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RESEARCH ARTICLE

Chao TANG, Yong GENG, Xue RUI, Guimei ZHAO

Spatiotemporal evolution and driving factors for GHG emissions of aluminum industry in China

Abstract China's aluminum (Al) production has released a huge amount of greenhouse gas (GHG) emissions. As one of the biggest country of primary Al production, China must mitigate its overall GHG emission from its Al industry so that the national carbon neutrality target can be achieved. Under such a background, the study described in this paper conducts a dynamic material flow analysis to reveal the spatiotemporal evolution features of Al flows in China from 2000 to 2020. Decomposition analysis is also performed to uncover the driving factors of GHG emission generated from the Al industry. The major findings include the fact that China's primary Al production center has transferred to the western region; the primary Al smelting and carbon anode consumption are the most carbon-intensive processes in the Al life cycle; the accumulative GHG emission from electricity accounts for 78.14% of the total GHG emission generated from the Al industry; China's current Al recycling ratio is low although the corresponding GHG emission can be reduced by 93.73% if all the primary Al can be replaced by secondary Al; and the total GHG emission can be reduced by 88.58% if major primary Al manufacturing firms are transferred from Inner Mongolia to Yunnan. Based upon these findings and considering regional disparity, several policy implications are proposed, including promotion of secondary Al production, support of clean electricity penetration, and relocation of the Al industry.

Keywords aluminum, material flow analysis, GHG (greenhouse gas) emissions, LMDI (logarithmic mean divisa index)

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Chao TANG
School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

Yong GENG (✉)
School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China; China Institute for Urban Governance, School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai 200030, China; SJTU-UNIDO Joint Institute of Inclusive and Sustainable Industrial Development, School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai 200030, China
E-mail: ygeng@sjtu.edu.cn

Xue RUI
School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China; SJTU-UNIDO Joint Institute of Inclusive and Sustainable Industrial Development, School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai 200030, China

Guimei ZHAO
School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China; School of Finance and Economics, Jiangsu University, Zhenjiang 212013, China

1 Introduction

Aluminum (Al) is the most abundant metal element in the earth's crust and has become one of the most versatile, pervasive, and inexpensive metals today [1]. Al is widely used in transportation, construction, packaging, and other sectors because of its excellent physical and chemical properties, including low density, high tensile strength, and remarkable corrosion resistance [2]. In addition, Al weight is about one third of that of steel or copper, making it the most used metal in human society after iron [3]. However, the unit greenhouse gas (GHG) emission of primary Al production is 12.4 times that of iron and 2.3 times that of copper due to the characteristics of its smelting process [4], which poses great challenges to the GHG emission reduction of the Al industry all over the world.

With rapid economic development and continuous improvement of people's living standards, China's demand for Al is growing. China's primary Al production increased from 2.99 megatons (Mt) in 2000 to 37.08 Mt in 2020 [5], and its proportion in the world increased rapidly from 12.12% in 2000 to 56.79% in 2020 [6]. This means that a large amount of GHG emissions were generated from the Al industry in China. In 2013, the GHG emission from China's primary Al production was

421 Mt, accounting for about 4% of the country's total GHG emission [7]. In 2017, approximately 547 Mt of GHG were emitted from the whole life cycle of China's Al industry [8], accounting for about 6% of the country's total GHG emission [9]. To address climate change, the Chinese government committed to peak its carbon emission in 2030 and achieve carbon neutrality in 2060 [10,11]. Under such a circumstance, it is critical to take necessary actions to mitigate the overall GHG emission from China's Al industry, one of the most energy and emission intensive sectors.

Material flow analysis (MFA) is a useful method to systematically account the flows and stocks of different materials within specific spatial and temporal boundaries. Such MFA results can help prepare policies to effectively improve resource utilization and waste management so that corresponding environmental impacts can be mitigated. MFA has been widely employed to present the anthropogenic flows of Al in China in several studies. For instance, Chen et al. conducted the first static MFA to study China's Al flows and established a framework to analyze China's Al cycles [12]. They then conducted a dynamic MFA for the period of 2001–2007 to further uncover the evolution features of Al metabolism in China [13]. Wang and Graedel performed the first bottom-up MFA to investigate China's Al flows and presented a detailed list for various Al-containing products [14]. Chen and Shi accounted China's per capita Al in-use stock by applying an MFA for the period of 1950–2009 [15]. Ding et al. evaluated the overall resource efficiency of China's Al industry for year 2013 by applying MFA [16]. In summary, these previous studies focus on China's primary Al production and in-use stocks, but without considering secondary Al supply, i.e., recycling Al from scraps [17,18]. Regional analysis is often used to analyze carbon emissions results [19,20], while few studies are conducted focusing on the spatial evolution and regional disparity of Al. In addition, these previous studies were published several years ago and used quite old data. Thus, they cannot reflect the most recent progress of China's Al industry.

