



# The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders



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## ABSTRACT

Over the last few years, waste management strategies are shifting from waste disposal to recycling and recovery and are considering waste as a potential new resource. To monitor the progress in these waste management strategies, governmental policies have developed a wide range of indicators. In this study, we analyzed the concept of the recyclability benefit rate indicator, which expresses the potential environmental savings that can be achieved from recycling the product over the environmental burdens of virgin production followed by disposal. This indicator is therefore, based on estimated environmental impact values obtained through Life Cycle Assessment (LCA) practices. We quantify the environmental impact in terms of resource consumption using the Cumulative Exergy Extraction from the Natural Environment method. This research applied this indicator to two cases of plastic waste recycling in Flanders: closed-loop recycling (case A) and open-loop recycling (case B). Each case is compared to an incineration scenario and a landfilling scenario. The considered plastic waste originates from small domestic appliances and household waste other than plastic bottles. However, the existing recyclability benefit rate indicator does not consider the potential substitution of different materials occurring in open-loop recycling. To address this issue, we further developed the indicator for open-loop recycling and cascaded use. Overall, the results show that both closed-loop and open-loop recycling are more resource efficient than landfilling and incineration with energy recovery.

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## 1. Introduction

Our society has grown through the extraction and usage of natural resources. Nonetheless, for many natural resources on earth, the available supply is at risk (Boryczko et al., 2014). If our current rate of natural resource use persists, then we will require more than one planet to sustain our consumption and production patterns (Footprintnetwork, 2014). To balance economic growth and natural resource consumption, our society has to utilize resources more efficiently, or in other words, drastically increase its resource efficiency (BIO-SEC-SERI, 2012).

Apart from finding more efficient processes, a better management of waste represents the most apparent potential to increase resource efficiency (BIO-SEC-SERI, 2012). This management can be achieved by preventing waste or by reusing, recovering energy from or recycling the waste (Directive 2008/98/EC, 2008). Instead

of focusing on waste disposal, waste materials can be considered as potential new resources, so-called 'waste-as-resources'. This change in mindset from waste disposal to waste-as-resources is becoming increasingly implemented in the waste management strategies of governmental policies. To ensure the progress in waste management, several institutions have been developing a wide range of indicators to provide quantitative information on the current status and to communicate results. Through these indicators, the existing status can be evaluated and future policy directions for waste prevention, reuse, energy recovery and recycling can be developed. A framework for the classification of these resource efficiency indicators at different levels can be found in the work of Huysman et al. (2015).

One of the leading governmental organizations in the field of developing and applying waste-as-resources indicators is the European Union. Various waste-as-resources indicators have been developed by the European Commission's Joint Research Centre (JRC) (Ardente and Mathieux, 2014; EC-JRC, 2012a,b). One of these indicators is the Recyclability Benefit Rate (RBR), expressing the potential environmental savings related to the recycling of a

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product over the environmental burdens of virgin production followed by disposal. This indicator is generally calculated using environmental impact values obtained through Life Cycle Assessment (LCA) (ISO, 2006a,b). The intended application of this indicator is to support the European Commission with the integration of measures aiming at improving resource efficiency in European product policies (Ardenete and Mathieux, 2014).

The first objective of this paper is to explore the applicability of the recyclability benefit rate indicator concept in two cases of plastic waste treatment in Flanders: closed-loop recycling (case A) and open-loop recycling (case B). In closed-loop recycling, the inherent properties of the recycled material are not considerably different from those of the virgin material. The recycled material can thus substitute the virgin material and be used in the identical type of products as before. In open-loop recycling, the inherent properties of the recycled material differ from those of the virgin material in a way that it is only usable for other product applications, mostly substituting other materials (Nakatani, 2014; Williams et al., 2010; Wolf and Chomkhamisri, 2014). Based on these two cases, the indicator is further developed for open-loop recycling and cascaded use.

The considered plastic waste originates from small domestic appliances (e.g., radios, vacuum cleaners) and household plastics other than plastic bottles (e.g., foils, bags). Given the indispensable role of plastics in our modern society, these products provide a relevant case study. In 2012, the global production of plastics was 288 million tons (Plastics Europe, 2013). The development of synthetic polymers used to make these plastics consumes almost 8% of the global crude oil production (Nkwachukwu et al., 2013). However, after use, plastics become a major waste management challenge. Because the degradation of plastics in the environment takes a

considerable amount of time, plastics impose risks to human health and the natural environment (Nkwachukwu et al., 2013).

These environmental concerns, combined with the impending supply risk of crude oil, are important incentives to stimulate the recovery of plastics. To compare different plastic waste treatments, several LCA studies have been performed in the literature. Comprehensive reviews can be found in the work of Lazarevic et al. (2010) and Laurent et al. (2014). In all of these studies, the environmental impact assessment is largely focused on the emissions and to a lesser extent on resources, the latter by using the abiotic depletion potential as an indicator. However, a good analysis focusing on the full asset of natural resources (Swart et al., 2015) in combination with resource efficiency indicators is still missing.

Therefore, the second objective of this paper is to perform such an analysis using an impact methodology which accounts for resource consumption: the Cumulative Exergy Extraction from the Natural Environment or CEENE (Dewulf et al., 2007). This methodology is based on the exergy concept, enabling accounting for both the quantity and the quality of a wide range of natural resources (Dewulf et al., 2008).

