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Analysis

Dynamic analysis of aluminum stocks and flows in the United States: 1900–2009

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ABSTRACT

A dynamic analysis of anthropogenic aluminum stocks and flows in the U.S. from 1900 to 2009 has been conducted. Key findings include (1) historical cumulative aluminum input into the U.S. anthroposphere amounts to 438 Tg, with only about 35% of it accumulating in domestic in-use stock; (2) less than 5% of most flows take place before 1950, while more than 50% of them happen after 1990; (3) flows into fabrication, manufacturing, and use processes, as well as trade flows, are vulnerable to energy crises; basically, after an energy crisis, the U.S. tends to produce less primary aluminum, less semis, as well as less final products, and therefore import less bauxite and alumina but import more unwrought aluminum and final products; (4) the U.S. has been a net importer of aluminum from the life cycle perspective, with its total annual net import increasing from 1945 to 2005; (5) as a result of the continuous increase of net import, total domestic stock of aluminum in the U.S. dramatically increases in the period of 1945–2009 and amounts to 316 Tg in 2009, about nine times of that in 1900; (6) in-use stock comprises about 48% of total domestic stock in 2009 and is dominated by two sectors, Buildings and Construction (32%) and Transportation (35%); (7) total per-capita stock in use of aluminum keeps increasing until 2009 and currently amounts to 490 kg; (8) per-capita stock of aluminum in Transportation sector increases substantially after 1990s because of the light-weighting of automobiles, while that in the Buildings and Construction and Electrical Engineering sectors seems have reached a saturation level after 2005.

1. Introduction

The study of anthropogenic resource cycles can offer new perspectives on a variety of topics, including resource availability, resource utilization, recycling potential, and environmental policy (Reck et al., 2008). Especially for metals, anthropogenic stocks and flows analysis provides insights into (1) identifying factors driving changes of metals demand, (2) quantifying recovery efficiencies of metals at the end-of-life (EOL) stage, (3) estimating international trade of metals embedded in all kinds of products, and (4) assessing emissions or loss of metals back into natural environments (Chen and Shi, 2012; Chen et al., 2010; Eckelman and Graedel, 2007; Gordon et al., 2003; Reck et al., 2008; Spatari et al., 2005; Wang et al., 2007). In addition, quantified resource cycles help to evaluate the future availability of metals, estimate the potential for urban mining, and explore patterns of metals use in societal evolution from the perspective of stocks (Gerst and Graedel, 2008; Gordon et al., 2006; Hatayama et al., 2009; 2010; Müller et al., 2006; Müller et al., 2011).

Aluminum is widely recognized for its technological versatility, and its rate of use now cedes first place only to steel among the metals. If measured by volume rather than by weight, aluminum now exceeds in quantity all other non-ferrous metals combined, including copper and its alloys, lead, tin, and zinc (Altenpohl and Kaufman, 1998). However, production of alumina and primary aluminum is highly resource, energy, and emissions intensive. In addition, although the energy required for producing secondary aluminum might be only 5–10% of that needed for primary aluminum (Melo, 1999), there are still substantial environmental emissions, such as dioxins, associated with the separation and remelting of aluminum scrap (European Aluminum Association, 2008; Zhang et al., 2007; Zhang et al., 2008). Since industrial production of aluminum began in 1888 (Altenpohl and Kaufman, 1998), the United States has played a very important role in the global aluminum industry. According to U.S. Geological Survey (2009), historical cumulative apparent consumption[1] of aluminum in the United States from 1900 to 2009 is more than 255 Tg, about 28% of global cumulative production in

Abbreviations: ACPs, aluminum-containing products; B&C, building and construction; CES, collection of EOL products and scrap; ConDur, consumer durables; C&P, containers and packaging; EE, electrical engineering; EOL, end-of-life; F&M, fabrication and manufacturing; MFA, material flow analysis; MS, melting of scrap; M&E, machinery and equipment; NM, non-metallic use; Others, other sectors; SFA, substance flow analysis; Trans, transportation; TS, treatment or preparation of scrap; TUAFlow, total unwrought aluminum flow into fabrication process; WM&R, waste management and recycling.

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[1] *Consumption* and *apparent consumption* have been used for several decades by the industrial community to indicate the amount of metals used by a country. However, as metals are not consumed but rather used and accumulated in in-use stock, we prefer to use *flow of metal from one stage to the next stage* rather than *consumption* or *apparent consumption*.

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that period. Therefore, it is important to conduct a multi-year dynamic analysis of aluminum stocks and flows in the United States.

By applying the material flow analysis (MFA) or substance flow analysis (SFA) framework of aluminum which has been developed and used in (Chen and Shi, 2009, Chen and Shi, 2012; Chen et al., 2010), this paper reports on a dynamic analysis of aluminum stocks and flows in the United States from 1900 to 2009, aiming at quantifying how much aluminum has entered, left, passed through, and accumulated in the U.S. anthroposphere. The paper is organized as follows: Section 2 defines the scope and system boundaries, and describes the accounting methods and data preparation; Sections 3 and 4 present results on flows and stocks, respectively; Section 5 discusses uncertainties and policy implications of the results. The paper ends with a summary and conclusion.

