste can recover electricity (and heat), however, it also disables the cascaded use of the material in subsequent applications. The European Union’s Waste Framework Directive (2008/98/EC) therefore prioritises recycling over incineration (European Union, 2008). However, of the about 25 million tonnes of post-consumer plastic waste annually produced in Europe, less than 30% is recycled, while landfilling (31%) and incineration (39%) remain high (Plastics Europe, 2016). Plastic packaging plays an important role as today it accounts for about 60% of post-consumer plastic waste. By 2025, the European Commission sets a recycling target of 55% for plastics packaging (European Commission, 2018a).

To foster the transition to a circular economy, the European Commission published in the past decade several policy documents, such as 'Roadmap to a Resource Efficient Europe' (European Commission, 2011), 'Closing the loop - An EU Action Plan for the Circular Economy' (European Commission, 2015), 'European Strategy for Plastics in a Circular Economy' (European Commission, 2018) and 'Monitoring framework for the circular economy' (European Commission, 2018b). Because the absence of adequate metrics for performance measurements was seen as a barrier to this transition, several institutions, in particular the European Commission itself, have been developing a wide range of quantitative indicators (Huysman et al., 2015b). Indicators that were developed from the product's end-of-life or waste perspective can be distinguished from indicators that focus on the new product designer's perspective. An example of the first group is the Recyclability Benefit Rate (RBR) (Ardente and Mathieux, 2014b), which is defined as the ratio of the net environmental savings that can be obtained from recycling a product, over the environmental burdens related to the linear life cycle of the product (virgin material production, manufacturing, use phase and disposal such as landfill or incineration). These savings and burdens are calculated as environmental impacts through Life Cycle Assessment (LCA). In the second group, the Recycled Content Benefit Rate (RCBR) (Ardente and Mathieux, 2014b) is a similar indicator, which can be used to evaluate the environmental benefits of introducing recycled materials in the manufacturing of a new product, compared to producing the product entirely from virgin material. This is an important indicator to boost the demand for recycled materials, which is the main necessity when the recycled materials have a low market value (European Commission, 2010). This is true for recycled plastics, of which the use in new products is low and often remains limited to low-value or niche applications. Current demand for recycled plastics accounts for only about 6% of plastics demand in Europe (European Commission, 2018a). In its vision for Europe's new plastics economy, the European Commission (2018a) sees by 2030 a four-fold increased demand for recycled plastics in Europe since 2015.

Although the mentioned indicators are developed in such a way that they can be broadly applied, adaptations to specific cases or general improvements are still needed. For example, Huysman et al. (2015a) further developed the original RBR indicator (Ardente and Mathieux, 2014b) in two aspects. First, the indicator was adapted for application on open-loop recycling, because the original indicator assumed that the recycled material will be used to replace the identical material as in the original product, which is only the case in closed-loop recycling. Second, the possibility of accounting for the multiple successive (cascaded) use of the material was introduced, which is a general improvement applicable to both closed-loop and open-loop recycling. However, the proposed indicator did not yet consider the final step in the cascaded use, i.e. incineration (or landfilling as the last resort). Considering the material's life cycle until the grave is essential to have a fair comparison between (i) recycling the material as long as possible until finally the material can still be incinerated for energy recovery and (ii) immediate incineration of the material for energy recovery. Additionally, Huysman et al. (2015a) did not account in the denominator of the RBR indicator for the same basket of products as the one in the nominator, which is not a fair comparison. By recycling the material for a certain number of cascades, a certain number of products is considered in the nominator, while similar products (made from virgin material) should be taken into account in the denominator. Further investigation in the equation of the RBR indicator is also needed when the net impact (burdens minus avoided burdens or benefits) in the denominator becomes negative (if benefits are larger than burdens), which causes the opposite sign for the calculated RBR result and thus confusion about whether recycling is more beneficial than disposal or not. It is possible that the net impact in the denominator is negative for a certain impact category, for example, when the product is incinerated with energy recovery, the avoided burden of virgin electricity (and heat) production is taken into account. In a similar way, the original RCBR indicator (Ardente and Mathieux, 2014b) could be improved by including the abovementioned aspects.

The lifetime of products is another important aspect in a circular economy, which is not considered in both of the abovementioned circular economy benefit indicators. In a circular economy, the resource potential of materials is preserved as long as possible, either by extending the lifetime of the products manufactured from them or by looping them back in the economic system (den Hollander et al., 2017). Den Hollander (2017) defined product lifetime as the duration of the period that starts at the moment a product is released for use after manufacture and ends when the product is no longer considered useful or significant by its user. Ardente and Mathieux (2014a) developed an indicator to assess the environmental benefits of the potential lifetime extension of a product. Lifetime extension is generally considered as favourable, although in the case of energy-using products it is not necessarily the optimal strategy because their substitution by more energy-efficient products could be more environmentally beneficial (Ardente and Mathieux, 2014a). When recycling materials into new products, the lifetime of the product made from recycled material compared to the product made from virgin material will affect the environmental benefits. A product with a shorter lifetime will generally be replaced earlier by a new product. Accounting for the product lifetime in the RBR indicator was already suggested by Huysman et al. (2015a) as a challenge for future development. In a similar way, the original RCBR indicator (Ardente and Mathieux, 2014b) could be improved by inclusion of the lifetime effect.

The objective of this paper is to advance the existing RBR and RCBR indicators by introducing improved equations. More specifically, we further developed these indicators in four aspects, i.e. (i) by including the final step (incineration) in the cascaded use of the material, (ii) by accounting for the same basket of products in the denominator as the one in the nominator, (iii) by eliminating confusion about the calculated result when the denominator is negative, and (iv) by introducing a new parameter 'd' to account for the lifetime of the product made from recycled material compared to the product made from virgin material. These adjustments should clarify and advance the monitoring of the environmental benefits of material cascading. The existing and improved indicators will be applied to a case of mixed and contaminated plastic waste, which is very challenging to recycle. In current practice, this waste is typically incinerated (Bonifazi et al., 2016; Ragaert et al., 2017). Our choice for such case can be explained by the fact that the benefits of recycling tend to decrease until a cut-off point is reached where recycling becomes environmentally and economically too expensive to achieve a net benefit (Ghisellini et al., 2016).

2. Materials and methods

2.1. Further development of the indicators

2.1.1. Recyclability Benefit Rate (RBR)

The equation to calculate the RBR indicator for application on 1 cascade of open-loop recycling according to Huysman et al. (2015a) is presented in Eq. (1). The question what to do with product α_0 at its end-of-life is under study: it can either be disposed (e.g. incineration) or it can be recycled into product α_1. Because landfilling is seen as the last resort, we will assume incineration as the disposal option further on in this paper. The benefit of produced electricity (and heat) by incinerating waste is taken into account by calculating the impact of incineration as the net impact, i.e. the burdens of incineration minus the avoided burdens of virgin electricity (and heat) production. The indicator in Eq. (1) equals the ratio of the net environmental savings that can be obtained from recycling a product, over the net environmental burdens related to virgin material production and disposal. Eq. (2) shows how to calculate the RBR indicator for application on n cascades of open-loop recycling according to Huysman et al. (2015a).

$$RBR_{OL,1,2015} = \frac{RCR\left(\frac{m_{v,\alpha_1}}{m_{r,\alpha_1}} V_{\alpha_1}^* - R_{\alpha_0\to\alpha_1}^* + D_{\alpha_0}^*\right)}{V_{\alpha_0}^* + D_{\alpha_0}^*} \times 100 \quad (1)$$

$RBR_{OL,1,2015}$: Recyclability Benefit Rate for 1 cascade [%], version of Huysman et al. (2015a)
RCR: recycling rate [%], defined as the ratio of the amount of recycled material produced over the amount of input waste material.
m_{v,α_1}: mass of virgin material used to produce product α_1 [kg]
m_{r,α_1}: mass of recycled material used to produce the product α_1 [kg]
$V_{\alpha_1}^*$: impact of production of virgin material for the product α_1 [impact unit/kg virgin material]
$R_{\alpha_0\to\alpha_1}^*$: impact of recycling the product α_0 into the recycled material for product α_1 [impact unit/kg recycled material]
$V_{\alpha_0}^*, D_{\alpha_0}^*$: impacts due to production of virgin material and disposal of the product α_0 made from virgin material [impact unit/kg of product α_0]

$$RBR_{OL,n,2015} = \frac{\sum_{i=1}^{n}\left(RCR^i\left(\frac{m_{v,\alpha_i}}{m_{r,\alpha_i}} V_{\alpha_i}^* - R_{\alpha_{i-1}\to\alpha_i}^*\right)\right) + RCR^n D_{\alpha_0}^*}{V_{\alpha_0}^* + D_{\alpha_0}^*} \times 100 \quad (2)$$