## 2. Materials and methods

### 2.1. Scope definition

The scope of the paper is to evaluate the resource efficiency in two cases of plastic waste treatment in Flanders (see Fig. 1): closed-loop recycling of plastics extracted from electronic waste (case A) and open-loop recycling of plastics from household waste (case B). For each case, three possible scenarios are available: (1) material recovery by closed-loop or open-loop recycling, (2) incineration for

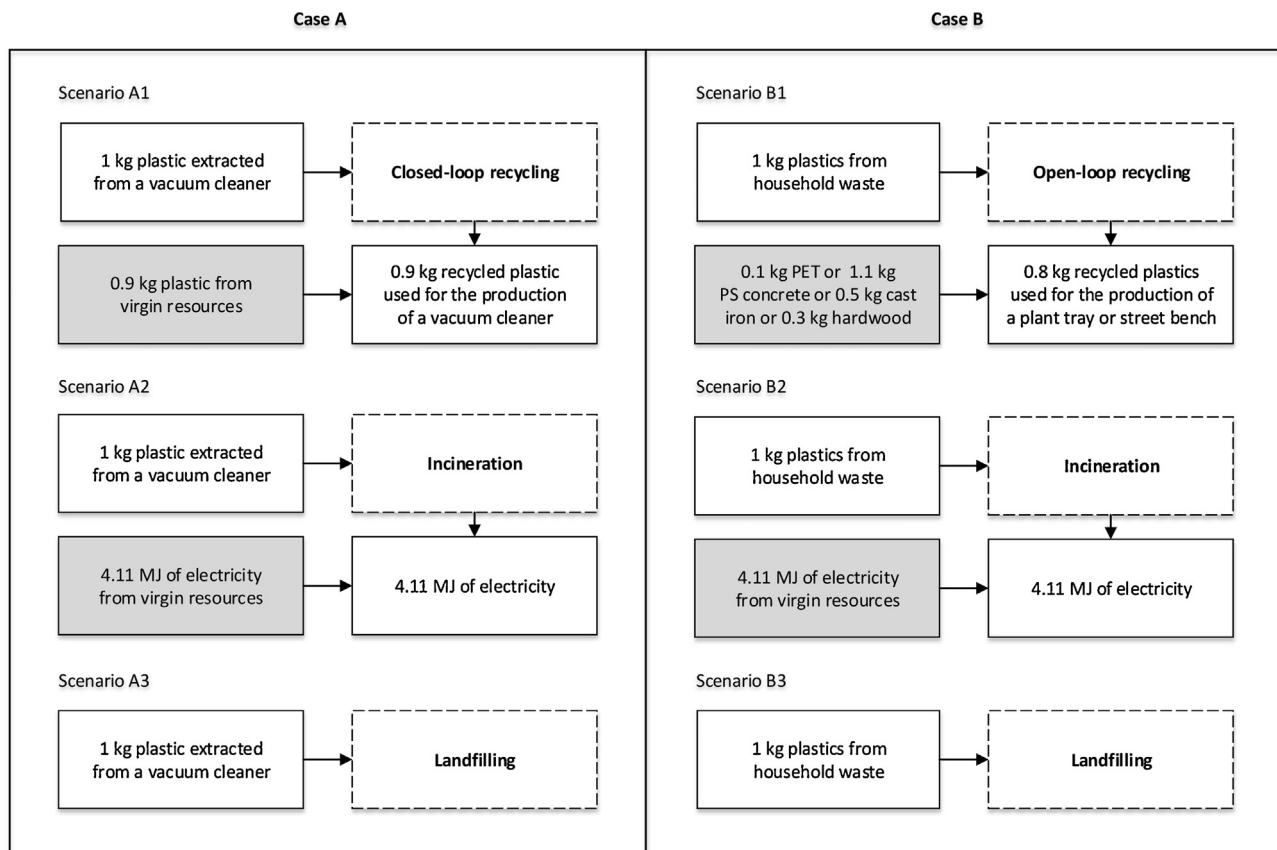


Fig. 1. Presentation of case A and case B. For each case, three possible scenarios are available: closed-loop/open-loop recycling, incineration for electricity recovery and landfilling. The grey colored blocks are the products for which the production from virgin resources ('virgin production') can be avoided.

electricity recovery and (3) landfilling. The calculations are based on LCA practices performed according to the ISO 14040/14044 guidelines (ISO, 2006a,b). Foreground data were collected in close collaboration with the companies. To model the background system and assess the environmental impacts, we used the Ecoinvent v2.2 database (Swiss Centre for Life Cycle Inventories, 2010) and OpenLCA software (Greendelta, 2014).

## 2.2. Description of case A

### 2.2.1. Functional unit

The functional unit of case A is the waste treatment of 1 kg of plastics extracted from small domestic appliances, e.g., a vacuum cleaner. Possible waste treatment scenarios are closed-loop recycling (A1), incineration for electricity recovery (A2) and landfilling (A3).

### 2.2.2. Data inventory

The closed-loop recycling scenario (A1) is performed by the company Galloo. This company recycles plastics extracted from electronic waste. The recycling process consists of four main steps: shredding, separation of metal and plastics, further separation of plastics and extrusion of plastics into pellets. The subdivision of the recycled plastic pellets is in general 50% polystyrene (PS), 20% acrylonitrile butadiene styrene (ABS), 15% polyethylene (PE) and 15% polypropylene (PP). The recycling rate of Galloo is 90%, indicating that 0.9 kg of recycled plastic is produced per kg waste input. The recycled plastics can be used in the identical product as before, i.e., a vacuum cleaner. This implies that the production of 0.9 kg plastics from virgin resources can be avoided. Data for the foreground system was gathered on-site (Galloo, personal communication). These data includes the detailed mass balance, electricity use, additives and on-site transport. Transport of waste from the waste-producing activity to the company and collection of waste are not included because of the unavailability of data. Data for the background system was retrieved from the Ecoinvent v2.2 database. Additional detailed information can be found in the Supplementary Information.

