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Performance indicators for a circular economy: A case study on post-industrial plastic waste

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ABSTRACT

A linear economy approach results in many environmental challenges: resources become depleted and end up as waste and emissions. One of the key strategies to overcome these problems is using waste as a resource, i.e. evolving toward a circular economy. To monitor this transition, suitable indicators are needed that focus on sustainability issues whilst taking into account the technical reality. In this paper, we develop such an indicator to quantify the circular economy performance of different plastic waste treatment options. This indicator is based on the technical quality of the plastic waste stream and evaluates resource consumption by using the Cumulative Exergy Extraction from the Natural Environment (CEENE) method. To illustrate the use of this new indicator, it was applied in a case study on post-industrial plastic waste treatment. The results show that the indicator can be a very useful approach to guide waste streams towards their optimal valorization option, based on quality of the waste flow and the environmental benefit of the different options.

1. Introduction

The transition towards a more sustainable society is a complex task. One of the key strategies to manage this transition is the circular economy concept. Preston (2012) defined the idea of a circular economy as follows: "*open production systems – in which resources are extracted, used to make products and become waste after the product is consumed – should be replaced by systems that reuse and recycle resources and conserve energy*". This idea has been implemented in several governmental policies, with Japan and Europe at the forefront. The Japanese government introduced the material-cycle society vision in the year 2000. This vision involves a number of laws based on the 3R (reduce, reuse, recycle) principle (Government of Japan, 2010). Recent strategies in the European Union (EU) are the 'Zero waste programme for Europe' (EC (European Commission), 2014) and 'Closing the loop action plan for the Circular Economy' (EC (European Commission), 2015).

An important material that still can be improved within the circular economy is plastic, as also confirmed in the recent report *The New Plastics Economy: Rethinking the future of plastics* (World Economic Forum, 2016). Indeed, the role of plastics in our daily life cannot be underestimated. Ever since the production of Bakelite in 1907, the importance of plastics in society kept growing. In 2014, the global production of plastic was 311 million tonnes. Europe is the second largest producer of plastic materials, responsible for 20% of the world production. Packaging applications are the largest application sector, representing 39.6% of the total plastics demand (Plastics Europe, 2015).

However, the problem is that all these plastics end up as waste. In 2014, Europe produced 25.8 million tonnes of post-consumer plastics waste: 29.7% was recycled, 39.5% was incinerated with energy recovery, and 30.8% was landfilled. Landfill of plastic waste may cause environmental problems, as plastics are often not biodegradable. Further, there is also the problem of resource conservation. The production of plastics consumes yearly 4 to 8 % of the global crude oil extraction (Kreiger et al., 2014). If plastics are disposed instead of being recycled, these resources are lost (EC (European Commission), 2013).

Hence, the role of plastic waste is a major issue in circular economy strategies. To monitor plastic waste treatment management, suitable indicators are needed. In the current policies, most indicators are situated at the macro-economic level (countries, regions),

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for example in the Japanese 3R-policy (Takiguchi and Takemoto, 2008). Fewer indicators are situated at the micro-level (products, companies). One example is the recyclability benefit rate (RBR) indicator, developed by the European Commission's Joint Research Centre (JRC) (EC-JRC, 2012; Ardente and Mathieux, 2014), which is based on an LCA-approach (Life Cycle Assessment). It is defined as the ratio of the environmental benefits that can be obtained from recycling a product, over the environmental burdens related to production from virgin resources followed by disposal. These benefits and burdens are expressed in terms of environmental impacts, calculated through LCA. In our previous work, this indicator was further developed for open-loop recycling systems (Huysman et al., 2015).

The report of JRC (EC-JRC, 2012) suggested also an alternative version of the RBR indicator, attempting to take the quality loss occurring during recycling into account. Indeed, once plastics have gone through a recycling process, they most often have no longer the properties they had in their original virgin state. This is due either to thermo-mechanical degradation during (re-)processing or to the fact that the plastics get mixed with other types during the recycling process (Ignatyev et al., 2014). To bring this potential quality loss into account, the report proposes to use a quality factor that is defined as the ratio of the quality of the recycled material over the quality of the virgin material.

The measurement of quality however is a difficult issue, which has no common understanding in the scientific community. The report suggests that this quality can be measured through physical parameters (e.g. the tensile strength) or economic parameters (e.g. market price) (EC-JRC, 2012). In most cases, the price of the recycled material versus the virgin material is used, as described in the work of Villalba et al. (2002). Nonetheless, the use of monetary values has its disadvantages, as market values and prices fluctuate heavily over time. Problems may also arise when prices are missing or distorted, e.g. monopolies, or when there are government interventions, e.g. subsidies (Ardente and Cellura, 2011). Physical parameters on the other hand are independent from changes in the economy. However, they are rarely applied, as is it difficult to determine a suitable physical parameter for each material type, and it is another research field.

