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In-depth analysis of aluminum flows in Austria as a basis to increase resource efficiency

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ABSTRACT

Based on the method of material flow analysis (MFA), a static model of Austrian aluminum (Al) flows in 2010 was developed. Extensive data research on Al production, consumption, trade and waste management was conducted and resulted in a detailed model of national Al resources. Data uncertainty was considered in the model based on the application of a rigorous concept for data quality assessment. The model results indicated that the growth of the Austrian "in-use" Al stock amounts to 11 ± 3.1 kg yr^{-1} cap^{-1}. The total "in-use" Al stock was determined using a bottom-up approach, which produced an estimate of 260 kg Al cap^{-1}. Approximately 7 ± 1 kg of Al yr^{-1} cap^{-1} of old scrap was generated in 2010, of which 20% was not recovered because of losses in waste management processes. Quantitatively, approximately 40% of the total scrap input to secondary Al production originated from net imports, highlighting the import dependency of Austrian Al refiners and remelters. Uncertainties in the calculation of recycling indicators for the Austrian Al system with high shares of foreign scrap trade were exemplarily illustrated for the old scrap ratio (OSR) in secondary Al production, resulting in a possible range of OSRs between 0 and 66%. Overall, the detailed MFA in this study provides a basis to identify resource potentials as well as resource losses in the national Al system, and it will serve as a starting point for a dynamic Al model to be developed in the future.

1. Introduction

Because of its manifold material properties (e.g., lightweight, flexibility, corrosion resistance and conductibility) Al is the most widely applied metal after iron (Recalde et al., 2008). Especially with regards to innovative (lightweight) transportation concepts (e.g., electric vehicles and aviation) aiming at the reduction of environmental impacts of public and private mobility, Al is a promising material for breaking the weight spiral (Hirsch, 2011). Despite the fact that Al is the third most abundant element in the Earth's crust (after oxygen and silicon) and known Al reserves (in the form of bauxite ore) will last at least for 200 years at current consumption rates (UNEP, 2011), secondary Al production is becoming increasingly important. In addition to high savings of emissions (e.g., fluorides, perfluorocarbons, polyaromatic hydrocarbons, sulfur dioxide and carbon dioxide) (Moors, 2006), the production of secondary Al only requires 10% of the energy needed for primary production (Quinkertz et al., 2001). Thus, with regard to reducing energy consumption and emissions, facilitating Al recycling would be an adequate approach, however, with the percentage of secondary Al being limited by the ratio of available scrap and total (global) Al demand (Rombach, 2013). Nevertheless, companies in regions with restricted access to primary resources and strict environmental regulations (i.e., the European Union) already depend on the use of Al scrap to a large degree. Against the background of current resource policies, such as those of the European Union, which state that more efficient use of minerals and metals is crucial for heading toward a sustainable closed-loop economy (EU Commission, 2011), the share of secondary metals (including Al scrap) in the production process should further increase in the future.

In numerous research studies aiming to evaluate and improve resource efficiency on a global or national scale, material flow analysis (MFA) has been used (Bertram et al., 2009). This finding also applies also to Al, for which different investigations have been conducted in the last decade. Cullen and Allwood (2013), for instance, recently published their work on global Al flows in 2007, which mainly focused on raising material efficiency in Al production and manufacturing. Milford et al. (2011) further exemplified material

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efficiencies by analyzing production and processing of five different Al products. Dynamic MFA studies of the anthropogenic Al flows have been published for several countries. Chen and Graedel (2012b) presented a study for the U.S., Chen and Shi (2012) for the mainland of China, Dahlström et al. (2004) for the UK, Ciacci et al. (2013) for Italy and Liu and Müller (2013) published a study including 144 countries. Studies focusing specifically on one "in-use" sector have been carried out by Cheah et al. (2009) for the U.S. passenger vehicles and by Mathieux and Brissaud (2010) for commercial vehicles in Europe. In addition to quantitative Al balances, other MFA studies have also focused on material qualities. In Hatayama (2009), the current and future Al scrap flows according to the "in-use" sectors were calculated for Japan, China and the U.S. Hatayama (2007) analyzed the flows of alloying elements in Al goods to determine the maximum recycling rates of Al scraps. Potential limits in Al scrap recycling, especially for end-of-life vehicles, have also been analyzed by Modaresi and Müller (2012) and Løvik et al. (2014). The economic benefits of advanced sorting technologies in Al recycling were presented by Li et al. (2011). Furthermore, the MFA studies conducted provide a database for the calculation of greenhouse gas emissions along the Al life-cycle (Liu et al., 2013; Liu and Müller, 2013; McMillan, 2011). A comprehensive review on dynamic MFA methods to model metal stocks and flows was recently published by Müller et al. (2014).