With symbols previously not introduced:

n: number of cascades [-]
$RBR_{OL,n,2015}$: Recyclability Benefit Rate for n cascades [%], version of Huysman et al. (2015a)
RCR: recycling rate, assumed to be similar in each cascade [%]
m_{v,α_i}: mass of virgin material required to produce product α_i [kg]
m_{r,α_i}: mass of recycled material required to produce product α_i [kg]
$V_{\alpha_i}^*$: impact of production of virgin material for the product α_i [impact unit/kg virgin material]
$R_{\alpha_{i-1}\to\alpha_i}^*$: impact of recycling the product α_{i-1}into the recycled material for product α_i [impact unit/kg recycled material]

2.1.2.Recycled Content Benefit Rate (RCBR)

The equation to calculate the RCBR indicator for 1 cascade according to Ardente and Mathieux (2014b) is presented in Eq. (3). For simplification we consider a product consisting of only one part. The question whether to introduce recycled material in a new to be designed product α_1 is under study: it can either be produced entirely from virgin material or it can be produced (partially or entirely) from recycled material. The indicator in Eq. (3) equals the ratio of the net environmental savings that can be obtained from introducing recycled material in a product, over the net environmental burdens related to virgin material production, manufacturing, use and disposal.

$$RCBR_{1,2014} = \frac{m_{r,\alpha_1}\left(V_{\alpha_1}^* - R_{\alpha_0\to\alpha_1}^*\right)}{V_{\alpha_1} + M_{\alpha_{1,v}} + U_{\alpha_{1,v}} + D_{\alpha_{1,v}}} \times 100 \quad (3)$$

With symbols previously not introduced:

$RCBR_{1,2014}$: Recycled Content Benefit Rate for 1 cascade [%], version of Ardente and Mathieux (2014b)

$V_{\alpha_1}, M_{\alpha_{1,v}}, U_{\alpha_{1,v}}, D_{\alpha_{1,v}}$: impacts due to production of virgin material, manufacturing, use and disposal of the product α_1 made from virgin material [impact unit/product]

2.2. Illustration with a case study

This section consists of four parts. First, the case study on plastic waste is described. Subsequently, the first three phases of the LCA study, i.e. goal and scope definition, inventory analysis and impact assessment, are described according to ISO 14040/14044 (2006a, b). The fourth and final phase, i.e. interpretation, is presented in the results and discussion section.

2.2.1. Description of the case study

An overview of the case study is presented in Figure 1. The chosen case is open-loop recycling of plastics from household waste performed by the Belgian company ECO-oh!. This specific waste excludes PET and HDPE bottles, as in Belgium these are collected in the so-called PMD system, for which a separate non-profit organisation (Fost Plus) is responsible for the collection and recycling. The recycling process of ECO-oh! consists mainly of shredding, depollution, float-sink separation, drying, wind sifting and milling into granules or extrusion into pellets ('open-loop recycling part I' in Figure 1). After the float-sink separation, two main recycled plastic outputs are distinguished: about 80% is the float fraction (PE and PP) and 20% is the sink fraction (mainly PET, PP, PVC and PS). The sink fraction also contains non-plastic contaminants such as aluminium. The PE-PP pellets are used to produce new products such as plant trays, compost bins, street or garden benches, etc. Because of its composition and low quality, today the company can only use the sink fraction as filling material in thick-walled products. The share of the sink fraction shows an increasing trend and is expected to increase further in the future, due to a changing composition of the input, due to a new collection scheme which will take effect from 2019 onwards (Coberec-GO4CIRCLE, 2018). When the quantity of the sink fraction becomes higher than what can be used as filling material, the surplus sink fraction would be incinerated unless its quality can be increased through additional separation processes. These additional processes can only be justified when a net benefit exists compared to incineration. Although economic benefits are the most determining factor for a feasible implementation in practice, we focus in this paper on environmental benefits. In this case study a modular tile for a green roof was designed and produced based on the sink fraction. The additional processing steps that were necessary to bring the material to the required minimum quality are PVC removal (Near Infra Red (NIR) sorting), aluminium removal (eddy current sorting), and further (thermal) drying to decrease the moisture content from 0.5 to 0.02% ('open-loop recycling part II' in Figure 1). The PVC removal is absolutely necessary to be able to process the mix with a reasonable quality and without corrosion affecting the equipment (Ragaert et al., 2017). Finally, the green roof tile is produced by injection moulding.

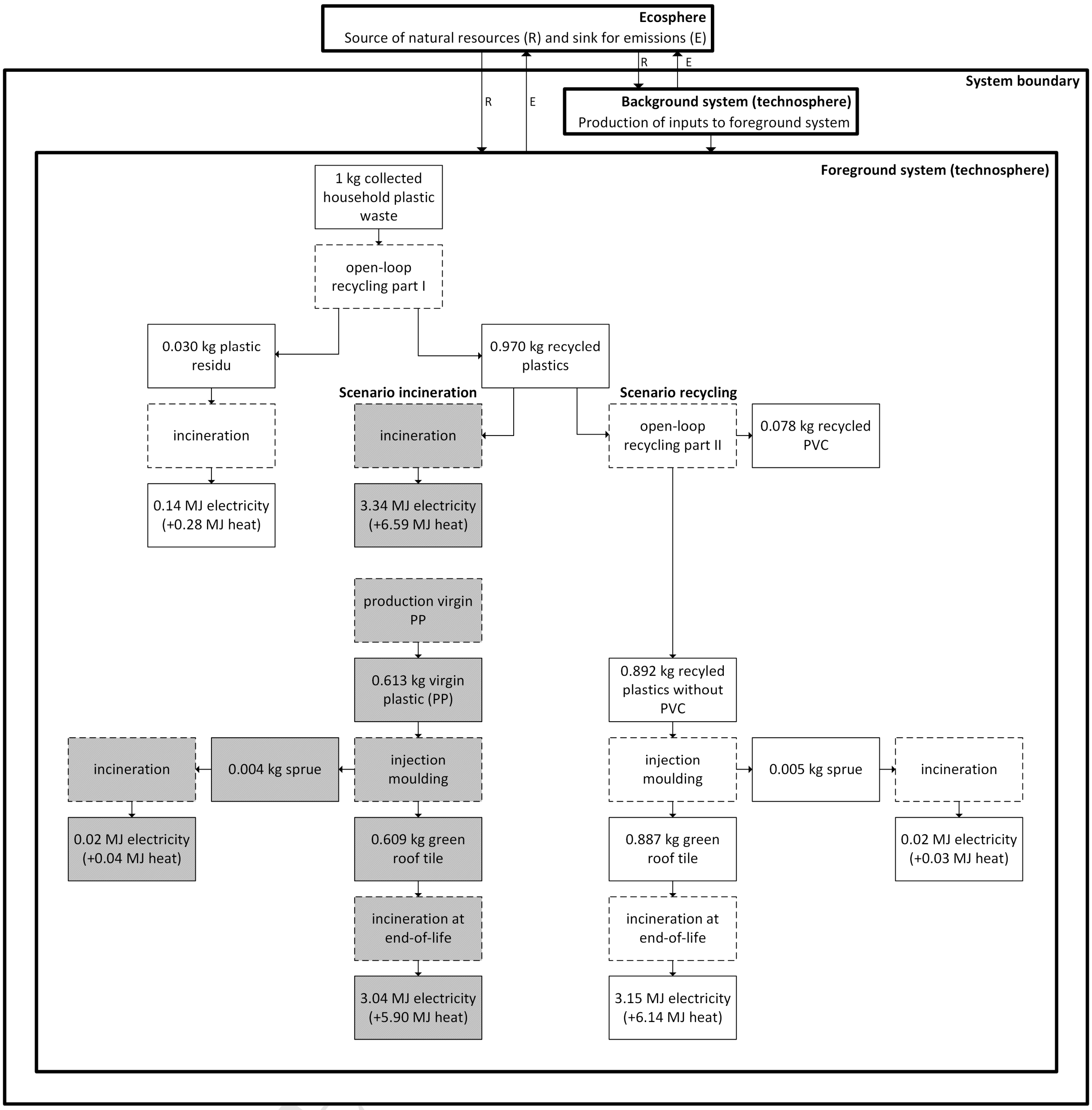

Figure 1 Overview of the compared scenarios in the case study for 1 cascade: recycling versus incineration. Open-loop recycling part I includes the current recycling process (shredding, depollution, etc.), while open-loop recycling part II includes the additional processing steps (PVC and aluminium removal, and drying). Processes are represented as blocks with dashed lines. Products are represented as blocks with solid lines. Processes and products in the incineration scenario are represented as grey colored blocks. Focus in this figure is only on the plastic material in the surplus sink fraction (separated aluminium is not presented).