In the incineration scenario (A2), the plastic waste is incinerated for electricity recovery. The incineration was modeled by the Ecoinvent process 'Disposal, plastics, mixture, 15.3% water, to municipal incineration'. This process does not include waste collection and transport (Doka, 2003). Per kg incinerated plastics, 4.11 MJ of electricity is delivered (Ecoinvent v2.2). Considering the Belgian electricity mix, this result implies that the production of the identical amount of electricity from virgin resources, mainly fossil fuels and nuclear ores, can be avoided. The avoided virgin electricity production was modeled by the processes 'Electricity, medium voltage, production BE, at grid' (Schmidt et al., 2011).

The landfilling scenario (A3) was modeled by the Ecoinvent process 'disposal, plastics, mixture, 15.3% water, to sanitary landfill'. This process does not include waste collection and transport (Doka, 2003). Further, the vacuum cleaner itself is modeled as a 'Commercial Canister' type (AEA Energy and Environment, 2009). This type of vacuum cleaner has a plastic fraction consisting of 1.96 kg PS, 1.96 kg PP and 1.96 kg acrylonitrile butadiene styrene (ABS), and a metal fraction consisting of 1.45 kg ferrous and 2.25 kg non-ferrous materials. Data for the production phase of these materials was retrieved from the Ecoinvent v2.2 database, see Supplementary Information. The assembling phase was assumed to be negligible (Boustani et al., 2010). During the use phase, the vacuum cleaner consumes 1650 kWh electricity over its lifetime (EC, 2010), which was modeled by the Ecoinvent process 'Electricity, low voltage, at grid BE'. We assumed that all of the plastics in the vacuum cleaner are recycled by Galloo. Next, the recycled plastics are used for the production of a new vacuum cleaner. For this study, it was assumed

that the entire plastic fraction in this new vacuum cleaner is comprised from recycled material. In practice, the maximum fraction of recycled plastic in vacuum cleaners currently on the Belgian market is 70% (Electrolux, 2014). Recycling of the metal fraction was not considered in this study because the focus is on plastic waste treatment.

## 2.3. Description of case B

### 2.3.1. Functional unit

The functional unit of case B is the waste treatment of 1 kg of household plastics (e.g., bags, foils, toys) other than plastic bottles. Possible waste treatment scenarios are open-loop recycling (B1), incineration for electricity recovery (B2) and landfilling (B3).

### 2.3.2. Data inventory

The open-loop recycling scenario (B1) is performed by the company Ekol. This company recycles plastic waste from households excluding plastic bottles; plastic bottles are collected separately. The main steps in the recycling process are the following: depollution, shredding, separation, drying, wind sifting and extrusion into pellets. Two types of polymer composites are produced at Ekol: one consists of 80% polyethylene (PE) and 20% polypropylene (PP), and the other consists of 20% polyvinylchloride (PVC), 40% polystyrene (PS) and 40% polyethylene terephthalate (PET). In this study, the focus will be on the PE-PP polymer. The recycling rate of Ekol is 80%, indicating that 0.8 kg PE-PP pellets are produced per kg waste input. The PE-PP pellets are used to produce new products, i.e., plant trays and street benches. The production of one plant tray requires 140 kg PE-PP pellets, whereas the production of one street bench requires 95.5 kg PE-PP pellets.

With 0.8 kg PE-PP pellets obtained per kg waste input, either 1/175th (=0.8/140) of a plant tray or 1/119th (=0.8/95.5) of a street bench can be produced. However, the 'virgin alternatives' of the plant tray and the street bench are produced from other materials. A 'virgin' plant tray is often produced from polyethylene terephthalate (PET) (19 kg) or PS concrete (195 kg) (Plantenbak, 2014). The latter is a type of concrete that utilizes polymers to substitute cement (Frigione, 2013). A 'virgin' street bench is mostly comprised of cast iron (63 kg) or tropical hardwood (32.5 kg) with a cast iron pedestal (26 kg) (Claerbout, 2014). This composition indicates that 0.8 kg recycled PE-PP can substitute the virgin production of 0.1 kg PET (=1/175 × 19 kg), 1.1 kg PS concrete (=1/175 × 195 kg), 0.5 kg cast iron (=1/119 × 63 kg) or 0.3 kg hardwood + 0.2 kg cast iron (=1/119 × 32.5 kg + 1/119 × 26 kg). The products produced by Ekol are heavier than their virgin alternatives because of the quality loss in the recycled material: additional mass is required to fulfill the identical requirements.

Data for the foreground system was gathered on-site (Ekol, personal communication). These data includes the detailed mass balance, electricity use, natural gas, water and additives. Data for the transport of waste from the waste-producing activity to the company and collection of waste was not included because of the unavailability of data. Data for the background system and the substituted materials was retrieved from the Ecoinvent v2.2 database. Additional detailed information can be found in the Supplementary Information. The incineration scenario (B2) and the landfilling scenario (B3) are modeled by the identical Ecoinvent processes as used in case A.

## 2.4. The use of LCA in resource efficiency indicators

### 2.4.1. Life cycle impact assessment

In this study, the focus lies on the environmental impact savings related to changes in resource consumption. Therefore, the Cumulative Exergy Extraction from the Natural Environment (CEENE)

version 2.0 was applied as impact assessment method (Alvarenga et al., 2013; Dewulf et al., 2007). The CEENE method quantifies all resources extracted from nature in terms of exergy. Exergy is a thermodynamics-based metric that can be used to evaluate both the quality and quantity of resources. Exergy stands for the maximal amount of work that can be retrieved from a resource when bringing it into equilibrium with the defined reference system which approximates the natural environment (Dewulf et al., 2008). CEENE was selected over other exergy-based impact methods because it offers the most comprehensive coverage of natural resources (Liao et al., 2012; Swart et al., 2015): fossil energy, nuclear energy, metal ores, minerals, water resources, land use, abiotic renewable resources (including wind power, geothermal energy and hydropower) and atmospheric resources. For each of these categories, the cumulative resource extraction is quantified and expressed in megajoules of exergy ( $\text{MJ}_{\text{ex}}$ ).