Meanwhile, significant efforts have been made to evaluate the global warming impact of China's Al production. Gao et al. quantified the GHG emission from China's primary Al production for year 2003 by using life cycle assessment (LCA) [21]. Ding et al. recognized the differences of energy consumptions and carbon emissions between primary and secondary Al production in China [22]. Zhang et al. evaluated the impact of China's primary Al production processes on energy conservation and identified the corresponding emission reduction potential [23]. Yue et al. found that economic growth is an important driving factor affecting energy consumption and GHG emissions related with China's primary Al production [24]. Liu et al. assessed the impact of electricity structure and secondary Al production on GHG emissions of primary Al production at the national level [25]. Li et al. used system dynamics to predict the growth trend of GHG emission from China's primary Al industry up to 2030 [26]. Zhang et al. updated the life cycle inventory of China's primary and secondary Al production [27]. Li et al. forecasted the GHG emissions of China's Al metabolism until 2030 [8]. However, these GHG emission-related studies do not consider the spatial evolution characteristics of China's Al cycles due to the lack of connection with Al-related MFA studies, nor do they consider regional disparity although regional realities should be addressed when preparing the relevant mitigation policies [28]. Therefore, the study described in the present paper aims to fill the above research gaps by conducting a dynamic MFA to examine the Al flows in China from 2000 to 2020. After uncovering both temporal and spatial evolution characteristics, it also identifies the driving factors of corresponding GHG emissions by employing a decomposition analysis method. Different from traditional decomposition method focusing on economy and population, it decomposes the practical and feasible effects refined from field investigations, including the effects of secondary Al production, electricity structure, and regional disparity, so that valuable insights can be obtained for preparing appropriate policies.

2 Methods and data

2.1 System boundary

The study described in the present paper combines both the dynamic MFA method and the life cycle assessment (LCA) method to account for China's Al flows and corresponding GHG emission for the period of 2000–2020. MFA is frequently used to assess the past, present, and future stocks and flows of metals in the anthroposphere [29,30]. The Al life cycle includes four stages: primary Al production (PAP), manufacturing and fabrication (M&F), use (U), and secondary Al production (SAP, referring to Al recycling) (Fig. 1). The PAP stage includes bauxite mining (BM), Al refining (AR), and primary Al smelting (PAS). Bauxite is mined in the BM stage and refined as alumina at a high temperature in AR. Alumina is then processed as primary Al with electrolysis in PAS. The M&F stage includes semi-products and final products processed by primary Al. The U stage is essential for connecting the M&F stage and the SAP stage in mathematical calculations of MFA although it is excluded from GHG emissions accounting. Finally, Al scraps are processed into secondary Al in the SAP stage.

The LCA method is applied to identify energy inputs at different stages of China's Al cycle. The study described in the present paper only considers carbon emissions directly generated by energy consumption from the Al production, such as carbon emissions from diesel, resi-