2.2.2. LCA

2.2.2.1. Goal and scope definition

The goal of the LCA is to quantify the environmental impacts (burdens and benefits) of the scenarios recycling and incineration, presented in Figure 1, to feed the circular economy benefit indicators. The scope of the study is described by the system boundary (Figure 1). The foreground system boundary starts when the plastic waste is delivered at the company ECO-oh!. The plastic waste is considered as burden-free, i.e. the environmental impacts associated with the production of the virgin plastics and the manufacture of the product α_0 are fully attributed to the first product α_0 (cut-off approach (Allacker et al., 2014)). Because the question about what to do with the surplus sink fraction arises only after the ECO-oh! recycling process took place ('open-loop recycling part I' in Figure 1), the impact of the ECO-oh! recycling process is included in both scenarios. In case of the scenario recycling, the additional processing steps ('open-loop recycling part II' in Figure 1) to increase the quality of the surplus sink fraction (PVC and aluminium removal, and drying) are taken into account. The recovered PVC and aluminium are assumed to be recycled and, therefore, the avoided burdens from the virgin production of PVC and aluminium are taken into account. After that, injection moulding of the green roof tile is considered. The avoided burdens from the production of the green roof tile based on virgin material (PP) are taken into account. The use phase of the green roof tile is assumed to be negligible as it is not an energy-using product. After the use phase, the green roof tile is incinerated when considering 1 cascade, or it is again recycled when considering 2 cascades. In case of 2 cascades, we assume that, in Belgium, the green roof tile is collected with other household plastics (no individual collection) and becomes input of ECO-oh! again, and that the recycled material is used to produce again a green roof tile. After the second use phase the foreground system boundary also ends after the incineration of the green roof tile. More than 2 cascades were not considered in this case study. In case of the scenario incineration, incineration of the surplus sink fraction produced by ECO-oh! followed by the complete life cycle of the green roof tile made from virgin PP are taken into account (Figure 1). The avoided burdens from the virgin production of electricity (and heat) in case of incineration (of the surplus sink fraction itself or of the end-of-life green roof tile or of the sprue) are considered.

When calculating the RBR indicator, the incineration scenario is compared to the recycling scenario. The functional unit is 1 kg of plastics from household waste (excluding non-plastic waste and moisture). When calculating the RCBR indicator, the production of the green roof tile based on recycled material is compared to the production based on virgin PP. The functional unit is 1 production unit of the green roof tile made from the recycled sink fraction or from virgin PP. Because of a different density, the weight of the green roof tile based on recycled material is 3.39 kg, while the weight of the virgin alternative is 2.33 kg.

2.2.2.2. Inventory analysis

Attention was paid to the quality of data used in this study by collecting data as representative as possible in terms of time, geography and technology. Primary data were collected for the ECO-oh! recycling process and the additional processes to improve the quality of the sink fraction. Data on the recycling process were received from the company ECO-oh! for the year 2016. ECO-oh! data include the detailed mass balance, the consumption of electricity, diesel, water and chemicals. The recycling rate was 97% when considering only the plastic mass balance (excluding non-plastic waste and moisture) (Figure 1). The company purchased a green electricity mix, mainly produced from 85% hydropower (imported) and 12% wind energy. Infrastructure was not included due to unavailable data. Data on the electricity and heat consumption of the additional processes (PVC and aluminium removal, thermal drying) were gathered in close collaboration with industrial partners (Vanheede, BULK.ID and TOMRA) in order to obtain a good estimate for these processes at industrial scale. The recovered amounts of PVC and aluminium from the sink fraction were 80 and 7 kg per ton, respectively. For these processes, average electricity and heat produced in Belgium was assumed. Tables with the data inventory of the ECO-oh! recycling process and the additional processes to improve the quality of the sink fraction can be found in the supporting information. Also the used datasets from the ecoinvent v3.3 database to model incineration of the sink fraction and data about the production of electricity and heat per type of polymer are included in the supporting information.

Data for the background system (e.g. life cycle inventory data on diesel, tap water, electricity, heat, etc.), for the process of injection moulding, and for the avoided processes and products were retrieved from the ecoinvent v3.3 database. For injection moulding only data about electricity and heat consumption were included because they were considered as relevant for this case. When retrieving data from ecoinvent, we chose the data type 'Cut-off', which means that waste streams in the background system were modelled as burden-free. Information about the used datasets from ecoinvent can be found in the supporting information. Regarding data quality, the ecoinvent database is transparent about the quality of its datasets.

The green roof tile was produced entirely from recycled material, thus parameter p in Eq. 4-7 equals 100%. Based on communication with the designers/manufacturers of the green roof tile, we considered a similar lifetime of the green roof tile made from recycled material compared to the green roof tile made from virgin PP, thus d in Eq. 4-7 equals 1. To illustrate the effect of parameters p and d on the potential environmental savings, a sensitivity analysis is performed.

2.2.2.3. Impact assessment

Two impact assessment methods were chosen to obtain a broad coverage of environmental impacts, i.e. (i) Cumulative Exergy Extraction from the Natural Environment (CEENE) version 2013 (Alvarenga et al., 2013; Dewulf et al., 2007) and (ii) ReCiPe 2016 (H) Midpoint and Endpoint (Huijbregts et al., 2017). The CEENE method quantifies and adds up a very broad range of extracted natural resources (fossil + nuclear + renewable (wind and hydro energy) + water + mineral + metal + land = total) in terms of megajoule exergy (MJ_{ex}). The RECIPE Midpoint method includes the impact categories Global Warming (kg CO_2-eq.), Stratospheric Ozone Depletion (kg CFC11-eq.), Ionizing Radiation (kBq Co-60 eq.), Ozone Formation (kg NO_x-eq.), Fine Particulate Matter Formation (kg PM2.5-eq.), Terrestrial Acidification (kg SO_2-eq.)and Freshwater Eutrophication (kg P-eq.), Terrestrial Ecotoxicity (kg 1,4-DCB eq.), Freshwater Ecotoxicity (kg 1,4-DCB eq.), Marine Ecotoxicity (kg 1,4-DCB eq.), Human carcinogenic toxicity (kg 1,4-DCB eq.), Human non-carcinogenic toxicity (kg 1,4-DCB eq.), Land Use (m^2a crop eq.), Mineral Resource Scarcity (kg Cu-eq.), Fossil Resource Scarcity (kg oil eq.) and Water Consumption (m^3). The RECIPE Endpoint method includes the damage categories or Areas of Protection (AoPs) Human Health (DALY), Ecosystem Quality (species.yr) and Natural Resources (USD2013). In contrast to the total CEENE, the ReCiPe AoP Natural Resources only accounts for fossil, mineral and metal resources, but the latter quantifies the future surplus extraction costs of these non-renewable resources. The results of the CEENE method and the ReCiPe Endpoint method will be presented in the next section, whereas the ReCiPe Midpoint results are provided in the supporting information.

3. Results and discussion

3.1. Further development of the indicators

Figure 2 represents the considered foreground processes in the calculation of the developed indicators for 1 cascade and for 2 cascades. Avoided burdens (e.g. the virgin production of electricity (and heat) in case of incineration) and background processes (e.g. tap water production) are taken into account but not shown in Figure 2.

