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Dynamic analysis of aluminum flows in production stage in mainland China: 1996-2014

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This paper applies substance flow analysis (SFA) and stocks and flows framework (STAF) to conduct dynamic analysis of aluminum flows in the production stage in mainland China from 1996 to 2014. Key findings include: (1) aluminum production industry of China developed rapidly from 1996 to 2010, larger and larger scrap was recycled and reused, while almost all flows declined at various degrees from 2011 to 2014; (2) in bauxite mining process, resource efficiency indices did not rise but dropped slowly, and net import dependence indices increased little by little, from 0.019 in 1996 to 0.413 in 2014; (3) in alumina production and primary aluminum electrolysis processes, resource efficiency indices were both large and stable, basically above 0.9, and net import dependence indices declined generally and gradually; (4) although secondary aluminum increased sharply from 1996 to 2011, its proportion grew slowly, reached the maximum of 0.198 in 2010 and decreased after 2011. Therefore, ore dressing-Bayer method, tailing reelection technologies, intelligent use of scrap and Go-Out Strategy must be promoted at a large scale as soon as possible.

Key words: Substance flow analysis; Production stage of aluminum industry; Resource efficiency and net import dependence.

INTRODUCTION

Aluminum is the second most abundant metallic element in the earth's crust after silicon, accounting for 8% of the earth's crust [1], yet it is a comparatively new industrial metal that has been produced in commercial quantities for just over 100 years. However, more aluminum is produced today than all other nonferrous metals combined [2]. Great growth in demand and consumption of aluminum containing products (aluminum used in transportation (automobiles, airplanes, trucks, railcars, marine vessels, etc.), buildings and constructions (windows, doors, siding, etc.), consumer durables (appliances, cooking utensils, etc.), machinery and equipment (manufacturing, construction, agricultural equipment, etc.), electrical engineering (wires and cables, transformers, generation equipment, etc.), containers and packaging (cans, foil, etc.), and other products)) [3] in recent decades owns to its wonderful properties: (1) light weight. It weighs about one-third as much as steel or copper; (2) it has low density and it is malleable, ductile, and easily machined and cast; (3) it has excellent corrosion resistance and durability; (4) it has high thermal conductivity, electrical conductivity and reflectivity, no low temperature brittleness and magnetism. So, measured either in quantity or value, the usage of aluminum exceeds that of any other metal except iron, or it is important in virtually all segments of the world economy.

Modern society and recent decades have witnessed a significant increase in aluminum use [4], particularly in China. China, an extraordinarily populous, fast developing, but still underdeveloped country, has the potential to influence the entire world's use of materials. From 1991 to 2007, the average increasing rates of aluminum production and consumption in China were about 4 times the global level. However, the production of aluminum requires much more energy than of many other metals and causes large amounts of greenhouse gas (GHG) emissions [5], especially in the primary aluminum electrolysis process. Production of primary aluminum is highly energy-intensive and with heavy environmental burdens associated with resources extraction and pollutant emissions [6]. The environmental impacts of primary aluminum industry are much higher than that of aluminum recycling industry and aluminum semi-production industry. Although the energy required for producing secondary aluminum (separation and remelting of aluminum scrap) might be only 5-10% of that needed for primary aluminum [7], China as a developing country has been lacking scrap for domestic secondary aluminum production in recent years [8]. In addition, China's static depletion time of bauxite was less than 15 years since 2009. Given the potential to increase its in-use stock, a secure supply of bauxite may become a challenge for China in the near future.

So, in consideration of the large energy consumption of primary aluminum production and the lack of scrap and bauxite in mainland China, this paper applies substance flow analysis (SFA) and stocks and flows framework (STAF) to analyze aluminum element stocks and flows and its whole

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life cycle in the Production stage in mainland China from 1996 to 2014. The object of this paper is to explore the segments of higher net import dependence index and lower resource efficiency index to finally realize environment-friendly metallurgy in the Production stage. Conducting the detailed aluminum substance flow analysis of Production stage helps to understand the overall condition of aluminum production industry in China in recent years, and contributes to providing quantitative and scientific policy evidence to implement cleaner production, develop circular economy and realize sustainable development.

EXPERIMENTAL

Fig. 1 depicts the stocks and flows system boundary of aluminum, and the entire life cycle and sub-processes of aluminum in China is distinct. In Production stage, there are three sub-processes: mine/mill, smelter and refinery. Then comes the Fabrication and Manufacture stage, aluminum alloys and pure aluminum are fabricated to foundry casting, rolling, extrusion, rod and wire, and other semi-products; next, final aluminum-containing products are manufactured combined with other raw materials. As for consumption structure, aluminum-containing products in the Use stage are sorted into 7 categories: building and construction (B&C), transportation (T), consumer durables (CD), machinery and equipment (M&E), electrical engineering (EE), containers and packaging (C&P), and others. In the Waste Management and Recycling stage, end-of-life products and scrap are collected, separated and treated.