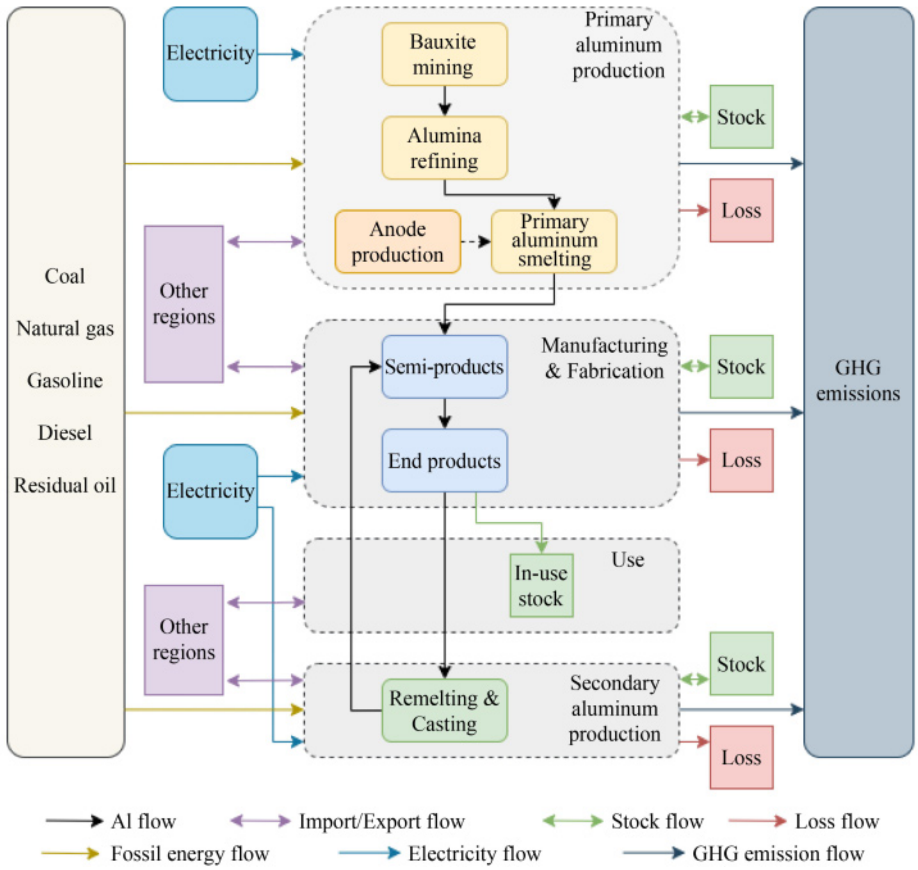

Fig. 1 System boundary of GHG emission and MFA in China's Al cycle.

dual oil, gasoline, coal, and natural gas combustion and embodied carbon emission from electricity consumption. In addition, since the LCA framework in the study described in the present paper is only linked with the Al industry, it is not fully consistent with the MFA framework. For example, the Al industry is not involved in the anode production, this anode production is excluded from the MFA boundary. However, it is included in the GHG boundary because it provides necessities (carbon anodes for electrolysis process) to the PAS stage. As such, the U stage is excluded from the GHG emission boundary because it is related to consumption behaviors, but not relevant to the Al industry.

2.2 China's Al flows

The law of matter conservation is the basis of MFA [31]. Al flows could be calculated from the mass flows of the Al contained products, shown in Eq. (1). Equation (2) shows the Al flows balance in each Al life stage. The Al inflows of one stage must equal those of the same stage.

$$X_i = c_i \times M_{i,\text{mass}}, \tag{1}$$

$$X_{\text{input},j} + X_{\text{import},j} = X_{\text{output},j} + X_{\text{export},j} + X_{\text{loss},j} + X_{\text{stock},j}, \tag{2}$$

where i = 1, 2, ..., m, indicating various Al contained products; j = 1, 2, ...,n, indicating different stages of Al life cycle; c_i is the Al concentration in product i; $M_{i,\text{mass}}$ is the mass flow of product i; X_i is the pure Al flow of product i; $X_{\text{input},j}$ is the Al outflow from stage j–1; $X_{\text{import},j}$ is the Al contained product imported into stage j; $X_{\text{output},j}$ is the Al mass flow to stage j + 1; $X_{\text{export},j}$ is the Al contained product generated from stage j but exported to other regions; $X_{\text{loss},j}$ is the Al loss from stage j; and $X_{\text{stock},j}$ is the Al mass flow of stage j to stocks.

2.3 Energy consumption and GHG emission related to China's Al production

The energy consumption generated from China's Al production was calculated by using the LCA framework, in which the coal, natural gas, gasoline, diesel, residual oil, and electricity consumption are included [32]. Equation (3) shows the calculation of the energy consumption of China's Al industry in year y, while Eqs. (4)–(6) show the calculation of the GHG of China's Al industry in year y:

$$E_y = \sum_i \alpha_i \times Q_{i,y}, \tag{3}$$

$$GHG_y = \sum_j GHG_{j,y} + \sum_k GHG_{\text{electricity},k,y}, \tag{4}$$

$$GHG_{j,y} = \beta_j \times Q_{j,y}, \tag{5}$$

$$GHG_{\text{electricity},k,y} = GEF_{\text{electricity},k,y} \times Electricity_{k,y}, \tag{6}$$

where i = 1, 2, ...,6, indicating the coal, natural gas, gasoline, diesel, residual oil, and electricity consumption; j = 1, 2, ...,5, indicating the coal, natural gas, gasoline, diesel and residual oil; y is the selected year in the study period; k is the selected province in the study; E_y is the total energy consumption of China's Al industry in year y; α_i is the average low calorific value of energy source i; $Q_{i,y}$ is the consumed energy amount from source i in year y; GHG_y is the total GHG emission from China's Al industry in year y; $GHG_{j,y}$ is the GHG emission from energy source j in year y; $GHG_{\text{electricity},k,y}$ is the GHG emission from electricity consumption in province k in year y; β_j is the coefficient of carbon emission of energy source j; $GEF_{\text{electricity},k,y}$ is the GHG emission factor of the power system in province k in year y; and $Electricity_{k,y}$ is the electricity consumption of the Al industry in province k in year y.