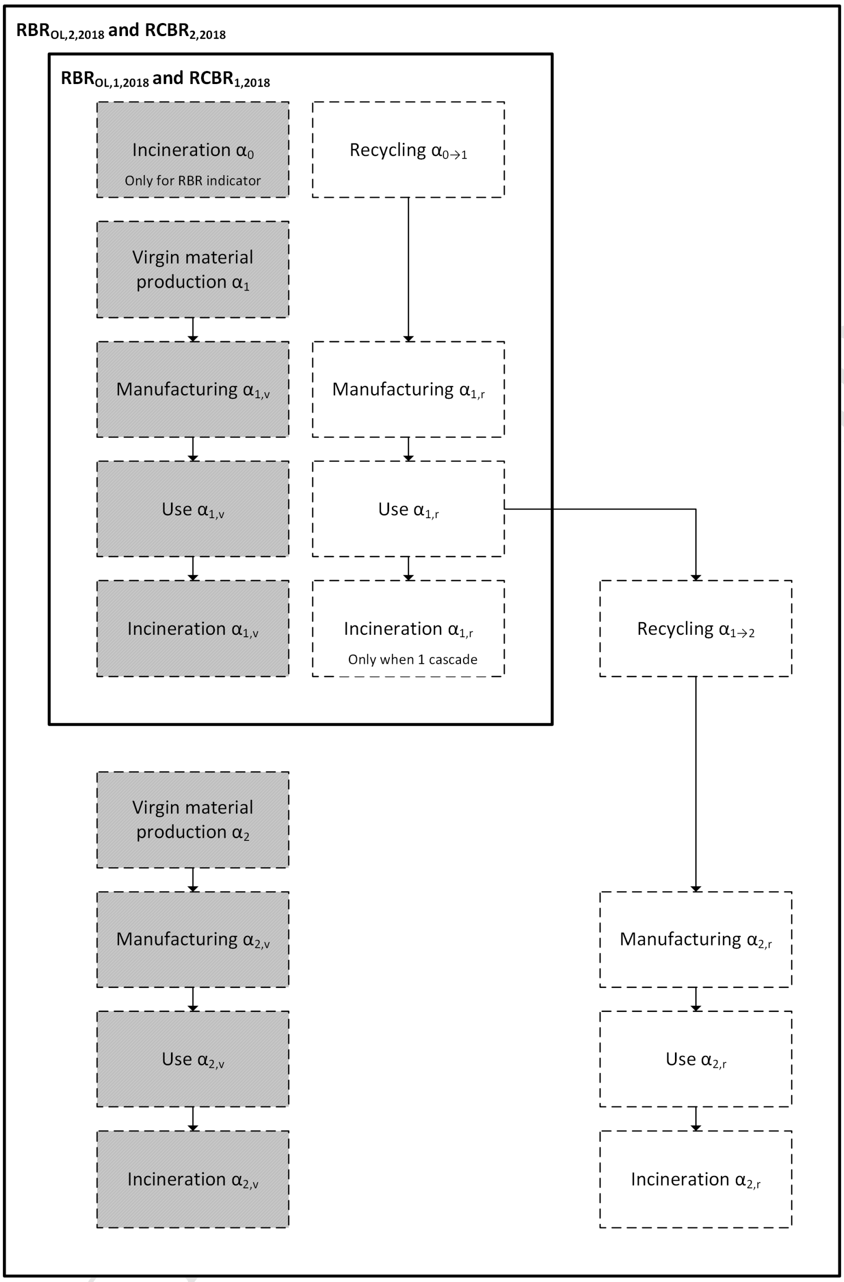

Figure 2 Generic representation of the considered foreground processes in the benefit indicators for 1 cascade and for 2 cascades. Recycling of α_0 into α_1 and the subsequent processes are represented as white blocks with dashed lines. Incineration of α_0 and the subsequent processes are represented as grey colored blocks. Avoided burdens (e.g. the virgin production of electricity (and heat) in case of incineration) and background processes (e.g. tap water production) are taken into account but not shown.

3.1.1. Recyclability Benefit Rate

We further developed Eq. (1) according to the comments mentioned in the introduction of this paper, resulting in the new indicator in Eq. (4). While the impacts of manufacturing and use were left out in Eq. (1) according to Huysman et al. (2015a), they were included in Eq. (4) for the sake of completeness. Whereas the denominator in Eq. (1) includes the production of virgin material in product α_0, the denominator in Eq. (4) considers only the disposal of product α_0, but followed by the impacts for the product α_1 due to virgin material production, manufacturing, use and disposal. The reasoning behind this change is that we should only account for the future impacts caused by the decision about what to do with product α_0 at its end-of-life. When product α_0 is incinerated and thus no longer available to be recycled in product α_1, we account for the life cycle impact of product α_1 produced from virgin material in order to account for the same basket of products in the denominator as the one in the nominator.

Comparing the nominator between Eq. (1) and Eq. (4), we can see that the final step (incineration) in the cascaded use of the material ($D^*_{\alpha_{1,r}}$) is now included in Eq. (4). By introducing parameter d_{α_1}in Eq. (4), we can now account for the potential difference in lifetime between the product α_1 made from recycled material and the product α_1 made from virgin material. Additionally, by introducing parameter p_{α_1} in Eq. (4), we offer the possibility of substituting the virgin material in product α_1 only partially with recycled material, whereby the virgin material is added to fulfill the quality requirements. In case the product α_1 made from recycled material has a shorter lifetime compared to the product α_1 made from virgin material, Eq. (4) shows that this will decrease the net environmental savings of recycling, whereby we assume that the product α_1 made from recycled material will be replaced by a new product α_1 made from recycled material.

The simplified representation of the formula for the RBR indicator is actually [reference net impact (when choosing for disposal) - future net impact (when choosing for recycling)]/reference net impact. Because we want the RBR indicator to equal a positive value when recycling is environmentally more beneficial than disposal, we should avoid that a nominator (which can have a positive or negative value) is divided by a negative denominator, which will change the sign of the resulting value of the RBR indicator. The latter creates confusion about whether recycling is more beneficial than disposal or not. It is possible that the denominator equals a negative value because we account for the net impact, i.e. burdens minus avoided burdens or benefits. In case of incineration, the avoided burden of virgin electricity (and heat) production can be larger than the induced burdens. To avoid confusion we, therefore, add the additional instruction to the definition of the indicator that if the denominator < 0, the nominator should be divided by the value of the denominator with a positive sign. If the RBR indicator then results in a positive value, the larger the value the more beneficial is recycling compared to disposal. If the RBR indicator results in a negative value, disposal is more beneficial than recycling and the larger the value the more beneficial is disposal compared to recycling. Eq. (5) shows how to calculate the new version of the RBR indicator for application on n cascades of open-loop recycling.

$$RBR_{OL,1,2018} = \frac{\begin{array}{c} RCR_{\alpha_0\rightarrow\alpha_1}\left(\dfrac{m_{v,\alpha_1}}{m_{r,\alpha_1}}\left(\left(p_{\alpha_1} - (d_{\alpha_1}-1)(1-p_{\alpha_1})\right)\ V^*_{\alpha_1} + M^*_{\alpha_{1,v}} + U^*_{\alpha_{1,v}} + D^*_{\alpha_{1,v}}\right) - d_{\alpha_1}\left(R^*_{\alpha_0\rightarrow\alpha_1} + M^*_{\alpha_{1,r}} + U^*_{\alpha_{1,r}} + D^*_{\alpha_{1,r}}\right)\right) \\ +D^*_{\alpha_0}\left(1 - d_{\alpha_1}\left(1 - RCR_{\alpha_0\rightarrow\alpha_1}\right)\right) \end{array}}{D^*_{\alpha_0} + RCR_{\alpha_0\rightarrow\alpha_1}\dfrac{m_{v,\alpha_1}}{m_{r,\alpha_1}}\left(V^*_{\alpha_1} + M^*_{\alpha_{1,v}} + U^*_{\alpha_{1,v}} + D^*_{\alpha_{1,v}}\right)} \times 100 \quad (4)$$

If the denominator <0, $RBR_{OL,1,2018} = \frac{nominator}{-denominator}$

When $RBR_{OL,1,2018}$>0, recycling the product α_0 for 1 cascade is environmentally more beneficial than disposal (e.g. incineration) of the product α_0.