Although numerous studies on global metal flows have been conducted, a detailed understanding of national material demand as well as consumption and usage patterns on a country level are crucial to evaluate and improve current and future resource efficiencies. Thus, it is the aim of this work to establish the Austrian Al budget for the year 2010 as a basis for anthropogenic resource management. Scrap flows differentiating between old, new and internal scrap are calculated, further a detailed analysis of the waste management system is carried out in order determine recycling efficiency and losses in Al scrap processing in the current system. Finally the "in-use" stock increase is calculated for the given year including considerations of packaging and EOL vehicle exports. Flows at every stage of the Al life-cycle are analyzed at a high level of detail, highlighting data limitations preventing higher resolution of the material flow model. With respect to establishing a national Al resource inventory, this work provides profound insights into how data can be gathered and checked for consistency.

In the first part of this work, the Austrian Al flow model is described in detail, followed by a description of the collection and characterization of MFA data. As many data from different sources with varying quality are integrated into the MFA model, a procedure for the systematic characterization of uncertainty is presented and applied to all material flow data. The resulting Al flows in Austria in 2010 are presented in Sankey style diagrams with special emphasis on Al flows in waste management and domestic secondary Al production. The results are discussed in view of scrap generation data from other European MFA studies and also with respect to determining robust resource efficiency indicators (i.e. recycling ratios) based on the information available about the Al budget. Finally, conclusions about the utility of MFAs on a national level for Al resource management and an outlook on future research activities are provided.

2. Materials and methods

2.1. Material flow analysis (MFA)

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within an arbitrarily complex system defined in space and time (Brunner and Rechberger, 2004). In general, MFA is used to quantitatively characterize the flows of a specific material into, within, and from a system (Chen and Graedel, 2012a). MFA can build on rather simple accounting schemes, static models, or sophisticated dynamic models (van der Voet, 2002), depending on the desired level of mechanistic understanding about material flows within the system to be included in the model. With respect to resource and recycling systems of metals and minerals, MFA has been typically used to connect the sources, the pathways, and the sinks of a material via static or dynamic models (Chen and Graedel, 2012a). Based on the law of the conservation of matter, the results of any MFA can be controlled by a simple material balance comparing all inputs, changes of stocks, and outputs of a process. MFA is performed using an iterative procedure continuously improving the quality of the material flow model and MFA data to arrive at an adequate description of the system.

In this study, the STAN software (Cencic and Rechberger, 2008; TU Vienna, 2013) was used to conduct the MFA, because it is a tailor-made MFA software including routines to consider uncertain quantities of material flows and perform data reconciliation in case of inconsistent input data (free download: www.stan2web.net). Uncertain quantities are expressed by the mean and the standard deviation, assuming a normal distribution (Cencic and Rechberger, 2008). In the case of over-determined systems (more balance equations than unknowns), data reconciliation is used to enforce mass balance constraints on conflicting input data, with quantities having high uncertainty being reconciled more strongly than quantities with low uncertainty (Laner et al., 2014). Subsequently, unknown variables, including their uncertainties, are computed using Gaussian error propagation. In addition, the material flows can be illustrated in Sankey-style diagrams with their width proportional to their value. STAN has been widely used to perform MFA on regional or plant level using models of different sophistication (e.g. Andersen et al., 2011; Dos Santos et al., 2012; Ott and Rechberger, 2012).

2.2. The Austrian aluminum balance

In this study, static MFA modeling (cf. Brunner and Rechberger, 2004) is used to investigate the flows of Aluminum within the geographical border of Austria for the balance year 2010. Only metallic Al flows are considered in this study, ignoring elemental Al contained in many other chemical compounds (e.g., industrial minerals such as kaolinite). Because of the focus on Al on the goods level, the alloying elements of Al are not addressed in this study, notwithstanding the fact that high concentrations of alloying elements could limit Al scrap recycling (Modaresi and Müller, 2012). All numbers given are on the basis of Al content and in 10^3 t (Mg).

In the established material flow model, the Al lifecycle is illustrated using five main stages, namely, production/processing, manufacturing/trade of semis, trade of Al-containing goods, "in-use" phase, and waste management (see Fig. 1). The main direction of Al flows is from production (left) to waste management (right). Imports into the system are presented from top and exports to bottom. As primary Al production in Austria stopped in 1993, production refers to the output of refiners and remelters of the secondary Al industry. The "production" stage represents the melting of secondary Al from scrap and imported unwrought metal.

The "production/trade" stage consists of several individual processes, including secondary production as well as rolling, extrusion and casting. The latter processes allow tracing single processing routes and of the Al related to different semi products. To allocate the flow of imported unwrought metal (potentially including slabs and billets in addition to ingot material for melting) to secondary Al production and processing, a separate process "imp. unwrought metal" is introduced. In addition to the production of semis (rollings, extrusions, and castings), the production of deoxidized Al for the steel industry and Al powders are considered within