Different provinces have different GHG emission factors (GEF). The formula of $GEF_{\text{electricity},k,y}$ is expressed in Eq. (7). The electricity transfer among different provinces is excluded due to the existence of captive power plants. Al industries upload their electricity from their own captive power plants to local power grids in order to purchase electricity from local power grids with extremely low prices, which means that they do not need to purchase electricity from other provinces,

$$GEF_{\text{electricity},k,y} = \frac{\sum_l \beta_l \times Q_{l,k,y}}{kWh_{k,y}}, \tag{7}$$

where l is the type of energy sources consumed for power generation; β_l is the coefficient of carbon emission of energy source l; $Q_{l,k,y}$ is the consumed energy amount from source l for power generation in province k in year y; and $kWh_{k,y}$ is the total electricity generation in province k in year y.

A cradle-to-grave perspective is adopted in the LCA framework of the study described in the present paper. The PAP stage, the M&F stage, and the SAP stage were taken into consideration when calculating the energy consumption and corresponding GHG emission of China's Al industry, while the U stage was excluded because it belongs to consumer behaviors rather than industrial production. $GEF_{\text{electricity},k,y}$ was used to calculate GHG emissions in the PAP stage and the M&F stage. The average GEF of the national power system was used to calculate the GHG emissions in the SAP stage due to a lack of province-specific data for secondary Al production. The anode production is regarded as a part of PAS when accounting the corresponding GHG emission.

2.4 Decomposition analysis

The study described in the present paper utilizes the logarithmic mean divisa index (LMDI) method to uncover the driving factors of Al production-related GHG emission at the province level. The LMDI decomposition method is widely applied to identify the drivers of CO_2 emission changes [33] due to its advantages of no residual terms and aggregation consistency [34]. The PAS stage is selected for this decomposition analysis because of data integrity and representativeness. GHG emissions are generated from primary Al smelting and anode production in the PAS stage. The electricity structure, industrial distribution, secondary Al production ratio, and Al demand are the key driving factors that can affect China's Al production-related GHG emission. The Al demand effect (ADE) is one positive driving factor that increases GHG emission, while the electricity structure effect (ESE), industrial distribution effect (IDE), and SAP ratio effect (SRE) are negative factors and can mitigate GHG emission. These driving factors are refined from the spatiotemporal evolution features of China's Al industry, and the application of such a LMDI method can help identify their contributions to mitigating GHG emission in different historical periods. Equations (8)–(14) present the application of the LMDI method,

$$\begin{aligned} GHG_i^t &= GEF_i^t \times \frac{PAP_i^t}{PAP^t} \times \frac{PAP^t}{TAP^t} \times TAP^t \\ &= ESE_i^t \times IDE_i^t \times SRE^t \times ADE^t, \end{aligned} \tag{8}$$

$$\begin{aligned} \ln(GHG_i^t) &= \ln(ESE_i^t) + \ln(IDE_i^t) \\ &\quad + \ln(SRE^t) + \ln(ADE^t), \end{aligned} \tag{9}$$

$$\begin{aligned} \Delta GHG_i^{t-m} &= GHG_i^t - GHG_i^m = \Delta ESE_i^{t-m} \\ &\quad + \Delta IDE_i^{t-m} + \Delta SRE^{t-m} + \Delta ADE^{t-m}, \end{aligned} \tag{10}$$

$$\Delta ESE_i^{t-m} = \frac{GHG_i^t - GHG_i^m}{\ln(GHG_i^t) - \ln(GHG_i^m)} \times \ln\left(\frac{ESE_i^t}{ESE_i^m}\right), \tag{11}$$

$$\Delta IDE_i^{t-m} = \frac{GHG_i^t - GHG_i^m}{\ln(GHG_i^t) - \ln(GHG_i^m)} \times \ln\left(\frac{IDE_i^t}{IDE_i^m}\right), \tag{12}$$