#### 2.4.2. Resource efficiency indicators

The impact assessment results will be used in the recyclability benefit rate (RBR) indicator concept (Ardenne and Mathieux, 2014). This indicator is defined as the ratio of the potential environmental savings that can be achieved from recycling the product over the environmental burdens of virgin production followed by disposal:

$$\text{RBR}_n = \frac{\sum_{j=1}^P \sum_{i=1}^N m_{\text{recyc},i,j} \text{RCR}_{i,j} (V_{n,i,j} + D_{n,i,j} - R_{n,i,j})}{\left( \sum_{j=1}^P \sum_{i=1}^N m_{i,j} V_{n,i,j} + M_n + U_n + \sum_{j=1}^P \sum_{i=1}^N m_{i,j} D_{n,i,j} \right)} \quad (1)$$

where the  $\text{RBR}_n$  is the recyclability benefit rate for the  $n^{\text{th}}$  impact category,  $m_{i,j}$  is the mass of the  $i^{\text{th}}$  material of the  $j^{\text{th}}$  part of the product [kg],  $D_{n,i,j}$  is the impact of disposing 1 kg of the  $i^{\text{th}}$  material of the  $j^{\text{th}}$  part [unit/kg],  $V_{n,i,j}$  is the impact of producing 1 kg of the  $i^{\text{th}}$  virgin material of the  $j^{\text{th}}$  part [unit/kg],  $R_{n,i,j}$  is the impact of producing 1 kg of the  $i^{\text{th}}$  recycled material of the  $j^{\text{th}}$  part [unit/kg],  $M_n$  is the impact of manufacturing the product [unit],  $U_n$  is the impact of the use phase of the product [unit],  $N$  is the number of materials in the  $j^{\text{th}}$  part of the product,  $P$  is the number of parts of the product and  $\text{RCR}_{i,j}$  is the recycling rate of the  $i^{\text{th}}$  material of the  $j^{\text{th}}$  part. The recycling rate is defined as the amount of recycled material produced per kg waste input when considering that part of the materials are lost during recycling.

### 3. Results and discussion

#### 3.1. Impact assessment results

##### 3.1.1. Case A: closed-loop recycling

Fig. 2 shows the environmental burdens and savings in terms of resource consumption (CEENE) related to the treatment of 1 kg of plastic waste extracted from a vacuum cleaner. The results are presented in a resource-contribution profile, showing how much each natural resource category contributes to the total environmental impact.

The positive part of the y-axis shows the environmental burdens of each scenario. The recycling scenario (A1) has an impact of  $11.39 \text{ MJ}_{\text{ex}}$  per kg waste, the incineration scenario (A2) has an impact of  $1.06 \text{ MJ}_{\text{ex}}$  per kg waste and the landfilling scenario (A3) has an impact of  $0.54 \text{ MJ}_{\text{ex}}$  per kg waste. In all of these scenarios, the main resource contribution comes from fossil fuels and nuclear energy, which mainly results from electricity consumption.

The negative part of the y-axis shows the environmental savings, which are the impacts that can be avoided by each treatment scenario. In the recycling scenario, the impact of producing 0.9 kg plastics from virgin resources can be avoided when taking the recycling rate into account. As an example, we consider the virgin production of 0.9 kg PS. This avoided impact has a value of  $85.32 \text{ MJ}_{\text{ex}}$ . The main resource contribution originates from fossil fuels because virgin PS is synthesized from crude oil. In the incineration scenario, the impact of producing 4.11 MJ of electricity from virgin resources can be avoided. This avoided impact has a value of  $12.60 \text{ MJ}_{\text{ex}}$ . In the landfilling scenario, no impact savings are noted in terms of resource consumption.

The net balance of environmental burdens versus savings is  $-73.93 \text{ MJ}_{\text{ex}}$  ( $=11.39 - 85.32 \text{ MJ}_{\text{ex}}$ ) for the recycling scenario,  $-11.64 \text{ MJ}_{\text{ex}}$  ( $=1.06 - 12.70 \text{ MJ}_{\text{ex}}$ ) for the incineration scenario and  $0.54 \text{ MJ}_{\text{ex}}$  ( $=0.54 - 0 \text{ MJ}_{\text{ex}}$ ) for the landfilling scenario. These net balances indicate that in this case study, recycling is the most resource efficient scenario.

##### 3.1.2. Case B: open-loop recycling

Fig. 3 shows the environmental burdens and savings in terms of resource consumption (CEENE) related to the treatment of 1 kg of waste from household plastics. The results are again presented in a resource-contribution profile.