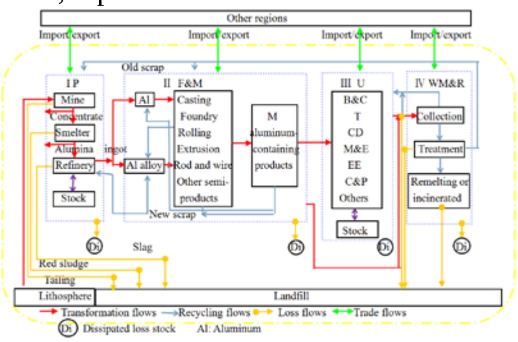

Fig. 1. System boundary of the stocks and flows framework for anthropogenic aluminum cycle (refer to Chen)

Some products are remelted to produce secondary aluminum, but others that have no economic values are incinerated. Trade or exchange with other regions occurs in every stage sub-processes. At the same time, resources and energy consumption, dissipated loss and pollutant emissions to the environment happen at every stage too.

The system boundaries include spatial boundary, temporal boundary and scope. The spatial boundary of this paper is the geographical border of mainland China, and the temporal boundary is the period of 1996-2014. The scope means 3 sub-processes (bauxite mining, alumina production and primary aluminum electrolysis) of the entire life cycle only in the Production stage, not all four stages. Actually, aluminum, either bauxite, alumina or primary aluminum, exists in its chemical compound form in the nature. But all values of aluminum stocks and flows in this study are in terms of aluminum content, therefore the aluminum content was calculated using atomic weights and some transfer coefficients estimated from the literature and experts (Fig. 2).

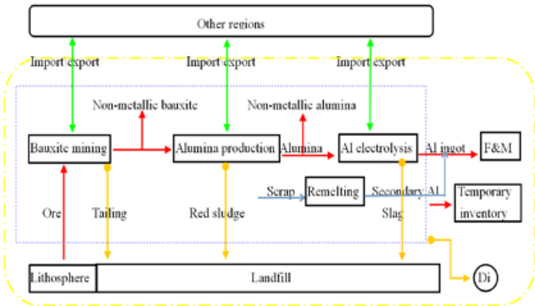

Fig. 2. System boundary of the Production stage of aluminum

For the calculation of stocks and flows with respect to sub-processes in the Production stage, the basic relationship given in Eq. (1) adheres to the mass conservation principle:

$$\Delta Stocks = \sum F^{i}_{input} - \sum F^{i}_{output} \qquad (1)$$

ΔStocks means net accumulation, loss to environment or depletion of aluminum, and F designates the whole flows into or out of process i. However, change in stock is so small that can be negligible [9] in theoretical and real world, and Eq. (1) becomes

$$\sum F^{i}_{input} = \sum F^{i}_{output} \qquad (2)$$

This corresponds to the substance flows diagram of Production stage, and the input and output include domestic and net imported production, respectively.

The index of resource efficiency measures the ratio of qualified products or output (namely excluding waste flows), and R_{re} is defined as follows:

$$R^{i}_{re} = \left(\sum F^{i}_{output} - \sum F^{i}_{waste}\right) / \sum F^{i}_{input} \qquad (3)$$

The larger value of resource efficiency implies that the production of process i is efficient within the Production stage of aluminum industry. And the lower value of it implies the contrary.

The index of net import dependence measures the degree of domestic aluminum production industry dependence upon foreign aluminum production or foreign raw materials supply, and R_{id} is defined as follows:

$$R_{id}^{i} = \sum F_{netimport}^{i} / \sum F^{i} \qquad (4)$$

In this equation, F^{i} can represent not only output flows, but also input flows, and $F_{netimport}^{i}$ means net imported aluminum-containing products or raw materials in process *i*. Obviously, one country or region can master the lifeline of aluminum production industry regardless of foreign aluminum production status, raw materials supply or aluminum market demand if its value is small. On the contrary, the aluminum industry of one country or region is threatened by international market, like walking on the thin ice.

This index is a criterion used to measure the ratio of secondary aluminum remelted from scrap occupying the total output of Production stage (excluding trade volume) to weigh the recycling situation of scrap.

$$R_{s} = \sum F_{secondary} / \left(\sum F_{primary} + \sum F_{secondary}\right) \quad (5)$$

A larger value of this index indicates that secondary aluminum occupies a large proportion and is essential to the aluminum production industry, of course, and the lower value indicates that scrap is not used wisely, which produces huge waste and pollution to the whole ecosystem due to the absence of waste management and recycling.

RESULTS AND DISCUSSION

Fig. 3 illustrates the trends of some indices: resource efficiency and net import dependence in bauxite mining process, alumina production process and primary aluminum electrolysis process respectively, as well as the proportion of secondary aluminum of the entire Production stage from 1996 to 2014.

Although secondary aluminum increased sharply from 1996 to 2011, its proportion only reached a maximum of 0.198 in 2010. The values of this index grew slowly on the whole, rising in some years and dropping in other years. After 2011, secondary aluminum was too much reduced. Along with gradually decreasing bauxite output, drastically decreasing alumina and primary aluminum production in 2014, this index went up after dropping. China's in-use stock of aluminum is still too "young" and small to generate high quantities of aluminum scrap for domestic secondary aluminum production [8]. On the other hand, the fare damage rate of secondary aluminum in remelting process is relatively high in China because of participation of many individual workshops and the low melting technologies level.