Another issue is the implementation of the quality factor in the formula of the RBR indicator. With this indicator, treatment of lower quality waste always has a lower benefit, regardless of how it is valorized. As a result industries that process waste of lower quality would always get a low result whereas the responsibility of the quality of the waste is mainly determined by the preceding production and application. From a perspective of waste valorization benefits, it would be more adequate to use the quality factor as a classification tool, to select the most suitable waste treatment option according to the quality of the plastic waste flow.

Therefore, the objective of this paper is to develop a circular economy performance indicator, defined as the ratio of the actual obtained environmental benefit (i.e. of the currently applied waste treatment option) over the ideal environmental benefit according to quality for this flow. Similar to the RBR indicator, these benefits can be quantified in terms of environmental impacts, calculated through LCA. From a historical perspective, the focus in LCA is on impacts related to emissions. In this paper, the focus is shifted to natural resources, as these are more relevant in the context of a circular economy. Therefore, we selected the CEENE (Cumulative Exergy Extraction from the Natural Environment) method, quantifying resource consumption (Dewulf et al., 2007).

The possible waste treatment options (closed-loop recycling, semi closed-loop recycling, open-loop recycling and incineration) are discussed more detailed in the Materials & Methods sections. To determine the most suitable waste treatment option from a technical point of view, we developed a quality factor for plastic waste, based on a physical parameter: the compatibility between the composing polymers in the mix, which plays a major role in the resulting mechanical properties of the polymer blend (Koning et al., 1998).

Finally, the use of the indicator is illustrated with a case study on plastic waste treatment. There are broadly two types of plastic waste to be dealt with: post-consumer waste, which is generated by end-users, e.g. households, and post-industrial (or pre-consumer) waste, which is generated during the manufacturing phase (Reynolds and Pharaoh, 2010). This is similar to the distinction made in steel industry: old scrap consists of used goods (e.g. vehicles, machine parts), while new scrap is generated during steel production (Bilitewski et al., 1997). Most research is focused on post-consumer waste. Examples are the studies on packaging waste recycling systems in Portugal (Ferreira et al., 2014) and in Istanbul (Yıldız-Geyhan et al., 2016). Other examples are the studies of Simon et al. (2016) and Tonioli et al. (2013), which are focused on the recycling of beverage bottles. However, case studies on the recycling of post-industrial plastic waste are more limited. Therefore, the indicator will be demonstrated in a case study on post-industrial plastic waste treatment.

2. Materials and methods

2.1. Development of the indicator

2.1.1. Possible waste treatment options

The ISO 14044 standard makes a distinction between two types of recycling: closed-loop recycling occurs when 'a material from a product is recycled in the same product system', open-loop recycling occurs when 'a material from one product system is recycled in a different product system'.

However, in this classification, the link with the material quality is missing. Therefore, we propose the following classification for the possible waste treatment options: if the plastic is of high quality, it can substitute the virgin original material in a 1:1 ratio (closed-loop recycling, option I). If the quality is lower, there are two possibilities: (1) the recycled material can still substitute the original virgin material, but not in a 1:1 ratio, as additional virgin material has to be added to meet the same quality requirements (semi closed-loop recycling, option II); (2) the recycled plastic can only be used in low-grade applications, in which it substitutes different types of materials (open-loop recycling, option III). In the worst case scenario, if the quality is extremely low, the waste can only be incinerated for energy recovery (incineration, option IV) (Fig. 1).

2.1.2. Calculating the performance indicator

For each of these waste treatment options, it is possible to calculate the 'circular economy performance indicator' (CPI). This paper defines the CPI as the ratio of the actual obtained environmental benefit (i.e. of the currently applied waste treatment option) over the ideal environmental benefit according to quality, the latter being the benefit of the waste treatment option to which the stream should be directed according to its composition/quality with a minimal required effort, assuming option I (closed-loop recycling) is better and option IV (incineration) is less preferable:

$$CPI = \frac{actual\ benefit}{ideal\ benefit\ according\ to\ quality}$$

These environmental benefits are expressed in terms of natural resource consumption, which can be calculated by Life Cycle Assessment, for example by using the CEENE method as LCIA.

In option I (closed-loop recycling), the recycled material has the potential to substitute the original virgin material (α) in a 1:1 ratio. For example, 1 kg recycled PE substitutes 1 kg virgin PE. However,