2. Methodology

2.1. Scope and System Boundaries

The system analyzed in SFA is defined by spatial and temporal boundaries (Chen et al., 2010). The spatial system boundary of the current study is the geographical border of the United States, while the temporal boundary is the period 1900–2009. As in Chen et al. (2010) and Chen and Shi (2012), all stocks and flows values of this study refer to the average annual mass of aluminum in pure form (i.e., not the mass of aluminum-containing mixtures and alloys). For bauxite and alumina, where aluminum exists in chemical compound form, the mass of aluminum is calculated according to the mass of aluminum included in Al_2O_3.

The life cycle of aluminum in the anthroposphere is composed of four principal life stages, as illustrated by Fig. S1 in the Supplementary Material: Production (P), Fabrication and Manufacturing (F&M), Use (U), and Waste Management and Recycling (WM&R). Except for the Use stage, each of these life stages is divided into several sub-stages depicted as solid line rectangles in Fig. S1 and described in Table S1 in the Supplementary Material. In this paper, both the four principal life stages and their sub-stages are referred to as life processes. Every life process generates aluminum-containing products (ACPs) as specified in Table S2. More details about anthropogenic aluminum life cycle are available at Chen and Shi (2009), Chen et al. (2010), and the Supplementary Material of this paper.

2.2. Accounting Methods of Stocks and Flows

Details on identifying and accounting for stocks and flows are described in the Supplementary Material. For the convenience of readers, we summarize some essential information here. Stocks are categorized into four groups: (1) bauxite ore stocks,[2] (2) in-use stocks, (3) hibernating stocks, and (4) loss stocks. Loss stocks are then divided into four categories according to their existence states: (1) tailing ponds, (2) slag repositories and landfills, (3) obsolete stocks and exports of EOL products, and (4) non-metallic use.

For each life process, the total input consisting of flows from previous life process and import should be equal to total output comprising flows to the next life process and export. All these flows are then classified into four groups: (1) the trade flows and (2) the loss flows, both of which take place along the whole life cycle of aluminum; (3) the transformation flows that transform aluminum from chemical compounds to refined metal, from pure metal to alloys, and from simple products to complex components of final products; and (4) the recycling flows of aluminum scrap, including old scrap from in-use stock and new scrap from Production and F&M stages.

By collecting data as mentioned in Section 2.3, each flow is calculated in one of four ways: (1) calculated directly based on statistics, such as the trade flows; (2) calculated by combining statistics with coefficients, such as the loss flows; (3) modeled by the “top-down” method, such as the old scrap generation; and (4) deduced by mass balance. With results on all flows available, annual changes of various stocks are determined, and each stock is deduced by accumulating its annual change from the initial year, 1900, to the final year, 2009.

2.3. Data Classification and Preparation

Details on data collection and compilation are described in the Supplementary Material. All data are grouped into six categories: (1) data on production, apparent consumption, or shipments of ACPs; (2) data on import and export of ACPs; (3) data on aluminum contents of various ACPs; (4) data on loss rates of aluminum from different life processes; (5) data on the composition of some flows, such as flows from Fabrication to Manufacturing processes; and (6) data on lifespans of final products in the Use stage.

Data sources are various, including governmental or industrial statistics, such as online database of U.S. Geological Survey (U.S. Geological Survey, 2006; 2011) and annual *Aluminum Statistical Review* compiled by the Aluminum Association (The Aluminum Association, 2010); books or research reports, such as *Aluminum Recycling* (Schlesinger, 2007) and many reports on aluminum material flow analysis (European Aluminum Association and Organisation of European Aluminium Refiners and Remelters, 2004; Troyes University of Technology, 2009), aluminum life cycle assessment (European Aluminum Association, 2008; International Aluminium Institute, 2007; PE Americas, 2010; The Aluminum Association, 1998), or aluminum contents (Ducker Worldwide, 2008a,b); academic papers, such as Recalde et al. (2008) and Wang and Graedel (2010); standards on ACPs, such as SECSPC (2004a,b); and other information, such as Anonymous (2011a).

3. Results on Flows

Historical cumulative aluminum cycles for the period of 1900–2009 in the United States are shown in Fig. 1. In this section, results on flow analysis are elaborated in the sequence from top (trade flows) to bottom (loss flows) and from left (bauxite mining) to right (scrap recovery). The section ends with a summary of total input, output, and accumulation of aluminum in the U.S. anthroposphere.

3.1. Evolution of Aluminum Trade Quantity and Composition

Traded ACPs measured in this study are listed in the Supplementary Material according to their relationship with each life process of aluminum life cycle. These ACPs are then classified into five categories: 1) Bauxite and Alumina, 2) EOL Products and Scrap, 3) Unwrought Aluminum, 4) Semis, and 5) Final Products. The first and second categories could be regarded as raw materials to produce unwrought aluminum (the third category), while the fourth and fifth categories could be regarded as further fabricated or manufactured products of unwrought aluminum. Unfortunately, trade of aluminum embedded in EOL Products could not be quantified due to data unavailability.

Trade of aluminum before 1940 was negligible compared to later years, as shown in Fig. 2(a). After 1945, both total import and total export of aluminum in the United States experienced an increasing trend until very recent times. As a result, the U.S. has been a net importer of aluminum for more than a century. During this 110-year period, the U.S. accumulated net import of aluminum was more than 280 Tg.

Analysis of net import of aluminum by categories, as illustrated in Fig. 2(b), shows that aluminum was mainly imported into the U.S. in the form of bauxite and alumina, particularly before 1990; and the

[2] Ore stocks existing in other forms, such as alunite, anorthosite, and coal ashes, are excluded here because they are not currently used to extract alumina, and are also difficult to quantify.