With symbols previously not introduced:

$RBR_{OL,1,2018}$: Recyclability Benefit Rate for 1 cascade [%], version of this study
$RCR_{\alpha_0\rightarrow\alpha_1}$: recycling rate from the product α_0 to the product α_1 [%]
p_{α_1} : proportion of the virgin material in the product α_1 substituted with recycled material [%]

d_{α_1} : the inverse of the lifetime of the product α_1 made from recycled material compared to the lifetime of the product made from virgin material [-], e.g. d=2 when the product made from recycled material has half the lifetime of the product made from virgin material
$M^*_{\alpha_{1,v}}, U^*_{\alpha_{1,v}}, D^*_{\alpha_{1,v}}$: avoided impact of manufacture, use and disposal of the product α_1 made from virgin material [impact unit/kg virgin material]
$M^*_{\alpha_{1,r}}, U^*_{\alpha_{1,r}}, D^*_{\alpha_{1,r}}$: impacts due to manufacturing, use and disposal of the product α_1 made from recycled material [impact unit/kg recycled material]
$M^*_{\alpha_0}, U^*_{\alpha_0}$: impacts due to manufacturing and use of the product α_0 made from virgin material [impact unit/kg of product α_0]

$$RBR_{OL,n,2018} = \frac{\begin{gathered}\sum_{i=1}^{n}\left(RCR_{\alpha_0\to\alpha_i}\left(\begin{gathered}\frac{m_{v,\alpha_i}}{m_{r,\alpha_i}}\left(\left(p_{\alpha_i}-(d_{\alpha_i}-1)(1-p_{\alpha_i})\right)\ V^*_{\alpha_i}+M^*_{\alpha_{i,v}}+U^*_{\alpha_{i,v}}+D^*_{\alpha_{i,v}}\right)\\ -d_{\alpha_i}\left(R^*_{\alpha_{i-1}\to\alpha_i}+M^*_{\alpha_{i,r}}+U^*_{\alpha_{i,r}}\right)\end{gathered}\right)\right)\\ +\left(1-d_{\alpha_1}(1-RCR_{\alpha_0\to\alpha_1})\right)D^*_{\alpha_0}-\sum_{i=2}^{n}\left(d_{\alpha_i}\ RCR_{\alpha_0\to\alpha_{i-1}}\ D^*_{\alpha_{i-1,r}}(1-RCR_{\alpha_{i-1}\to\alpha_i})\right)\\ -\left(\prod_{i=1}^{n}d_{\alpha_i}\right)RCR_{\alpha_0\to\alpha_n}\ D^*_{\alpha_{n,r}}\end{gathered}}{D^*_{\alpha_0}+\sum_{i=1}^{n}\left(RCR_{\alpha_0\to\alpha_i}\frac{m_{v,\alpha_i}}{m_{r,\alpha_i}}\left(V^*_{\alpha_i}+M^*_{\alpha_{i,v}}+U^*_{\alpha_{i,v}}+D^*_{\alpha_{i,v}}\right)\right)}\times 100 \quad (5)$$

If the denominator <0, $RBR_{OL,n,2018} = \frac{nominator}{-denominator}$

When $RBR_{OL,n,2018}>0$, recycling the product α_0 for n cascades is environmentally more beneficial than disposal (e.g. incineration) of the product α_0.

With symbols previously not introduced:

$RBR_{OL,n,2018}$: Recyclability Benefit Rate for n cascades [%], version of this study
$RCR_{\alpha_0\to\alpha_i}$: (cumulative if i>1) recycling rate from the product α_0 to the product α_i [%]
$RCR_{\alpha_{i-1}\to\alpha_i}$: recycling rate from the product α_{i-1} to the product α_i [%]
p_{α_i} : proportion of the virgin material in the product α_i substituted with recycled material [%]
d_{α_i} : the inverse of the lifetime of the product α_i made from recycled material compared to the lifetime of the product made from virgin material [-], e.g. d=2 when the product made from recycled material has half the lifetime of the product made from virgin material
$M^*_{\alpha_{i,v}}, U^*_{\alpha_{i,v}}, D^*_{\alpha_{i,v}}$: impact of manufacture, use and disposal of the product α_i made from virgin material [impact unit/kg virgin material]
$M^*_{\alpha_{i,r}}, U^*_{\alpha_{i,r}}, D^*_{\alpha_{i,r}}$: impacts due to manufacturing, use and disposal of the product α_i made from recycled material [impact unit/kg recycled material]
$D^*_{\alpha_{n,r}}$: impact due to disposal of the product α_n made from recycled material [impact unit/kg recycled material]

3.1.2. Recycled Content Benefit Rate

We further developed Eq. (3) according to the comments mentioned in the introduction of this paper, resulting in the new indicator in Eq. (6). While the denominator remains the same, the nominator is different. First, for the nominator in Eq. (3) it was assumed that 1 kg virgin material is substituted with 1 kg recycled material, therefore, it does not account for a potential density difference between virgin (for example virgin PP) and recycled material (recycled plastic mix) in the product α_1. Second, the impacts of manufacturing, use and disposal of product α_1 were left out in the nominator of Eq. (3), while a difference in these impacts may exist between the product α_1 made from virgin material and recycled material. The impact of manufacturing product α_1 based on recycled material, for example by injection moulding of recycled plastic material with a higher density than virgin plastic, may be higher than the impact of manufacturing product α_1 based on virgin plastic. Third, similar as for the RBR indicator, parameters p_{α_1} and d_{α_1} were introduced in Eq. (6). Eq. (7) shows how to calculate the new version of the RCBR indicator for n cascades.

$$RCBR_{1,2018} = \frac{\begin{array}{c} m_{v,\alpha_1}\left(\left(p_{\alpha_1} - (d_{\alpha_1} - 1)(1 - p_{\alpha_1})\right) V^*_{\alpha_1} + M^*_{\alpha_{1,v}} + U^*_{\alpha_{1,v}} + D^*_{\alpha_{1,v}}\right) \\ -d_{\alpha_1} m_{r,\alpha_1}\left(R^*_{\alpha_0\rightarrow\alpha_1} + M^*_{\alpha_{1,r}} + U^*_{\alpha_{1,r}} + D^*_{\alpha_{1,r}}\right) \end{array}}{m_{v,\alpha_1}\left(V^*_{\alpha_1} + M^*_{\alpha_{1,v}} + U^*_{\alpha_{1,v}} + D^*_{\alpha_{1,v}}\right)} \quad (6)$$

If the denominator <0, $RCBR_{1,2018} = \frac{nominator}{-denominator}$

When $RCBR_{1,2018}$>0, introducing of recycled material in product α_1 for 1 cascade is environmentally more beneficial than producing product α_1 entirely based on virgin material.

With symbols previously not introduced:

$RCBR_{1,2018}$: Recycled Content Benefit Rate for 1 cascade [%], version of this study

$$RCBR_{n,2018} = \frac{\begin{array}{c} m_{v,\alpha_1}\left(\left(p_{\alpha_1} - (d_{\alpha_1} - 1)(1 - p_{\alpha_1})\right) V^*_{\alpha_1} + M^*_{\alpha_{1,v}} + U^*_{\alpha_{1,v}} + D^*_{\alpha_{1,v}}\right) \\ -d_{\alpha_1}\, m_{r,\alpha_1}\left(R^*_{\alpha_0\rightarrow\alpha_1} + M^*_{\alpha_{1,r}} + U^*_{\alpha_{1,r}}\right) \\ +\sum_{i=2}^{n}\left(m_{r,\alpha_1} RCR_{\alpha_1\rightarrow\alpha_i}\left(\begin{array}{c}\left(\left(p_{\alpha_i} - (d_{\alpha_i} - 1)(1 - p_{\alpha_i})\right)\frac{m_{v,\alpha_i}}{m_{r,\alpha_i}} V^*_{\alpha_i} + M^*_{\alpha_{i,v}} + U^*_{\alpha_{i,v}} + D^*_{\alpha_{i,v}}\right) \\ -d_{\alpha_i}\left(R^*_{\alpha_{i-1}\rightarrow\alpha_i} + M^*_{\alpha_{i,r}} + U^*_{\alpha_{i,r}} + \left(1 - RCR_{\alpha_{i-1}\rightarrow\alpha_i}\right) D^*_{\alpha_{i-1,r}}\right)\end{array}\right)\right) \\ -\left(\prod_{i=1}^{n} d_{\alpha_i}\right) m_{r,\alpha_1} RCR_{\alpha_1\rightarrow\alpha_n} D^*_{\alpha_{n,r}} \end{array}}{\begin{array}{c} m_{v,\alpha_1}\left(V^*_{\alpha_1} + M^*_{\alpha_{1,v}} + U^*_{\alpha_{1,v}} + D^*_{\alpha_{1,v}}\right) \\ +\sum_{i=2}^{n}\left(m_{r,\alpha_1} RCR_{\alpha_1\rightarrow\alpha_i}\frac{m_{v,\alpha_i}}{m_{r,\alpha_i}}\left(V^*_{\alpha_i} + M^*_{\alpha_{i,v}} + U^*_{\alpha_{i,v}} + D^*_{\alpha_{i,v}}\right)\right) \end{array}} \times 100 \quad (7)$$