$$\Delta SRE^{t-m} = \frac{GHG_i^t - GHG_i^m}{\ln(GHG_i^t) - \ln(GHG_i^m)} \times \ln\left(\frac{SRE^t}{SRE^m}\right), \tag{13}$$

$$\Delta ADE^{t-m} = \frac{GHG_i^t - GHG_i^m}{\ln(GHG_i^t) - \ln(GHG_i^m)} \times \ln\left(\frac{ADE^t}{ADE^m}\right), \tag{14}$$

where i is the investigated province; t and m represents year t and year m in the study period, respectively; GHG_i^t is the GHG emission generated from the PAS stage in province i in year t; GEF_i^t is the GEF of the PAS in province i in year t, which could be regarded as electricity structure effect (ESE) because electricity is the main energy consumption of the PAS; PAP_i^t/PAP^t is the proportion of the PAP in province i in year t, which could be regarded as the industrial distribution effect (IDE); PAP^t/TAP^t is the proportion of the PAP in the total primary Al production (TAP) in year t, which could be regarded as the SAP ratio effect because the amount of the TAP equals the amount of the PAP and the SAP; and TAP^t is the total Al production in year t, which could be regarded as the Al demand effect because the total amount of the imports and exports in the PAS stage is neglectable compared with the primary Al production.

2.5 Uncertainty analysis

Both Gauss's law of error propagation and Monte Carlo simulation can be applied to evaluate the uncertainties in the MFA framework [35]. Monte Carlo simulation is more useful if the data are not normally distributed or if deviations are too large, while the error propagation formula are more convenient if data sources are more reliable. The study described in the present paper adopts the error propagation formula for uncertainty analysis since the data of the Al flows have been verified by previous literatures. Equation (15) shows the error propagation formula, while Eq. (16) shows the error propagation formula in additional multiplication:

$$X = \sqrt{\sum_i u_i^2}, \tag{15}$$

$$X = \sum_i u_i, \tag{16}$$

where $i = 1, 2, ..., k$, representing the number of independent variable; u represents the uncertainty of the independent variable, with values of 2%, 5%, and 10%, depending on data sources; and X represents the uncertainty of the dependent variable.

2.6 Data sources

The Yearbooks of Nonferrous Metals Industry of China (2000–2018) are the main data sources for China's Al flows and energy consumption in the study described in the present paper. Other public sources, such as the websites related to Al production, provide the additional information and data. Necessary coefficients for China's Al production are obtained from the International Al Institute (IAI), and several relevant papers [36–39]. The data related to electricity structure are obtained from the *China Electric Power Yearbooks* (2000–2017) and the *National Bureau of Statistics* (2018–2020). The GEF values are calculated from the *China Energy Statistical Yearbooks* (2000–2020). Tables S1 and S2 in Electronic Supplementary Material (ESM) list the data sources in detail. The uncertainty analysis results of MFA are presented in Fig. S1 in the ESM. The GEF of primary Al production in the study described in the present paper and other relevant studies are listed in Table S5 in the ESM. The GHG emission of the Al industry from other relevant studies are listed in Table S6 in the ESM.

3 Results and discussion

3.1 Spatiotemporal evolution features of China's Al flows

Figure 2 demonstrates the Sankey diagram of China's cumulative Al flows from 2000 to 2020. Table S3 in the ESM presents the detailed flow data of China's Al cycle. In total, 383.87 Mt of primary Al and 81.99 Mt of secondary Al were consumed in China in the last two decades, in which the ratio of the secondary Al (SAR) to the total Al is only 17.60%. To meet the soaring Al demand, China imported 244.15 Mt of Al and 205.19 Mt of bauxite, leading to the fact that the primary Al external dependency rate reached 54.34%. In the SAP stage, China consumed 92.53 Mt of Al scraps, including 39.67 Mt of imported scraps and 52.86 Mt of domestic scraps. In the M&F stage, China imported 11.98 Mt of Al and exported 85.53 Mt of Al through Al-containing products (ACPs) trade. In terms of China's Al consumption structure, the building and construction (BC) sector (111.11 Mt) was the dominant Al consumption sector, followed by the transportation (TR, 78.48 Mt), the electrical engineering (EE, 53.71 Mt), the machinery and equipment (ME, 39.90 Mt), containers and packaging (CP, 28.47 Mt), and the consumer durables (CD, 28.46 Mt). Taking the year 2000 as the baseline year, the cumulative in-use stock reached 363.63 Mt in 2020, of which 52.14% were stocked in building and construction, and transportation sectors.

