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Circular economy: To be or not to be in a closed product loop? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements

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ABSTRACT

Packaging, representing the second largest source of aluminium scrap at global level, deserves a key role in the transition towards the circular economy. Life Cycle Assessment (LCA) of aluminium products has been typically based on one life cycle considering pure aluminium flows and neglecting the presence of alloying elements and impurities. However, this simplification undermines the potentials of using LCA to quantify the environmental performances of products in multiple loops, as required in the circular economy. This study aims to investigate the effects of including the actual alloy composition in the LCA of aluminium can production and recycling, in order to understand whether a can-to-can (i.e. closed product loop) recycling should be promoted or not. Mass balance of the main alloying elements (Mn, Si, Cu, Fe) was carried out at increasing levels of recycling rate, corresponding to a temporal interval of five years. Different aluminium packaging scrap sources were considered: mixed packaging aluminium scrap and used beverage can scrap. The outcomes of the mass balance were used to quantify the amount of Mn and primary Al that needs to be reintegrated in each scenario according to the recycling rate and this information was further used to perform an LCA of 30 loops of aluminium can production and recycling, based on the actual alloy composition. The LCA revealed that the closed product loop option (considering used beverage can scrap) has lower climate change impacts over the other recycling scenario using mixed Al packaging scrap. The main recommendation from an LCA methodological point of view is to include the idea of multiple co-functions in the functional unit definition. To further improve the environmental performances of the aluminium beverage can sector towards circular economy implementation the key actions are: to reduce the weight of the lid, to develop methods to separate the body and lid at the point of collection, and to investigate the potentials of a closed supply chain loop for aluminium cans in terms of combined environmental and economic value creation.

1. Introduction

The aluminium industry, as part of the metal industry, is committed to reduce its emissions and energy consumption in the future towards a more sustainable sector (Liu and Muller, 2012). Aluminium production is indeed responsible for approximately 1.1% of global greenhouse gases (GHG) (IEA, 2009) and may in the future become limited by access to energy (Sverdrup et al., 2015). The generation of solid waste during aluminium production represents a further element of concern both for aluminium industry and society (EAA, 2013).

The largest reduction potential in energy use and GHG emissions is provided through recycling of post-consumer scrap, also called old scrap, which is available mainly in the form of Used Beverage Cans (UBC) and end-of-life (EoL) vehicles (Liu et al., 2012). Aluminium post-consumer scrap is a raw material commodity traded at global level (EAA, 2006), which deserves a key role towards the shift from a linear to circular economy (Sevigné-Itoiz et al., 2014). According to the Ellen MacArthur Foundation (EMF) definition, the circular economy aims to decouple economic growth from resource

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Abbreviations: BAU, business as usual; C2C, Cradle to Cradle® design framework; CR, collection rate; EAA, European Aluminium Association; EoL, end-of-life; FU, functional unit; GHG, greenhouse gases; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; MAP, mixed aluminium packaging; PEF, Product Environmental Footprint; RC, recycled content; RE, renewable energy; RR, recycling rate; UBC, used beverage can; $Y_{pre\text{-}proc}$, yield during pre-processing; Y_{remelt}, yield during remelting.

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constraints by maximizing use of residuals (EMF, 2013). Circular economy can be implemented at different levels, from a single company perspective to a value chain approach, to the global economy. Different overlapping concepts inspired the above-mentioned definition of circular economy, making it a broad vision that has a strong focus on the business strategy (CIRAIG, 2015). Besides the market aspects, efficient collection systems need to be built to capture the materials value of goods that are consumed far from their point of origin, as well as design better combinations of goods and packaging, and dramatically increase the attention management gives to recovering value in the post-use stages of the supply chain (EMF, 2013).

