Regional and sectoral disparities in global Aluminium use: Analysis of the global dynamic aluminium flows and footprints

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Abstract

Aluminium (Al) industry is historically characterized by high energy consumption, significant emissions and substantial pollution, the transition towards a circular economy and reduction in material use holds critical importance for global decarbonization efforts. Such a transformation necessitates collaborative actions across both production and consumption sectors. We employ a combination of dynamic material flow analysis and environmentally-extended multi-regional input-output analysis to map the global Al flows and footprints from its production to its consumption systems, over the period from 2007 to 2017. This approach enables us to examine the direct and indirect utilization of Al globally from both supply and demand perspectives, laying a foundation for research into the decarbonization of the Al industry. China emerges as the predominant Al consumer, China's efforts on promoting low-carbon transition of its Al industry will arguably contribute the process of the future development of circular economy in the global Al industry. The Transportation and Building & Construction sectors are the primary consumers of Al, jointly accounting for about 50% of its global utilization. The service sector is increasingly becoming a significant player in the Al industry, indirectly consuming around 17% of total Al use by 2017. Future policies should focus more on implementing targeted circular economy strategies that are specific to the Al industry, considering the regional and sectoral differences. Additionally, there is a pressing need to foster enhanced global collaboration among countries throughout the entire Al supply chain, aiming to harmonize efforts in sustainable management and utilization of Al resources.

Introduction

As a traditionally high-energy consumption, emissions, and pollution-heavy industry[1], achieving circularity and dematerialisation of the global Aluminium (Al) industry is of great significance in the pursuit of global decarbonisation. This requires joint efforts from both the production and consumption sides[2]. From the perspective of the supply-side, a detailed material flow map can identify opportunities to improve material efficiency, promote circular economy and further contribute to the decarbonisation[3]. From the perspective of the demand-side, with the increasingly prominent role of demand-side measures in reducing emissions in the Al industry, the need to trace the global Al footprint has become critical. Material flow analysis (MFA) is recognised as an effective tool for exploring the circularity and efficiency of materials and has been applied to a wide range of metallic materials, such as steel[4,5] and Al[1,6]. These studies provide detailed data references and policy implications for the conservation, efficiency, circularity, and sustainability of metal resources based on their characteristics. The metal footprint is a consumption-based indicator that describes the total amount of metal resources required to meet the final demand of an economy[7], and it can also be used as a comprehensive indicator to characterize metal consumption and its underlying global drivers[8]. Multi-regional input-output (MRIO) models has already been proved to effectively calculate the global metal footprints[9]. Thus, combining physical and economic models together helps to better trace the metal material uses from both supply and demand sides, as well as form the physical and monetary perspective.

This study conducts a comprehensive analysis of the global Al industry from Al flows in production system to Al footprints in consumption system, which helps decision-makers to develop more comprehensive and effective mitigation measures. Firstly, we traced the Al material flows (measured in Al content) from bauxite mining to final products manufacturing for 9 regions ((China, Japan, North America, South America, Europe, Other Asia, Other Producer, Middle East, and Rest of World) separately in 2007, 2011, 2014 and 2017 (GTAP database publication year). Secondly, the direct consumption amount of Al for the 9 regions in these years are used as satellite accounts of the global MRIO table. Then, combining with an environmentally-extended multi-regional input-output (EE-MRIO) model to calculate the dynamic changes of global Al footprint in the consumption system. The global MRIO table used for this study is derived from the Global Trade Analysis Project (GTAP, version 11) database[10]. The MRIO table comprises 141 regions and 65 industry sectors, and to match with the results in MFA, we harmonize the regional coverage and sector classification into 9 regions and 7 end-use sectors (Transportation, Building and Construction, Container & Packaging, Electricity Engineering, Machinery & Equipment, Consumer Durables, and Others), this uniform boundary can facilitate a relatively fair comparison of the performance of Al consumption in different regions and sectors. Finally, by linking the Al flow in the production system and the Al footprint in the consumption system, we drew the whole map of global Al use, and further characterized the dynamic evolution of global Al footprint.