The spatiotemporal evolution features of China's Al flows are illustrated in Fig. 3. China's TAP, including the PAP and the SAP, has increased steadily from 3.74 Mt in 2000 to 44.40 Mt in 2020. However, the secondary Al ratio (SAR) fluctuated and ranged from 15% to 20% (Fig. 3(a)). Although China's SAP had increased from 0.75 Mt in 2000 to 7.55 Mt in 2020, the low SAR indicated that secondary Al was not widely used in various sectors.

Figure 3(b) exhibits China's Al in-use stock from 2000 to 2020. China's Al in-use stock had increased from 4.18 Mt in 2000 to 35.01 Mt in 2020, with an annual growth rate of 11.21%. The BC sector and the TR sector are the top two Al consumption sectors, accounting for almost 50% of the total Al consumption. In particular, the annual growth rate of the BC sector is 10.20%, lower than the average growth rate, while the annual growth rate of the TR sector is 15.08%, which is the highest of all the relevant sectors. Besides, the annual growth rate of the

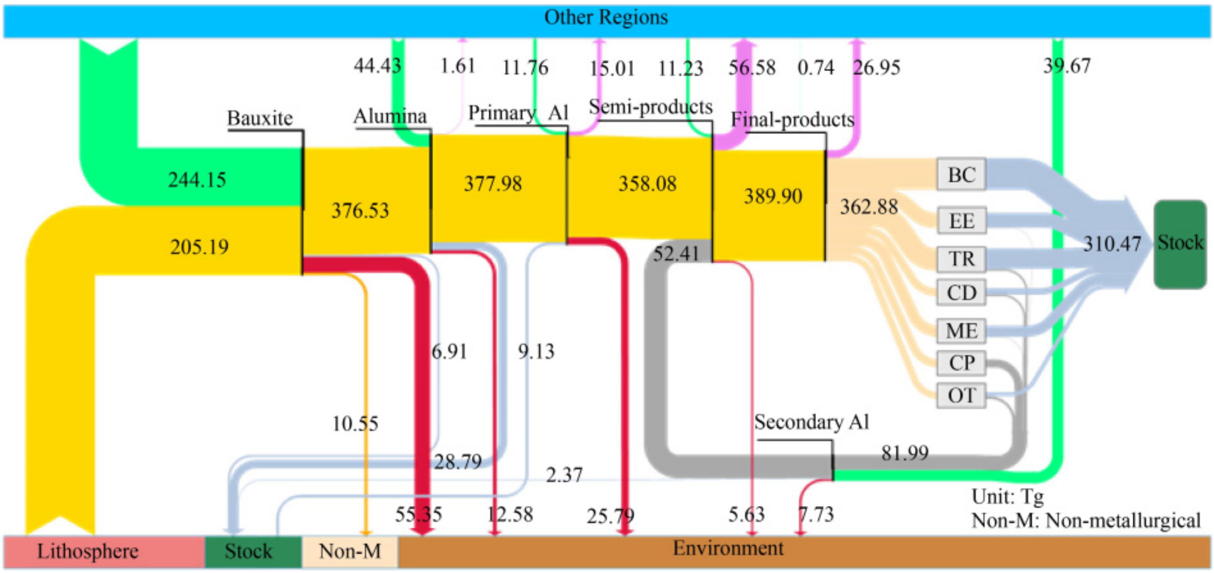

Fig. 2 China's cumulative Al flows from 2000 to 2020 (import flow (green), export flow (pink), production flow (yellow), loss flow (red), reuse flow (gray), and stock flow (blue)).

CP sector and the EE sector is 14.59% and 14.20%, respectively. The annual growth rate of the ME sector is the lowest, which is 6.96%.

Figure 3(c) presents the regional distributions of bauxite reserves, alumina production, primary Al production, and semi-products between 2010 and 2020. Due to the concerns on storage and transportation costs, China's Al industry mainly locate in those provinces with bauxite reserves. Shandong is one exception because this province has many seaports and can rely on bauxite import. Currently, Shandong, Shanxi, Henan, and Guangxi are major primary Al production centers.