The positive part of the y-axis shows the environmental burdens of each scenario. The environmental impact of the recycling

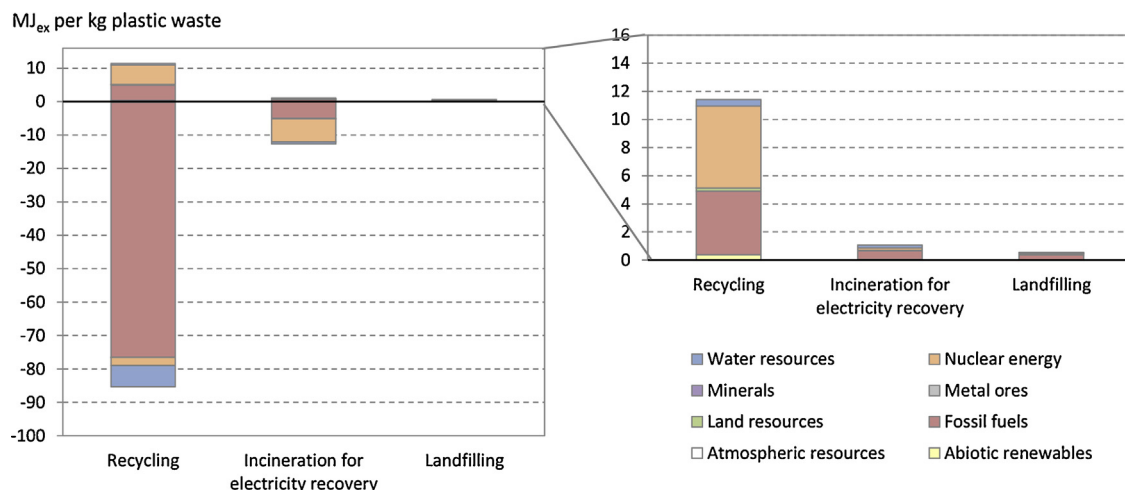
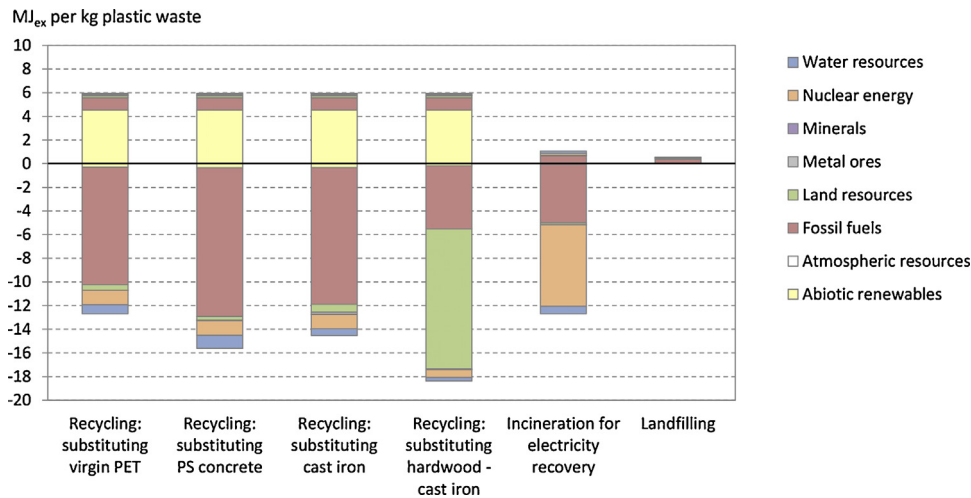


Fig. 2. Environmental burdens and savings related to the treatment of 1 kg of plastic waste. The different treatment scenarios are recycling (A1), incineration (A2) and landfilling (A3). The positive y-axis shows the environmental burdens and the negative y-axis shows the environmental savings for each treatment scenario.



**Fig. 3.** Environmental burdens and savings related to the treatment of 1 kg of plastic waste. The different treatment scenarios are open-loop recycling (B1), incineration (B2) and landfilling (B3). The positive  $y$ -axis shows the environmental burdens and the negative  $y$ -axis shows the environmental savings for each treatment scenario.

scenario (B1) is  $5.96 \text{ MJ}_{\text{ex}}$  per kg waste. Because Ekol uses a green electricity mix based on a European Guarantee of Origin for electricity from renewable resources (Directive 2009/28/EC, 2009), the main resource contribution comes from wind energy and hydropower. The environmental impacts of the incineration scenario (B2) and the landfilling scenario (B3) are identical to case A:  $1.06 \text{ MJ}_{\text{ex}}$  per kg waste and  $0.54 \text{ MJ}_{\text{ex}}$  per kg waste, respectively.

The negative part of the  $y$ -axis shows the environmental savings. These are the environmental impacts avoided by each treatment scenario. In the recycling scenario, different avoided impacts are possible. As mentioned earlier, 1 kg of waste delivers 0.8 kg of pellets. We will focus on the PE-PP pellets. If these pellets are used to produce a plant tray, then the substituted material is either 0.1 kg virgin PET or 1.1 kg virgin PS concrete. In the first case, the avoided impact is  $12.69 \text{ MJ}_{\text{ex}}$ , and in the second case, the avoided impact is  $15.61 \text{ MJ}_{\text{ex}}$ . The main resource contribution comes from fossil fuels, which are required to produce plastics from virgin resources. If the pellets are used to produce a street bench, the substituted material is either 0.5 kg cast iron or 0.3 kg hardwood (with a 0.2 kg cast iron pedestal). In the first case, the avoided impact is  $14.54 \text{ MJ}_{\text{ex}}$ . The main resource contribution comes from fossil fuels because of energy consumption. In the second case, the avoided impact is  $18.38 \text{ MJ}_{\text{ex}}$ . The main resource contribution comes from land resources, specifically wood extracted from nature.

In the incineration scenario, the avoided impact is the production of  $4.11 \text{ MJ}$  of electricity from virgin resources, which has a value of  $12.60 \text{ MJ}_{\text{ex}}$ . In the landfilling scenario, no avoided impacts are noted in terms of resource consumption.