Results and Discussion

The Sankey diagram shown in Figure 1 can quickly clarify the global Al flows from the production system to consumption system in 2007 and 2017. According to the concept in MFA model, the Al direct use means the total amount of materials directly used by an country or region and is defined as the annual quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports[11], which can be further defined as production-based use. Meanwhile, according to the previous study[3,7], the concept of the regional Al footprint refers to the global Al use driven by the regional final demand, including all the direct Al use and indirect Al use in the sectors of regions, which can be further defined as consumption-based use. Thus, in other words, the comparison between the global Al direct use and the Al footprint can be recognized as the comparison between the production-based Al use and the consumption-based Al use. Although total Al supply and demand is always equal, the structure of direct Al use and Al footprint may vary greatly. As shown in Figure 1, the total direct Al use amount equals with the total Al footprint both in 2007 and 2017 (which is ~59 Mt and ~99 Mt respectively), while there are regional and sectoral variations, this due to that the demand for different sectors in different regions will indirectly leads to different amount of Al use.

As mentioned above, there are 7 direct use sectors for Al in MFA model. Trans and B&C sectors are the primary consumers of Al, jointly accounting for about 50% of its global utilization. The rest 9 sectors have no direct Al use, while they still cause a certain amount of Al use indirectly because of the final demand. More specifically, the service industry does not have the direct Al use, but its demand for building, transportations and other industry indirectly consumed ~12 Mt and ~17 Mt of global Al use in 2007 and 2017 respectively, accounting for ~21% and ~17% of the total Al use of the year, even more than some end-use sectors. In addition to the Other Service sector, the Communication sector also indirectly consumed ~7 Mt and ~10 Mt of global Al use in 2007 and 2017 respectively, followed by Manufacturing and Textiles and Clothing sectors. This is something that overlooked in previous studies about Al material flow analysis[12–15].

The total global Al footprints has shown the upward trend from 2007 to 2017, and the largest Al footprint region has shifted from Europe to China. In 2007, Al footprint in Europe (~19 Mt) was around 1.4 times than that in China (~14 Mt), while in 2017

China's Al footprint (~43 Mt) increased to 2.2 times than Europe's Al footprint (~20 Mt). Notably, the Al footprint in Europe experienced a decrease over the past decade, this is also an indication that the Europe has basically reached the saturation stage of Al use[16]. The Al footprint in North America and Other Asia are followed by China and Europe, with the number of ~11 Mt and ~5 Mt in 2007 and then increased to ~15 Mt and ~9 Mt in 2017 respectively.