Geographically, north-west China is the production center of the primary Al while south-east China is the production center of Al semi-products. The Hu line (or the Heihe-Tengchong line, a straight line connecting Heihe City in Heilongjiang and Tengchong City in Yunnan) divides primary Al production and consumption places. North-west China has become China's PAP center because of its abundant natural resources, especially coal for electricity generation. South-east China has become China's primary Al consumption center and semi-products production center because of its large population and diversified industrial development [40]. For example, Henan, located in central China, produced 3.72 Mt of primary Al and 3.44 Mt of Al semi-products in 2010, while the PAP decreased to 1.70 Mt and the semi-products production increased to 8.40 Mt in 2020. The PAP in Xinjiang and Inner Mongolia, both located to the west of the Hu Line, increased dramatically from 2010 to 2020. In 2010, there were almost no primary Al industries in Xinjiang and only 1.66 Mt of primary Al were produced in Inner Mongolia. However, such figure reached 5.82 Mt and 5.62 Mt in Xinjiang and Inner Mongolia in 2020, respectively. Similarly, Yunnan, located in south-west China, increased its PAP from 0.77 Mt in 2010 to 2.44 Mt in 2020, partly due to its rich hydropower. Another key feature is that the PAP of Shandong increased quickly due to its high bauxite import. But the price of imported bauxite is higher than that of domestic bauxite, thus Shandong had to extend its Al industrial chain to gain its competitive advantage in the markets.

3.2 GHG emission of China's Al cycle

3.2.1 Overview of Al-related energy consumption and GHG emissions

The results of China's energy consumption in the Al industry are illustrated in Fig. 4(a). It shows that the accumulative energy consumption of China's Al cycle reached 36.39 EJ during 2000–2020, of which 57.57% was from electricity consumption and 31.50% was from coal consumption. From a life cycle perspective, the PAP stage consumed 31.60 EJ, in which the BM stage consumed 0.17 EJ, the AR stage consumed 10.83 EJ, the anode production stage consumed 1.78 EJ, and the PAS stage consumed 18.80 EJ. The M&F stage consumed 4.04 EJ and the SAP stage consumed 0.76 EJ. The average energy consumption factor (ECF) of Al in PAP was 79.33 kJ/g and the ECF of Al in SAP was 9.22 kJ/g in the period of 2000–2020.

Figure 4(b) manifests the accumulative GHG emission of China's Al cycle. Such a figure reached 6256.96 Mt CO_2 during 2000–2020, in which 78.14% was from consumed electricity and 17.31% was from coal combustion. From a life cycle perspective, 91.05% of the total GHG emission was generated in the PAP stage, in which GHG emissions generated from PAS and anode