If the denominator <0, $RCBR_{n,2018} = \frac{nominator}{-denominator}$

When $RCBR_{n,2018}$>0, introducing of recycled material in products for n cascade is environmentally more beneficial than producing those products entirely based on virgin material.

With symbols previously not introduced:

$RCBR_{n,2018}$: Recycled Content Benefit Rate for n cascades [%], introduced in this study

3.2. Illustration with a case study

3.2.1. Indicator results

Figure 3 presents the case study results of the former indicators and the new indicators proposed in this paper for 1 cascade and for 2 cascades (cfr. Figure 2). A positive indicator result means that recycling of the surplus sink fraction followed by the life cycle of the green roof tile made from this recycled material (scenario recycling) is more environmentally beneficial than incineration of the surplus sink fraction followed by the life cycle of the green roof tile made from virgin PP (scenario incineration). A table with results, including the results for the ReCiPe Midpoint impact categories that are not presented in Figure 3, can be found in the supporting information. Also the absolute values of the nominator and the denominator can be found in the supporting information.

Focusing first on the RBR indicators for 1 cascade (Figure 3-A), the $RBR_{OL,1,2018}$ is positive and higher than the $RBR_{OL,1,2015}$ for the aggregated impact category *CEENE Total*, the separate impact subcategories *CEENE Fossil*, *CEENE Metal* and *CEENE Mineral*, and all three *ReCiPe Endpoints Human Health*, *Natural Ecosystems* and *Natural Resources*. These higher results are mainly caused by a lower value for the denominator in case of $RBR_{OL,1,2018}$. This lower denominator value is due to the fact that the virgin material production in product α_0 ($V^*_{\alpha_0}$) is no longer considered as was explained in section 3.1.1, but replaced by the life cycle impacts for product α_1. The latter are for these mentioned impact categories/endpoints lower than $V^*_{\alpha_0}$ because less virgin PP is required to produce α_1. The negative results for $RBR_{OL,1,2018}$ for the impact subcategories *CEENE Renewable*, *CEENE Nuclear, CEENE Water* and *CEENE Land* mean that the scenario recycling is less beneficial compared to the scenario incineration. This is because we accounted for the benefits of incineration, i.e. the avoided burdens of average virgin electricity and heat produced in Belgium. The discrepancy between $RBR_{OL,1,2015}$ and $RBR_{OL,1,2018}$ is largest for the impact categories *CEENE Nuclear* and *CEENE Land*, which is caused by an error in the calculation of $RBR_{OL,1,2015}$ as was explained in section 3.1.1: the negative nominator ánd denominator for these impact categories cause a 'false positive' indicator result in case of $RBR_{OL,1,2015}$. When applying the instruction proposed in this paper "if the denominator < 0, the nominator should be divided by the value of the denominator with a positive sign", $RBR_{OL,1,2015}$ would also be negative for the impact categories *CEENE Nuclear* and *CEENE Land*, which largely reduces the discrepancy between $RBR_{OL,1,2015}$ and $RBR_{OL,1,2018}$.

When including 2 cascades, $RBR_{OL,2,2018}$ is still positive for the same impact categories/endpoints compared to $RBR_{OL,1,2018}$. $RBR_{OL,2,2018}$, however, is lower than $RBR_{OL,1,2018}$ for all presented impact categories/endpoints except *CEENE Mineral* (Figure 3-B). These lower results are mainly caused by a smaller increase in the nominator of $RBR_{OL,2,2018}$ compared to $RBR_{OL,1,2018}$. The smaller increase in the nominator of $RBR_{OL,2,2018}$ means that the environmental savings in the scenario recycling have decreased compared to the scenario incineration. First, this is again because we accounted for the benefits of incineration: in case of 2 cascades (cfr. Figure 2) these benefits increase in the scenario incineration. Second, the impact of injection moulding of the green roof tile made from the recycled material with a 46% higher density than virgin PP (see section 2.2.2) is accordingly 46% higher than the impact of injection moulding based on virgin PP, because the reference flow of the ecoinvent dataset for injection moulding is 1 kg plastics as input for injection moulding. The contribution of injection moulding to the life cycle impact of a green roof tile is significant: for example, 37% of *CEENE total* of the life cycle starting from virgin PP production, over injection moulding of the green roof tile, until incineration is due to injection moulding. Figure 3-B also shows that the $RBR_{OL,2,2018}$ is lower than the $RBR_{OL,2,2015}$ for all presented impact categories/endpoints except the impact subcategories *CEENE Metal* and *CEENE Mineral*, and the *ReCiPe Endpoint Human Health*. Two reasons explain these results. First, as abovementioned, $RBR_{OL,2,2018}$ is lower than $RBR_{OL,1,2018}$ (except for *CEENE Mineral*). Second, $RBR_{OL,2,2015}$ is higher than $RBR_{OL,1,2015}$ for all presented impact categories/endpoints except the impact subcategories *CEENE Renewable*, *CEENE Nuclear* and and *CEENE Land*. Because the denominator of $RBR_{OL,2,2015}$ and $RBR_{OL,1,2015}$ is completely the same (cfr. Eq. (2) and Eq. (1)), this can only be explained by a higher nominator in case of $RBR_{OL,2,2015}$, which is mainly due to the increased avoided burden of virgin PP production in case of 2 cascades. In the calculation of the $RBR_{OL,2,2015}$ an error was made for the impact subcategories *CEENE Nuclear* and *CEENE Land*. In case of *CEENE Nuclear*, the negative nominator ànd denominator cause a 'false positive' indicator result. In case of *CEENE Nuclear*, the positive nominator and the negative denominator cause a 'false negative' indicator result. Taking these errors into account, a large discrepancy between $RBR_{OL,2,2015}$ and $RBR_{OL,2,2018}$ remains for the impact categories *CEENE Nuclear* and *CEENE Water.* $RBR_{OL,2,2018}$ results in much lower values for these impact categories compared to $RBR_{OL,2,2015}$ because $RBR_{OL,2,2018}$ accounts for (i) the lower impacts of injection moulding in case of virgin material and (ii) the increased benefits due to incineration in case of 2 cascades.

Focusing on the RCBR indicators for 1 cascade (Figure 3-C), the $RCBR_{1,2018}$ is positive but lower than the $RCBR_{1,2014}$ for all presented impact categories/endpoints, except the impact subcategories *CEENE Renewable* and *CEENE Land* for which $RCBR_{1,2018}$ is negative (and lower than $RCBR_{1,2014}$). Because the denominator of $RCBR_{1,2014}$ and $RCBR_{1,2018}$ is completely the same (cfr. Eq. (3) and Eq. (6)), these results are explained by the difference in their nominator. The nominator of $RCBR_{1,2018}$ is lower because, in contrast to $RCBR_{1,2014}$, $RCBR_{1,2018}$ accounts for (i) the lower impacts of injection moulding in case of virgin material and (ii) the density difference between virgin PP and the recycled material, leading to a lower avoided impact from virgin material production. In the calculation of the $RCBR_{1,2014}$ an error was made for the impact subcategory *CEENE Land*: the negative nominator ánd denominator cause a 'false positive' indicator result. The large negative result for *CEENE Renewable* for both $RCBR_{1,2014}$ and $RCBR_{1,2018}$ is due to the green electricity mix used by the recycling company ECO-oh!. When the abiotic renewable energy resources are considered as freely available and their use not as an environmental burden (cfr. Huysman et al. (2015a)), the benefits of using recycled material in the green roof tile increase.