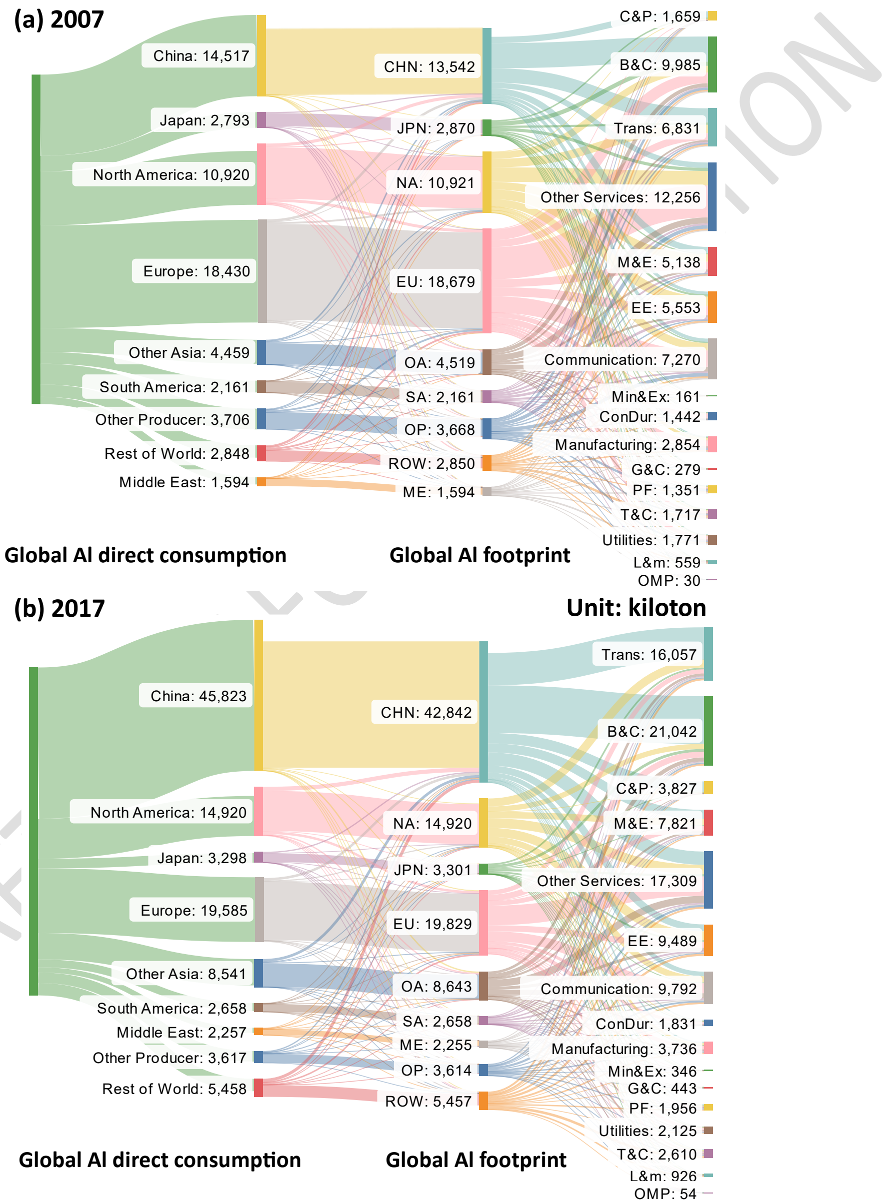

Figure 1. Global Aluminium flows in 2007 (a) and 2017 (b). (**Sectors:** Trans: Transportation, B&C: Building and Construction, C&P: Container & Packaging, M&E: Machinery & Equipment, EE: Electrical Engineering, ConDur: Consumer Durables,

Min&Ex: Mining and Extraction, G&C: Grains and Crops, PF: Processes Food, T&C: Textiles Clothing, L&M: Livestock and Meat Products, OMP: Other Metal Product.)

The global Al footprints reveal the Al use situation in production system and consumption system is different. As mentioned earlier, Other Services, Communication, Manufacturing and Utilities sectors didn't consume Al directly while cause a certain amount of Al use indirectly because of the final demand. This suggests that these services-based sectors are now emerging as important sectors for global Al use, especially in developed areas that are already highly urbanized (such as Europe and North America). The infrastructure facilities construction has already reached saturation in these regions, while the service indirectly drives significant Al use. Thus, for the developed countries, in addition to material reduction strategies based on the production side, there should be a greater focus on dematerialization in the future, such as the developing the sharing economy that reduces the demand for materials by consuming the services provided by commodities, rather than the commodities themselves, which can further promote to achieving the global Al sustainable use.

China's current Al production technology still has the improvement potential compared with the developed countries[17], and the domestic secondary Al production capacity still needs to be expanded. Therefore, as a major global Al consumer, China should vigorously develop the cleaner production technologies to achieve green and sustainable development of the Al industry. Besides, North America is an importer of the Al within the whole life cycle except for Al scrap[18]. Ironically, North America is a global leader region for Al recycling technology, but most of its domestic Al scrap were exported to developing regions with less advanced recycling technology. Hence, the corresponding global cooperation is needed to promote the developed regions recycle Al domestically accompanied by advanced industrial technology transfer from developed regions to developing regions and encourage the global consumer to use green Al manufactured through Al scrap. This study indicates that global cooperation between different countries along the entire Al supply chain should be promoted and suggest that the regional disparities and inequalities should be considered in designing global strategies toward the sustainable development of Al industry.

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