The net balance of environmental burdens versus savings is  $-6.73 \text{ MJ}_{\text{ex}}$  ( $=5.96 - 12.69 \text{ MJ}_{\text{ex}}$ ) for recycling with the substitution of PET,  $-9.66 \text{ MJ}_{\text{ex}}$  ( $=5.96 - 15.61 \text{ MJ}_{\text{ex}}$ ) for recycling with the substitution of PS concrete,  $-8.59 \text{ MJ}_{\text{ex}}$  ( $=5.96 - 14.54 \text{ MJ}_{\text{ex}}$ ) for recycling with the substitution of cast iron,  $-12.42 \text{ MJ}_{\text{ex}}$  ( $=5.96 - 18.38 \text{ MJ}_{\text{ex}}$ ) for recycling with the substitution of the combination hardwood-cast iron,  $-11.64 \text{ MJ}_{\text{ex}}$  for incineration and  $0.54 \text{ MJ}_{\text{ex}}$  for landfilling. These net balances show that in this case study, recycling with the substitution of hardwood-cast iron is the most resource efficient scenario. Additionally, incineration appears to be more resource efficient than the other recycling scenarios. However, Ekol uses a green electricity mix (Directive 2009/28/EC, 2009), consuming mainly abiotic renewable resources (i.e., wind energy and hydropower). If these renewable resources are considered as freely available and thus not as an environmental impact, the

**Table 1**

Input for the calculation of the recyclability benefit rate of the vacuum cleaner. PS = polystyrene, ABS = acrylonitrile butadiene styrene, PP = polypropylene,  $m$  = mass (kg),  $V$  = impact of virgin production ( $\text{MJ}_{\text{ex}}/\text{kg}$ ),  $D_L$  = impact of landfilling ( $\text{MJ}_{\text{ex}}/\text{kg}$ ),  $D_I$  = impact of incineration minus the avoided impact of virgin electricity production ( $\text{MJ}_{\text{ex}}/\text{kg}$ ),  $R$  = impact of recycling ( $\text{MJ}_{\text{ex}}/\text{kg}$ ), RCR = recycling rate. (In Section 3.1.1, the impact of the recycling scenario was  $11.39 \text{ MJ}_{\text{ex}}$  per kg plastic waste. For the indicator, we require the impact  $R$  for the production of 1 kg of recycled plastics, which is calculated as  $11.39 \text{ MJ}_{\text{ex}}$  divided by the recycling rate).

Material	$m$	$V$	$D_L$	$D_I$	$R$	RCR
PS	1.96	94.80	0.54	-11.64	12.67	0.9
ABS	1.96	107.2	0.54	-11.64	12.67	0.9
PP	1.96	76.93	0.54	-11.64	12.67	0.9
Ferro	1.45	27.56	0.25	0.44	/	/
Non-ferro	2.25	55.52	0.25	0.78	/	/

open-loop recycling scenarios have the highest resource efficiency:  $-11.26 \text{ MJ}_{\text{ex}}$  for the substitution of PET,  $-14.19 \text{ MJ}_{\text{ex}}$  for the substitution of PS concrete,  $-13.12 \text{ MJ}_{\text{ex}}$  for the substitution of cast iron and  $-16.96 \text{ MJ}_{\text{ex}}$  for the substitution of hardwood.

Incineration and landfilling are finite scenarios, whereas open-loop recycling is not necessarily finite. Recycling delivers new products, which might in turn be recycled, incinerated or landfilled at the end of their life. This concept is called cascaded use, i.e., the use of the identical material for multiple successive applications (Höglmeier et al., 2014). Consequently, additional avoided impacts may occur for each recycling scenario, resulting in higher resource efficiencies. This will be further discussed in Section 3.2.2.

### 3.2. Indicator results

#### 3.2.1. Case A: closed-loop recycling

The impact assessment results are then used to calculate and evaluate the recyclability benefit rate indicator, see Eq. (1). Originally, the impact of disposal  $D$  in Eq. (1) refers to landfilling. However, incineration is also a possible disposal scenario. To provide a distinction, subscripts will be used:  $L$  refers to landfilling and  $I$  refers to incineration. Consequently,  $D_L$  is the impact of landfilling, whereas  $D_I$  is the impact of incineration minus the avoided impact of virgin electricity production (when applicable). The recyclable product is the vacuum cleaner, as described in Section 2. The required inputs for the calculation of the RBR indicator are summarized in Table 1. Because the focus of this study is on plastic waste, we did not consider recycling the metal fraction.

When the impact of the use phase of the vacuum cleaner is included (i.e., 19,793 MJ<sub>ex</sub> per vacuum cleaner), the resulting RBR is only 1.8% (in case  $D_1$ ) or 2.1% (in case  $D_L$ ). Because the impact of the use phase of an electronic device such as a vacuum cleaner is high resulting from electricity consumption, this results in a low RBR indicator. However, such a result can be misleading when compared to the products in case B (i.e., a plant tray and a street bench), for which the impact of the use phase is negligible. This result could give the impression that the recycling scenario in case B is much better than in case A, which is not necessarily correct. In our study, we excluded the impact of the use phase because the focus is on plastic waste treatment, in which the production and end-of-life are key. When the impact of the use phase  $U$  of the vacuum cleaner is excluded, the resulting RBR is 56% (in case  $D_1$ ) or 60% (in case  $D_L$ ). This result indicates that in terms of resource consumption, the environmental benefit of recycling all of the plastics in the vacuum cleaner is 60% relative to the virgin production followed by landfilling, and 56% relative to virgin production followed by incineration with electricity recovery.

### 3.2.2. Case B: open-loop recycling

The recyclability benefit rate in Eq. (1) is based on the assumption that the recycled material will be used to replace the identical material as in the original product. Therefore, this indicator cannot be used for open-loop recycling involving different materials and products, as in case B. Additionally, the indicator is not suitable for cascaded use (as introduced in Section 3.1.2). To overcome these issues, we further developed the indicator to be more comprehensive and suitable for open-loop recycling and cascaded use involving different materials and products. To draw a clear distinction, the new indicator is named ‘the open-loop recyclability benefit rate’ (RBR<sub>OL</sub>).