When including 2 cascades, Figure 3-D only shows the results for the new indicator $RCBR_{2,2018}$, because Ardente and Mathieux (2014b) did not consider more than 1 cascade. Compared to $RCBR_{1,2018}$, $RCBR_{2,2018}$ is lower for all presented impact categories/endpoints except the impact subcategory *CEENE Mineral* and the *ReCiPe Endpoints Human Health* and *Natural Ecosystems*. Whether $RCBR_{2,2018}$ is lower than $RCBR_{1,2018}$ or not, the reason behind the difference is similar, i.e. incineration at the product's end-of-life. When $RCBR_{2,2018}$ is lower than $RCBR_{1,2018}$, this means that the increased benefits of avoided virgin electricity and heat production due to incinerating 2 products α_1 and α_2 made from virgin material instead of 1 product α_2 made from recycled material compensate for the increased burdens due to the incineration processes. On the other hand, when $RCBR_{2,2018}$ is higher than $RCBR_{1,2018}$, this means that the increased benefits of avoided virgin electricity and heat production due to incinerating 2 products α_1 and α_2 made from virgin material instead of 1 product α_2 made from recycled material are not large enough to compensate for the increased burdens due to the incineration processes.

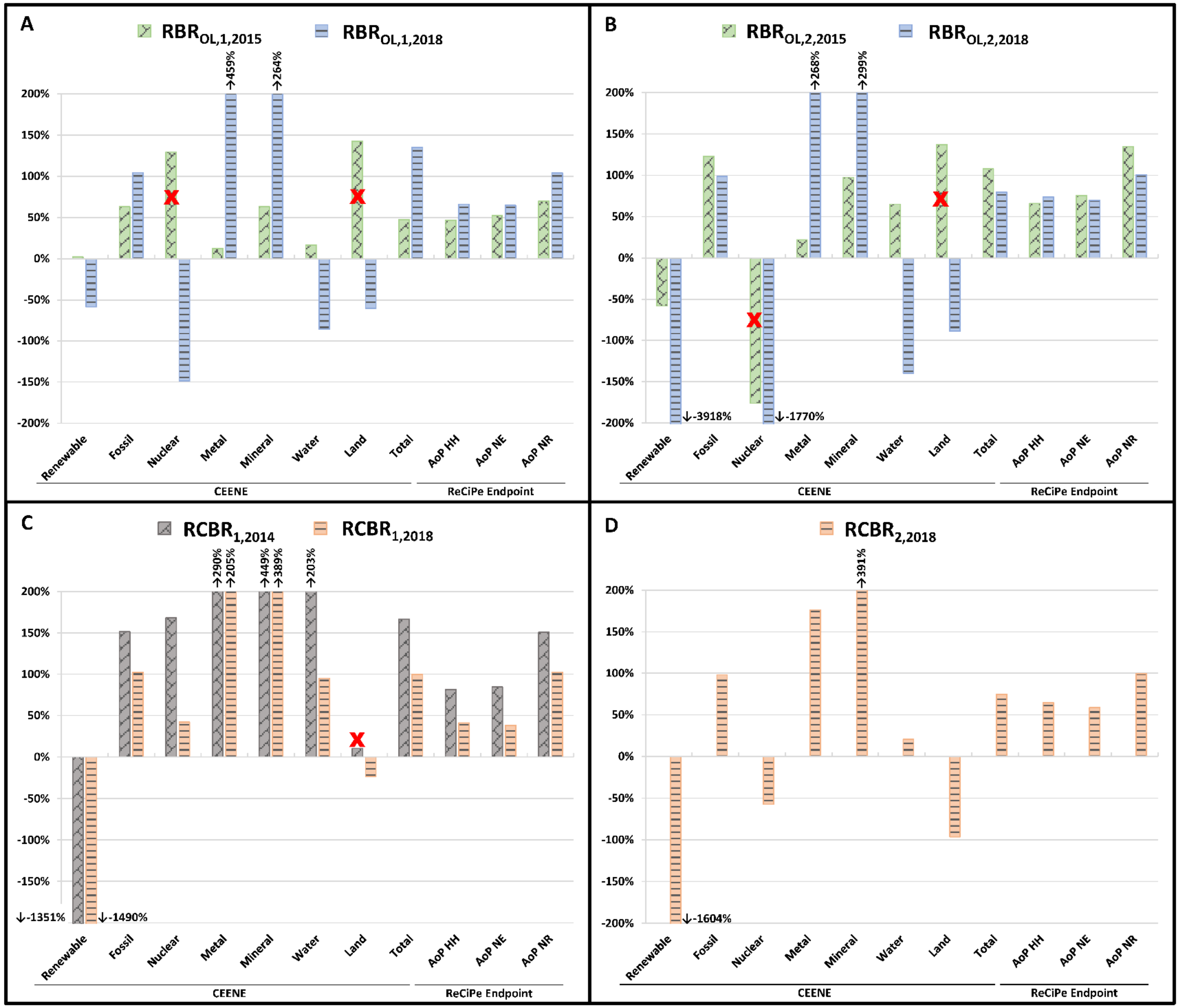

Figure 3 Results (selected; for more impact categories see supporting information) of the case study, with parameter p=100% and d=1. HH: Human Health; NE: Natural Ecosystems; NR: Natural Resources. Impact categories with a false positive or false negative result are indicated with a red cross.

3.2.2. Discussion and sensitivity analysis for parameters p and d

The main conceptual difference between the new version of the RBR and the RCBR indicator proposed in this paper is that the RCBR indicator does not account for the incineration of the first product α_0 in the reference situation in which it is not recycled. This is because the focus of the RCBR indicator is on the new product designer's perspective instead of the previous product's end-of-life or waste perspective. However, from a life cycle perspective we can conclude that the RBR indicator is more comprehensive than the RCBR indicator. Because we accounted (in both indicators), in addition to the burdens of incineration, for the benefits of incineration, i.e. the avoided burdens of average virgin electricity and heat produced in Belgium, the LCI dataset for the avoided electricity and heat production has an important influence on the RBR result. A sensitivity analysis for the electricity and heat LCI dataset is out of the scope of this paper.

Because the contribution of injection moulding to the life cycle impact of the green roof tile is large (see section 3.2.1), also the LCI dataset for injection moulding may play an important role in the indicator results. The many factors influencing the energy consumption of injection moulding (e.g. installed machine power, cycle time, part maximum thickness, etc.) (Ribeiro et al., 2015) are not reflected in the average ecoinvent LCI dataset that was used in this case study. It must be taken into account that the solid waste fraction considered in this study originated largely from extrusion products (foils, trays, etc.). Extrusion-grade materials typically have high viscosities, while injection moulding grades have low viscosities, allowing them to be injected into the cavity with little resistance. The particularly high energy consumption for injection moulding in this study is due to the fact that a mixture of extrusion-grade secondary materials were used for an injection moulding product. Should the source material be injection grade (like ELV or WEEE polymers) or should the chosen new product be an extrusion product (like plastic boards for a picnic bench), energy consumption would be reduced drastically. The virgin PP from the comparison is an injection-grade. As such, we risk a skewed perception that the material being recycled would be a cause for higher energy consumption, while in fact it is the viscosity of the sourced polymers.

In this case study, we have assumed that the collection efficiency for the green roof tile is 100%, going either to incineration or recycling. It is, however, important to note that the building's end of life is complex and that the material's recovery largely depends on the functioning of the local collection scheme. For cases where the collection efficiency is lower than 100%, future adjustments of the equations should account for additional material losses.

Figure 4 presents a sensitivity analysis for parameters p and d in Eq. 4-7. A table with results, including the results for the ReCiPe Midpoint impact categories that are not presented in Figure 4, can be found in the supporting information.

