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Environmental screening of novel technologies to increase material circularity: A case study on aluminium cans

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ABSTRACT

It is undisputed that the recycling of aluminium is desirable as long as the environmental and economic implications of its reintegration do not exceed the burdens of its primary production. The efficiency of any aluminium recycling system can be expressed by the total material losses throughout the entire process chain, ideally reaching 0%, thus equivalent to 100% metal recovery. However, in most cases metals are recycled in open/cascade recycling loop where dilution and quality losses occur. Innovations in aluminium beverage can (ABC) design as well as in sorting and recycling technologies have the potential to increase recyclability and avoid downcycling issues due to mixed alloy scrap streams. By means of Life Cycle Assessment (LCA) seven scenarios, comprising specific systemic changes, are compared to the current recycling practice of the used beverage can in the UK. The End-of-Life modelling of recycling is performed in accordance with the equal share method to account for impacts both on the recyclability and the recycled content. The results confirm the primary aluminium production and energy consumption in the ABC production as the hotspots in the life cycle of the ABC. The toxicity and energy-related impact categories show the highest susceptibility to increasing recycled content and recycling rate, while the technological novelties show little effect. In terms of abiotic resource depletion the introduction of novel technologies could have the potential to retain quality of the aluminium alloys by either establishing dedicated waste streams or upgrading the aluminium scrap by dedicated sorting strategies.

1. Introduction

Aluminium has diffused modern times like no other metal next to steel, and its production continues to grow with an average of 3.7% annually since 40 years (Bauxite Index, 2017). Its physical properties make it an ideal candidate for a large range of industries, from packaging to aerospace, from building and construction to automotive, among many others (EAA, 2017a). Both the primary and secondary production of aluminium is not uncritical. The former is associated with high energy consumption, resource depletion, and high material losses in the different life cycle stages (material production, semi-fabrication and part manufacturing process), as well as the generation of large volumes of bauxite residue (red mud). The latter faces issues with quality losses (when the purity-aluminium content of the produced material is lower than the input material, e.g. by the addition of alloying elements during re-melting) and dilution losses (addition of primary aluminium during re-melting to ‘dilute’ the concentration of the residual elements that cannot be refined during re-melting) due to a combination of: i) the uncontrolled mixing of scrap streams, ii) accumulation of impurities/tramp elements, and iii) limited melt purification options during re-melting (Paraskevas et al., 2015a). Further, secondary aluminium production is also affected by the high variety in the regional recycling rates (UNEP, 2011), negative social impacts depending on the geographical context (UNEP, 2013), and a potential scrap surplus once the current in-use stock becomes available for recycling (Modaresi and Müller, 2012). Several studies (e.g. Paraskevas et al., 2015b) highlight the fact that recycling of aluminium requires no more than 5% of the energy compared to primary production, hence presents a real opportunity to reduce environmental impacts, if managed in a sustainable way.

The circularity of any aluminium recycling system can be expressed by the total material losses throughout the entire process chain, ideally reaching 0%, thus equivalent to 100% material efficiency. Material circularity, as used in the context of this study, refers to a closed material loop, i.e. recycling of the material into the same product, e.g. remelting of used beverage cans (UBC) to produce new aluminium

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beverage cans (ABC). Various factors contribute to material circularity in a recycling system (adapted from Hagelüken, 2007). First, it depends on technical factors that determine the process capability (e.g. recovery of specific alloy series) and installed capacity for material recovery. Second, societal and legislative factors motivate or oblige stakeholders to provide the necessary infrastructure or initiate public campaigns to stimulate a 'recycling culture' (i.e. consumer awareness and behaviour). Finally, economic factors play a vital role by creating the incentive for recycling at the consumer level (e.g. deposit schemes) or scrap values (e.g. informal recycling sector). Even though the ultimate target may be a closed material loop, it should be acknowledged that in reality a fully closed material loop is likely to be impossible to achieve. According to UNEP (2013, p.93) "*There will always be a slight loss of metals due to imperfections in the systems and many other aspects, such as thermodynamics, technology, human error, politics, theft and economics*."

Its physical characteristics make aluminium an ideal material for a range of packaging solutions. As a result, packaging industry absorbs nearly 17% of the aluminium output, ranking third behind the construction and transportation industries in Europe (EAA, 2017b). The ABC is one of the most widespread form of packaging in Europe, with an output exceeding 64 billion ABCs in 2015, to which the market within the United Kingdom of Great Britain and Northern Ireland (UK) contributes with an annual production of almost 10 billion ABCs (BCME, 2016).

Life Cycle Assessment (LCA) is a scientific methodology that has been successfully applied to quantify the potential environmental impacts of beverage packaging in general (Van der Harst et al., 2016; Saleh, 2016; Simon et al., 2015), and the ABC in specific (Stichling and Nguyen-Ngoc, 2009; Niero et al., 2016; Niero and Olsen, 2016). Niero et al. (2016) have conducted a scenario-based LCA on the ABC in the UK market with varying recycled content and renewable energy consumption. Niero and Olsen (2016) performed a simulation of a closed loop scenario with reintegration of different sources and amounts of packaging scrap (mixed packaging scrap and UBC) in order to determine the effect on the alloying components. Main conclusion of the latter study was that the incorporation of alloying elements/composition of the metal streams into the LCA has a significant effect on the impact results and should consequently be considered (Paraskevas et al., 2013).