A simplified version of the current indicator is given in Eq. (2). The denominator describes the environmental burdens of the product that is going to be recycled, further called product  $\alpha_0$ , and the numerator describes the environmental savings obtained from the recycling of product  $\alpha_0$ . The impacts of manufacturing and use were left out because they were assumed to be negligible for the basic products (plant tray and street bench) in case B.

$$RBR = \frac{RCR(V_{\alpha_0} + D_{\alpha_0} - R_{\alpha_0})}{V_{\alpha_0} + D_{\alpha_0}} \quad (2)$$

We further developed Eq. (2) to include open-loop recycling. This RBR<sub>OL</sub> indicator is presented in Eq. (3) for a one-step cascaded use, indicating that product  $\alpha_0$  is recycled into product  $\alpha_1$ . Eq. (4)

provides a general expression for  $n$ -step cascaded use, indicating that product  $\alpha_0$  is recycled  $n$  times until product  $\alpha_n$  is obtained.

$$RBR_{OL,1} = \frac{RCR \left( \frac{m_{v,\alpha_1}}{m_{r,\alpha_1}} V_{\alpha_1} - R_{\alpha_0 \rightarrow \alpha_1} + D_{\alpha_0} \right)}{V_{\alpha_0} + D_{\alpha_0}} \quad (3)$$

$$RBR_{OL,n} = \frac{\sum_{i=1}^n \left( RCR^i \left( \frac{m_{v,\alpha_i}}{m_{r,\alpha_i}} V_{\alpha_i} - R_{\alpha_{i-1} \rightarrow \alpha_i} \right) \right) + RCR^n (D_{\alpha_0})}{V_{\alpha_0} + D_{\alpha_0}} \quad (4)$$

Eq. (3) and (4) will be explained using Fig. 4, which is an example of 1-step ( $n=1$ ) and 2-step cascaded use ( $n=2$ ). Here, product  $\alpha_0$  is 1 kg of household plastics. The denominator describes the environmental burdens of product  $\alpha_0$ , which are the impact of virgin production,  $V_{\alpha_0}$ , and the impact of disposal,  $D_{\alpha_0}$ . At the end of its life, product  $\alpha_0$  is recycled by Ekol with a recycling rate, RCR, of 80%, delivering 0.8 kg of PE-PP pellets. These PE-PP pellets are used for product  $\alpha_1$ , which is a plant tray. To produce one plant tray, 140 kg of recycled PE-PP is required ( $m_{r,\alpha_1}$ ). However, the ‘virgin alternative’ of this plant tray would be produced from 19 kg of PET ( $m_{v,\alpha_1}$ ). Therefore, 1 kg of recycled PE-PP can substitute for 0.14 kg ( $= \frac{19}{140} = \frac{m_{v,\alpha_1}}{m_{r,\alpha_1}}$ ) virgin PET, or 0.8 kg of recycled PE-PP can substitute for 0.11 kg ( $= \frac{0.8 \times 19}{140} = \frac{RCR \times m_{v,\alpha_1}}{m_{r,\alpha_1}}$ ) virgin PET. This value is multiplied with the avoided impact  $V_{\alpha_1}$  related to the virgin production of 1 kg PET.

At the end of its life, product  $\alpha_1$  can also be recycled by Ekol. A recycling rate of 80% results in 0.64 kg of PE-PP pellets. The pellets are used to make product  $\alpha_2$ , which is a street bench. To produce one street bench, 95.5 kg of recycled PE-PP is required ( $m_{r,\alpha_2}$ ). However, the ‘virgin alternative’ of this street bench would be produced from 63 kg cast iron ( $m_{v,\alpha_2}$ ). Therefore, 1 kg of recycled PE-PP can substitute for 0.66 kg ( $= \frac{63}{95.5} = \frac{m_{v,\alpha_2}}{m_{r,\alpha_2}}$ ) virgin cast iron, or 0.64 kg of recycled PE-PP can substitute for 0.42 kg ( $= \frac{0.64 \times 63}{95.5} = \frac{RCR^2 \times m_{v,\alpha_2}}{m_{r,\alpha_2}}$ ) virgin cast iron. This value is multiplied with the avoided impact  $V_{\alpha_2}$  related to the virgin production of 1 kg of cast iron. Further, the impact of the recycling process, which is identical for both steps, is now counted twice because both products  $\alpha_0 (R_{\alpha_0 \rightarrow \alpha_1})$  and  $\alpha_1 (R_{\alpha_1 \rightarrow \alpha_2})$  are recycled.

Table 2 presents several open-loop recyclability benefit rates for one- and two-step cascaded use in case B. A complete list with all possible scenarios for two-step cascaded use can be found in the Supplementary Information. These benefit rates represent the ratio of the environmental savings over the environmental burdens for virgin production followed by disposal, which can be either

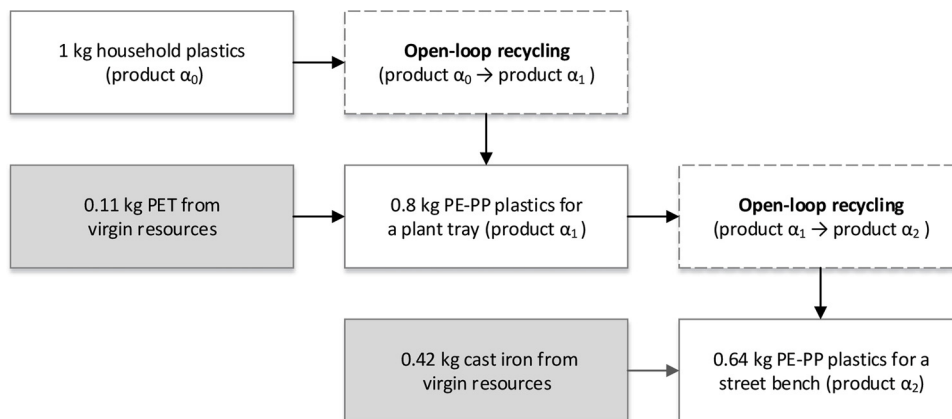


Fig. 4. Example of two-step cascaded use in case B. PE = polyethylene, PP = polypropylene, PET = polyethylene terephthalate. The grey colored blocks are the materials for which the virgin production can be avoided.