In the presented results of the case study (section 3.2.1) parameters p and d were both equal to 1 in both the first and the second cascade. Figure 4 compares the latter results with three other scenarios, i.e. (i) p=0.8; d=1 to show the effect of parameter p, (ii) p=1; d=2 to show the effect of parameter d, and (iii) p=0.8; d=2 to show the combined effect of parameters p and d. Decreasing parameter p from 1 to 0.8 means a 20% reduction in the proportion of recycled material in the green roof tile. Reducing parameter p and keeping parameter d equal to 1 shows always a reduction in the environmental benefits of the recycling scenario compared to the incineration scenario for all impact categories/endpoints and for all indicators (Figure 4 A-D). Increasing parameter d from 1 to 2 stands for a 50% reduction in the lifetime of the green roof tile made from recycled material compared to the green roof tile made from virgin material. Raising parameter d and keeping parameter p equal to 1, however, shows a reduction or an increase in the environmental benefits of the recycling scenario compared to the incineration scenario depending on the impact category/endpoint. The *ReCiPe Endpoints Human Health* and *Natural Ecosystems* show a decrease when raising parameter d and keeping parameter p equal to 1 for all indicators (Figure 4 A-D). On the other hand the *CEENE total* impact category and the *ReCiPe Endpoint Natural Resources* increase. An increase in the environmental benefits of the recycling scenario compared to the incineration scenario means that the increased benefits of avoided virgin electricity and heat production due to incinerating 2 recycled products (instead of 1 recycled product) for each cascade compensate for the increased burdens due to the additional incineration process and due to the additional recycling and manufacturing processes.

The practical implementation of accounting for the lifetime difference between the product made from recycled material and the one made from virgin material needs further research. For example, how to predict the lifetime of a new product? Lifetime can be interpreted in different ways, e.g. the economic lifetime (determined by the opportunity cost) and the technical lifetime (Ardente and Mathieux, 2014a). If lifetime would be determined based on the quality of the material, how to measure this quality? As pointed out by Huysman et al. (2017), the measurement of quality is a major challenge, which can be based also on physical or economic parameters.

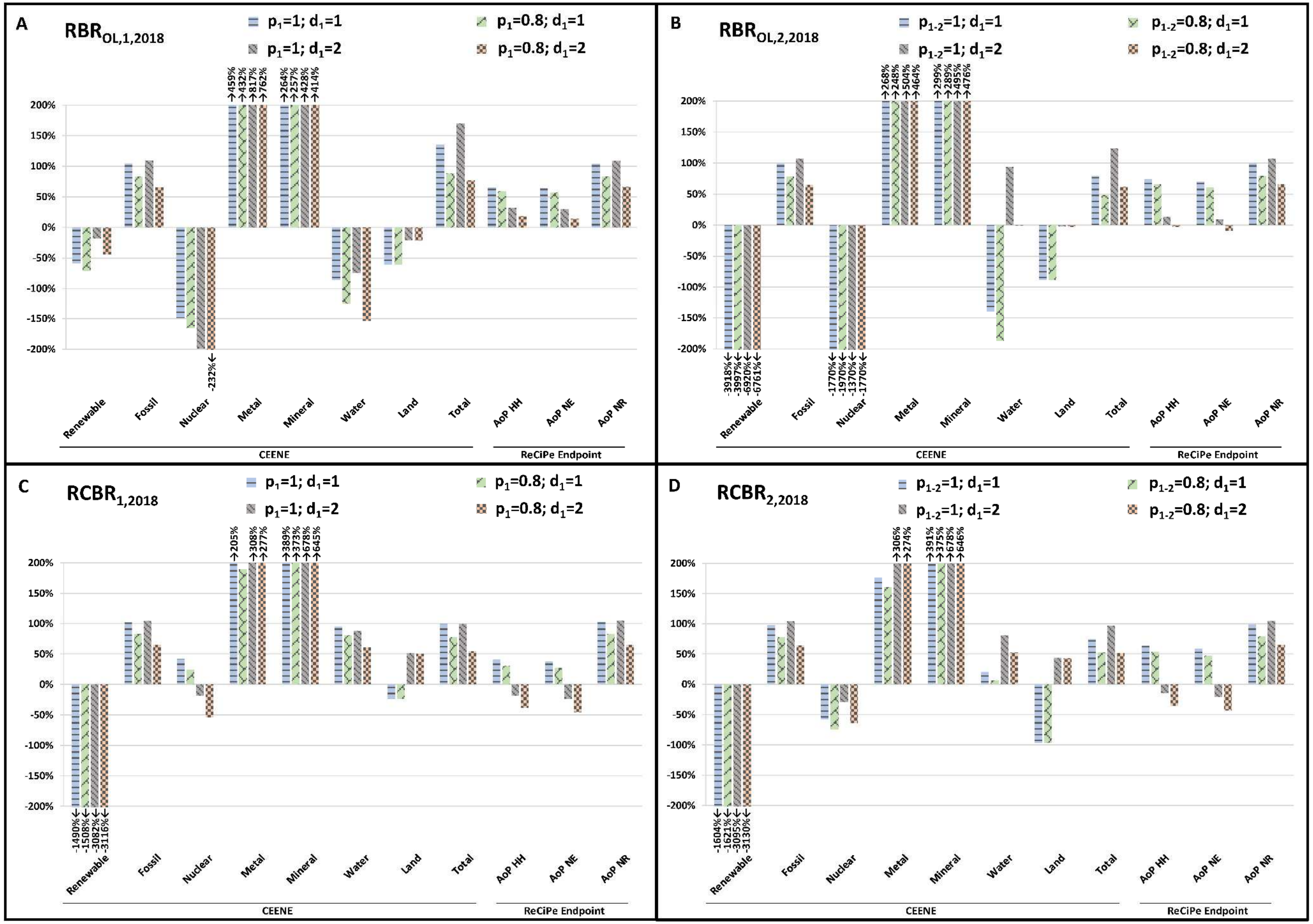

Figure 4 Results (selected; for more impact categories see supporting information) of the case study, with sensitivity analysis for parameters p and d. HH: Human Health; NE: Natural Ecosystems; NR: Natural Resources.

4. Conclusions and perspectives

By further developing the existing Recyclability Benefit Rate (RBR) and the Recycled Content Benefit Rate (RCBR) indicators, this paper clarifies and advances the monitoring of the environmental benefits of material cascading. Application of the existing and new indicators to a case of mixed and contaminated plastic waste shows that the adjustments have clear and not to be underestimated effects on the results.

Overall, the case study showed that the scenario recycling is more environmentally beneficial than the scenario incineration. By presenting a broad and detailed range of impacts, this paper showed that for some impact categories recycling could be less beneficial than incineration (e.g. land use). However, these cases are limited, and the results for the broad endpoints (*Human Health*, *Natural Ecosystems* and *Natural Resources*) and the aggregated impact category *CEENE total* representing overall natural resource consumption were favourable for recycling. However, some attention points can be concluded from this case study. First, the impact of injection moulding is large due to its energy consumption. Research into the reduction of the energy consumption or using more renewable energy are recommended, either by sourcing other secondary materials for injection moulding or applying the current waste fraction in an extrusion process.

Second, each case of waste is different and it depends on several case-specific aspects whether recycling becomes environmentally and economically too expensive to achieve a net benefit compared to incineration. Examples of case-specific aspects are the origin of the avoided electricity and heat in case of incineration, and the additional efforts needed to increase the quality of the recycled material to a minimum required level. However, certain material preparation steps could become unnecessary, thus further reducing the overall impact. It is not beyond imagination that PVC will be banned as a packaging material in the near future, as its presence in mixed plastic waste is a known bottleneck for effective recycling and the recently published EU Plastics Strategy (European Commission, 2018a) literally mentions that 'substances hampering recycling processes (will) have been replaced or phased out.'

Future research could focus on an economic cost-benefit analysis to complement the environmental analysis of this study. Additionally, the practical implementation of accounting for the lifetime difference between the product made from recycled material and the one made from virgin material needs further research. Also, future adjustments of the equations could account for additional material losses due to inefficient collection. Finally, it would be interesting to apply the indicators in a broader circular economy context, e.g. for bio-based products.

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Highlights

- Advancing Recyclability Benefit Rate and Recycled Content Benefit Rate indicators
- Application to a case of mixed and contaminated plastic waste
- In case study recycling is more environmentally beneficial than incineration