In bauxite mining process, resource efficiency index did not rise but dropped slowly, while the net import dependence index continuously rose on the whole from 1996 to 2014, especially from 2005 to 2006. The abnormal phenomenon of resource efficiency index implies that there exists more and more serious waste in bauxite mining process on the one hand, and on the other hand, it further exposes the current situation of more low-grade ore and less high-grade ore in China. China is a net importer of bauxite, and there is no doubt that China is relying more on foreign countries or regions due to the sustaining rise of the net import dependence index. The average growth rate (49.4%) of the net imported amount from other regions is much larger than that (6.8%) of domestic mining amount on account of globalization and more and more global corporation. In the condition of global market of fierce competition and constant change, this status must be paid more attention to in order to guard resource security.

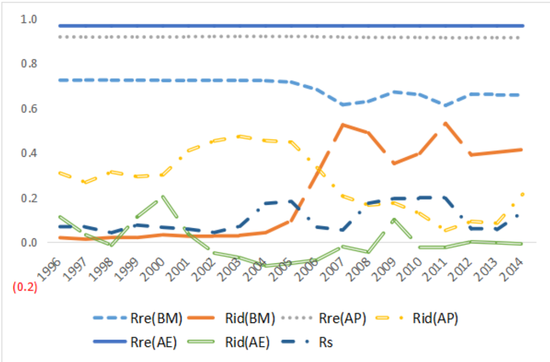

Fig. 3. The tendency of indices in three sub-processes of Production stage from 1996 to 2014. (BM: bauxite mining; AP: alumina production; AE: aluminum electrolysis)

In alumina production process, the values of resource efficiency index are relatively high without too big fluctuations, and it is more effective than bauxite mining process. What is more optimistic is that the net import dependence index had the tendency of decline in this process, although it rose slightly in 2014. This appearance can be explained mainly from the following two aspects: the amount of net import was gradually reduced since 2006, lessened sharply in 2011 and increased a little from 2012 to 2014; domestic alumina output augmented at a high speed for the period of 1996-2013 except 2014. These two conditions jointly determined the change of net import dependence index in this process.

In primary aluminum electrolysis process, the values of resource efficiency index are the highest in these three sub-processes of the Production stage. This means that primary aluminum electrolysis process is the most effective process and unit of resource consumption is minimum in Production stage. Like the variation of the net import dependence index in alumina production process, its values had the tendency of decline as a whole in this process. However, unlike the values of net import dependence index in alumina production process, there are mainly negative values in this process and China is basically a net exporter of primary aluminum. The decreasing amount of net import and increasing amount of domestic primary aluminum production can account for the declining tendency of the net import dependence index. The amount of primary aluminum import less than that of export can account for the negative values of the net import dependence index. What is noteworthy is that the values of net import dependence index reached up to 0.1 in 2009. Under the influence of financial crisis, there are some unusual points in 2009 other than for the rest of years: decrease in output of domestic primary aluminum and export, dramatic increase in import. From 2011 to 2014, the values of the net import dependence index were extremely close to 0, so China will be a country of balance between import and export for primary aluminum in the future.

CONCLUSION

Based on the input-output model and mass conservation principle, this paper applies the resource management method of SFA and STAF framework to illustrate the whole life cycle of aluminum in Production stage in China for the period of 1996-2014. The positive average growth rates of various flows for the period of 1996-2010 revealed that China is a net importer of bauxite and alumina, aluminum production industry of China developed rapidly, and large scrap was recycled and reused because of advancing concept of waste management and recycling. However, the condition of these flows and average growth rates is another image for the period of 2011-2014. Negative average growth rates show a decreasing tendency of various flows. It is a good time of optimization and integration of domestic aluminum market, and implementation of Go-Out Strategy to overseas merger and acquisition.

Resource efficiency index and net import dependence index of three basic sub-processes of Production stage, as well as the proportion of secondary aluminum of the entire Production stage from 1996 to 2014 were calculated in this way. Although secondary aluminum increased sharply from 1996 to 2011, the index of proportion of secondary aluminum grew slowly and reached only a maximum of 0.198 in 2010. After 2011, the amount of secondary aluminum was reduced too much. Participation of some large enterprises can improve utilization of aluminum scrap and reduce the fare damage rate in remelting process by higher technology level and standard management. Resource efficiency indices in alumina production and primary aluminum electrolysis processes are large and stable, while that in bauxite mining process does not rise but drops slowly. Net import dependence indices in alumina production and primary aluminum electrolysis processes decline generally and gradually, nevertheless that bauxite mining process goes up little by little.

From the perspective of environment-friendly metallurgy and resource security, bauxite mining process needs to be paid more and more attention to. Ore dressing-Bayer method must be promoted at a large scale as soon as possible and tailing reelection technologies must be advanced to realize comprehensive utilization of tailing.

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