**Table 2**

Open-loop recyclability benefit rates for one- and two-step cascaded uses in case B. PS = polystyrene, PET = polyethylene terephthalate.  $L$  = disposal is the impact of landfilling,  $I$  = disposal is the impact of incineration minus the avoided impact of virgin electricity production.  $L^*$  = identical to  $L$ , but the abiotic renewable resources are considered freely available,  $I^*$  = identical to  $I$ , but the abiotic renewable resources are considered freely available.

Open-loop recycling: one-step cascade				
Possible scenarios for avoided product $\alpha_1$	$L$	$I$	$L^*$	$I^*$
Plant tray (PET)	10%	-2%	15%	3%
Plant tray (PS concrete)	14%	2%	18%	8%
Street bench (cast iron)	13%	1%	17%	6%
Street bench (hardwood)	17%	6%	22%	12%
Open-loop recycling: two-step cascade				
Possible scenarios for avoided products $\alpha_1$ and $\alpha_2$	$L$	$I$	$L^*$	$I^*$
Plant tray (PET) – plant tray (PET)	18%	10%	26%	19%
Plant tray (PS concrete) – street bench (cast iron)	24%	16%	32%	26%
Street bench (cast iron) – plant tray (PS concrete)	23%	16%	31%	26%
Street bench (hardwood) – street bench (hardwood)	31%	25%	39%	34%

landfilling ( $L$ ) or incineration with electricity recovery ( $I$ ). The benefits increase when abiotic renewables resources, coming from the green electricity mix of Ekol, are considered as freely available and thus not as an environmental impact ( $L^*$ ,  $I^*$ ). For the one-step cascaded use, the open-loop recyclability benefit rate varies between 15–22% ( $L^*$ ) and between 3 and 12% ( $I^*$ ). The benefit of recycling is higher relative to landfilling ( $L^*$ ) than incineration ( $I^*$ ). This could also be derived from Fig. 3. For the two-step cascaded use, the open-loop recyclability benefit rate varies between 26 and 39% ( $L^*$ ) and between 19 and 34% ( $I^*$ ). This result shows that cascaded use increases the recyclability benefit rate.

#### 4. Conclusions

In this article, we studied the applicability of the recyclability benefit rate indicator concept in two plastic waste treatment cases: closed-loop recycling (case A) and open-loop recycling (case B). Both cases were compared with an incineration scenario and a landfilling scenario. As an environmental impact assessment method, the CEENE methodology (Cumulative Exergy Extraction from the Natural Environment) was used. The impact assessment results present the environmental burdens and savings per kg plastic waste in terms of resource consumption for each scenario. In case A, the net balance of environmental burdens versus savings showed that closed-loop recycling is more resource efficient than incineration and landfilling. Additionally, in case B, the net balances showed that when the abiotic renewable resources used for the green electricity mix are considered as freely available, the open-loop recycling scenarios are the most resource efficient.

These impact assessment results were used to calculate the recyclability benefit rate indicator, which is based on LCA practices. However, the current indicator is only applicable when the recycled materials are used to replace the identical materials as in the original product. Consequently, this indicator could be calculated for case A but not for case B. To overcome this issue, we further developed the indicator for open-loop recycling and cascaded use among different materials and products. To develop a distinction, the new indicator was named the 'open-loop recyclability benefit rate' ( $RBR_{OL}$ ). The RBR of case A varies between 56 and 60%, whereas the  $RBR_{OL}$  of case B varies between 3 and 22% for one-step cascaded use and 19–39% for two-step cascaded use when the abiotic renewable resources are considered as freely available.

These indicators provide quantitative results that might be useful for policy makers. First, the results show that the recycling of these two plastic waste flows in Flanders is more resource efficient than incineration or landfilling. Second, the results show that cascaded use can increase the benefit rate of open-loop recycling. Policy makers could implement these indicator results in

the legislation of subsidies and taxes for plastic waste management. A possible option is a refunded tax, which uses the revenues of disposal taxes to subsidize closed-loop recycling, whereas the open-loop recycling remains unaffected (Dubois, 2013). Therefore, the government can stimulate companies to select one waste treatment over another. Specifically for case B, policy makers could encourage administrative divisions such as municipalities to purchase products (e.g., street furniture) comprised of recycled plastics produced by local recyclers by introducing specific criteria in Green Public Procurement schemes. This is relevant not only from an environmental perspective but also from a social perspective: several studies have already highlighted that recycling provides more jobs than landfilling and incineration (FOE, 2010).

Several challenges remain for future research. For example, the new open-loop recyclability benefit rate indicator does not yet consider the final step in cascaded use, i.e., incineration or landfilling. They could be further developed to also include this final step. Further, the lifetime was not considered, i.e., how long the recycled plastics last when compared to their virgin alternatives. Finally, an economic analysis, e.g., a cost-benefit analysis, could complement our environmental analysis for policy making.

#### Disclaimers

The authors declare no competing financial interests. The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

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#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.resconrec.2015.05.014>

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