Packaging represents the second largest source of aluminium scrap at global level (Muchová and Eder, 2010). In the context of the EU action plan for the circular economy (EC, 2015a), clear targets for waste reduction are presented in the revised legislative proposals on waste, including a common EU target for recycling 75% of packaging waste by 2030 (EC, 2015b). To achieve higher recycling targets, lots of efforts have been put so far on the eco-efficiency concept, i.e. "making more with less", to reduce the GHG emissions in many metals using sectors, e.g. increasing the automotive (van Renssen, 2011) and packaging waste collection (Rigamonti et al., 2010). However, in the case of aluminium according to Rombach (2013) "*an increase in the efficiency of scrap collection has a significantly smaller impact on the relative availability of secondary raw materials than the growth in future demand for aluminium*". At the same time, even though the globalization of post-consumer aluminium scrap market could allow greater GHG savings, e.g. under Spanish conditions (Sevigné-Itoiz et al., 2014), the export of post-consumer aluminium scrap is against the objectives of the circular economy. Companies in the beverage packaging sector were among the pioneers in the adoption of eco-efficiency based methodologies to reduce the environmental impacts of their products. They have gained an extensive experience in the implementation of Life Cycle Assessment (LCA) methodology (UNEP and SETAC, 2013). In the case of beer packaging, cans represented the second major packaging format (30%) in 2012 at European level, and nearly half of all cans produced in the EU was destined for the brewing sector (Berkhout et al., 2013). LCA is widely used by the aluminium industry to assess its achievement in terms of environmental sustainability goals (Liu and Muller, 2012), as well as to quantify the environmental performances of aluminium recycling (e.g. Paraskevas et al., 2015). Extensive work in the application of LCA for aluminium cans has been performed by both the aluminium industry (e.g. Stichling and Nguyen-Ngoc, 2009; EAA, 2013), as well as by beer and packaging manufacturers companies, either for comparing the environmental performances of different packaging (Cordella et al., 2008; Detzel and Mönckert, 2009) or to identify the hotspot in beer production (Talve, 2001; Koroneos et al., 2005). The most effective solution for reducing the environmental impacts of beer packed in aluminium cans pointed by LCA studies is an increase in collection rate (Detzel and Mönckert, 2009; Stichling and Nguyen-Ngoc, 2009). The adoption of the LCA methodology to quantify the potential environmental impacts of a product system avoids burden shifting, both in terms of life cycle stages and among different impact categories (ISO, 2006a, 2006b). Moreover, a reduction of packaging weight can be considered as a form of waste prevention activity, since less materials will have to be disposed at the end of life, and the environmental impacts deriving from the transport of lighter packaging (e.g. glass) are reduced (Nessi et al., 2013). However, increasing material efficiency represents only one driver for achieving a continuous flow of resources in circular material loops.

To implement the circular economy, a broader approach oriented towards product quality and innovation, i.e. the Cradle to Cradle® (hereafter C2C) design framework, can inspire companies in the beverage sector. The C2C vision, as one of the main conceptual pillars of the circular economy (CIRAIG, 2015), defines a framework for designing products and industrial processes that turn materials into nutrients by enabling their perpetual flow within one of two distinct metabolisms: the biological metabolism and the technical metabolism (Braungart et al., 2007). C2C is oriented towards an increase of the positive footprint of products by designing "eco-effective" solutions, i.e. maximizing the benefit to ecological and economic systems, differently from the eco-efficiency approach, which instead aims to reduce the negative impacts of products (Bjørn and Hauschild, 2013). The C2C design framework is based on three key principles "waste equal food", "use current solar income" and "celebrate diversity" (McDonough and Braungart, 2002). The first principle calls for eliminating the concept of waste by designing systems where waste and emissions can be taken up as nutrients by other processes instead of reducing the amount of waste as eco-efficiency advocates. Eco-effectiveness focuses on the development of products that maintain or enhance the quality and productivity of materials through subsequent life cycles (Braungart et al., 2007). One key aspect of the C2C design framework is the "upcycling" concept, i.e. increasing the value of materials by improving the quality of recycling and recycled material.

The differences in quality between the metal inputs and the produced secondary metals are usually not taken into account in conventional LCA studies. There are several types of losses connected with the recycling of metals, including aluminium (Castro et al., 2004; Amini et al., 2007; Nakamura et al., 2012; Paraskevas et al., 2015): (i) material losses, i.e. physical losses during scrap preparation and separating processes and melting losses; (ii) quality losses, i.e. due to mismatch between the composition of secondary material and input material requiring alloying elements to be added, and (iii) dilution losses, due to the dilution with primary aluminium to lower the concentration of contaminants to the desired limits of the target alloy. After analysing the influence of scrap quality on the environmental assessment of aluminium recycling, Paraskevas et al. (2015) concluded that container and packaging scrap can be perfectly managed in a separate closed loop recycling strategy for the same application. However, according to the European Aluminium Association (EAA), from an environmental point of view it doesn't matter whether used cans end up again in new cans or in other product systems (Labberton, 2011). This statement leads to think that from an environmental perspective there is no preferred option for the next use of recycled aluminium. The Life Cycle Inventory (LCI) modelling of aluminium processes is traditionally based on a pure aluminium flow, therefore neglecting the presence of alloying elements and impurities (EAA, 2013). This simplification can threaten the capability of LCA to objectively quantify the environmental performance of closed loop aluminium can recycling. The accumulation of impurities can indeed limit a continuous can-to-can recycling in the future, as demonstrated by Løvik and Mueller (2014). Increased recycling rates could potentially lead to an increase of the mass fraction of impurities in aluminium cans (Løvik and Mueller, 2014), but the influence of alloying elements (e.g. Si, Cu, Zn, Mg, Mn) accumulation on closed loop aluminium recycling has not yet been systematically assessed.

Therefore, the aim of this study is to answer the following Hamlet dilemma: "In the circular economy context is it better for aluminium cans to be or not to be in a closed product loop (can-to-can) from an LCA standpoint?" To answer this question we focused on including the effect of alloying elements on the LCA modelling of aluminium can recycling and structured the study in two parts. First, we performed a mass balance of the main alloying elements (Mn, Fe, Si, Cu) in aluminium can recycling at increasing levels of recycling rate. The analysis distinguished between different aluminium packaging scrap sources to understand the limiting factors for continuous aluminium recycling. Secondly, we performed an LCA of aluminium can production and recycling in multiple loops