The present study investigates the potential increase of material circularity by employing novel sorting and recycling technologies. It considers mainly the conditions in Europe and focuses in particular on the UK, where the introduction of such novel technologies could lead to a substantial improvement of the purity of the waste stream.

1.1. Aluminium beverage cans in the UK context

The standard ABC is composed of a *body* (i.e. the container) and an *end*, in which the opening is punched and the tab riveted. The coil manufacturer supplies the respective aluminium sheets for the body (AA3004) and the end (AA5182). Production scrap is routed back to the coil supplier for recycling, hence is already managed in a closed loop (Stichling and Nguyen-Ngoc, 2009). Body and end are subsequently transported to the beverage producer, who fills and seams the ABC, and sells the product to the consumer through a distribution network of wholesalers and retailers.

Two individual collection schemes for used beverage cans (UBC) are implemented in the UK (Seyring et al., 2016). While any household may dispose of its UBC with a co-mingled waste stream (joint collection of plastic, metal and glass packaging), Every Can Counts, a UK-based partnership between drink can manufacturers and the recycling industry, has introduced bring-point solutions for a variety of organisations at which the UBC is collected separately (http://www.everycancounts.co.uk/). Mixed packaging scrap from households undergoes a sequence of sorting steps separating glass and plastic from the metal fraction, which is further sorted into ferrous and non-ferrous metals. The non-ferrous fraction is subject to additional sorting to separate heavy metals from aluminium (ALFED, 2017). The aluminium scrap at this point contains a mix of cast and wrought aluminium alloys, with high and low compositional tolerances in alloying element concentration respectively. This mixed alloy steam is mostly absorbed in the cast alloy production, which results in downcycling of the wrought scrap fraction to cast alloy. This form of recycling is commonly described in literature as "cascade recycling" or "downrecycling" or "open loop recycling", as there is an accumulation of residual/alloying elements to lower purity alloy systems. Dilution losses on the other hand, occur when primary aluminium is added to reduce the concentration of residual elements in the scrap stream. Both dilution and quality losses during re-melting results in primary resource depletion (primary aluminium and alloying elements addition) and can be minimised by optimal material clustering prior re-melting (Paraskevas et al., 2015a).

1.2. Technological innovations in aluminium recycling

A wealth of research is dedicated to the improvement of aluminium recycling routes, and is primarily focussed on the pyrometallurgical re-melting route. Three main objectives can be derived from the state-of-the-art in recycling technologies: i) retention of the purity of the metal streams, ii) reduction of material losses in pre-processing (e.g. collection and sorting) and re-melting and further processing, iii) reduction in energy consumption in primary and secondary production. Main research topics are dross recycling (Bellqvist et al., 2015; Ingason and Sigfusson, 2014), refining/removal of specific alloying elements (Nakajima et al., 2011, 2012; Gesing et al., 2015), or sorting technologies and strategies (Gaustad et al., 2012; Nogueira et al., 2015; Takezawa et al., 2014). However, the reduction of material losses and energy consumption by incremental improvements seem to have reached a plateau after which only marginal savings are conceivable, hence opening the field for alternative technologies.

Two notable approaches promised to deliver great benefit, not only in decreasing material and quality losses, but also a reduction of greenhouse gas emissions. *Laser induced breakdown spectroscopy* (LIBS) is a sorting technology which has had its market introduction at Düsseldorf's Aluminium Trade Fair in 2016 and has the capability to sort specific wrought alloys (Steinert, 2016; Hegazy et al., 2013; Takezawa et al., 2014). Several companies have developed prototypes that prove the concept with reliable and repeatable results. The LIBS technology can be applied as extension of the current sorting infrastructure to produce alloy-specific scrap streams, hence providing the re-melter with a high-quality feedstock that minimizes the input of alloying elements and primary aluminium to dilute impurities (see Gaustad et al., 2012 for a discussion on sorting technologies). *Solid state recycling* (SSR) has been in research since 1945 (Stern, 1945), but has recently attracted increased attention as various methods and studies have proven its potential to complement the traditional re-melting route by solid state scrap processing of light metal scrap (Paraskevas et al., 2014; Paraskevas et al., 2016; Behrens et al., 2016; Shamsudin et al., 2016). Current SSR prototypes are able to process 'new' or production scrap into near net semi-products and profiles by hot processing aluminium scrap below melting point in addition to exposure to severe plastic deformation (e.g. via hot extrusion) and/or by diffusion bonding (e.g. via Spark Plasma Sintering) (Paraskevas et al., 2014; Paraskevas et al., 2016). While all studies use machining chips, a relatively clean and high quality feedstock, for the recycling step, it has to be seen to which extent the technology is able to deal with varying scrap size and impurities. The major benefit of SSR is the avoidance of unrecoverable material losses due to oxidation during remelting (approx. 5% and at the levels of 15% for fine form scrap) (Duflou et al., 2015). However SSR does not offer the possibility to readjust the alloy composition (i.e. scrap input equals output alloy) and consequently requires well defined or single alloy stream. None of the SSR technologies has been introduced to market today (Paraskevas et al., 2013).