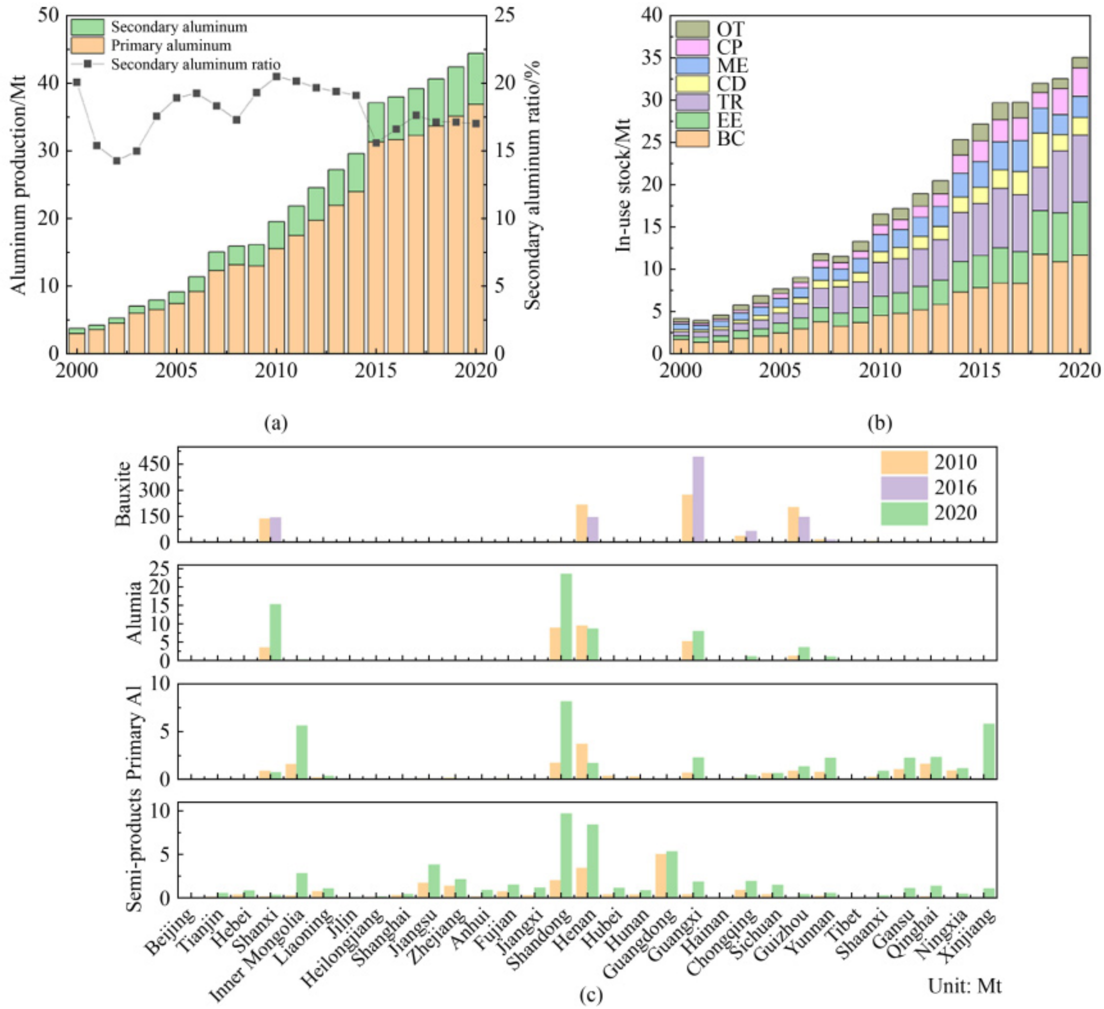

Fig. 3 Spatiotemporal evolution of China's Al industry.

(a) Secondary Al ratio from 2000 to 2020; (b) China's Al in-use stocks from 2000 to 2020; (c) regional distribution of bauxite reserves, alumina production, primary Al production, and semi-products production in 2010 and 2020.

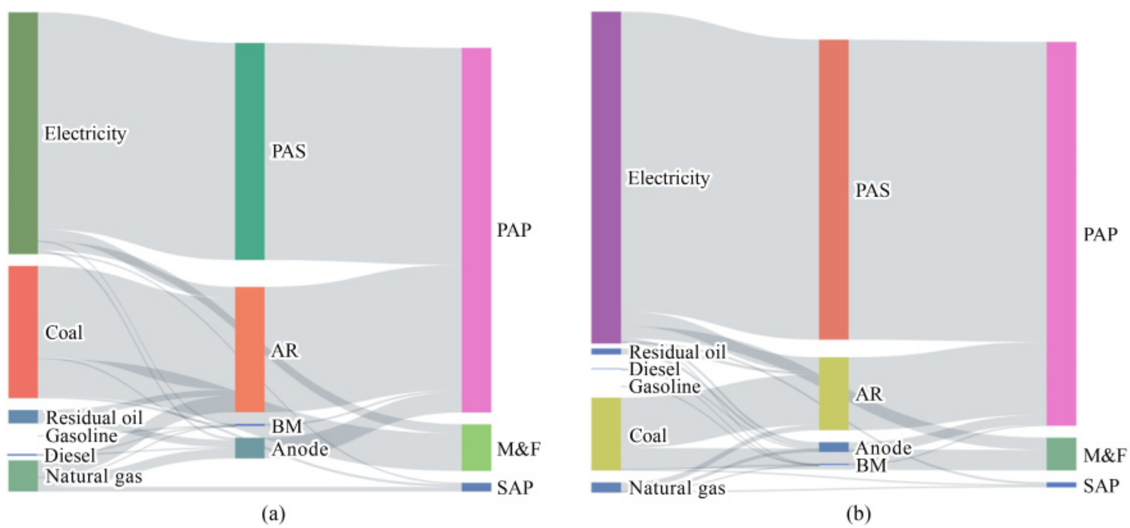

Fig. 4 Accumulative energy consumption and GHG emission from China's Al cycle during 2000–2020.

(a) Accumulative energy consumption, EJ; (b) accumulative GHG emissions, Mt CO_2.

production contributed 73.47% of the total accumulated GHG emission. 486.24 Mt of CO_2 and 73.59 Mt of CO_2 were generated in M&F and SAP, respectively. The average GEF of Al in PAP was 14.3 (the mass ratio of carbon dioxide to Al, g-CO_2/g-Al), while the average GEF of Al in SAP was 0.9. Especially, the overall GHG emission can be reduced by 93.73% if all the Al can be supplied by the secondary Al.

3.2.2 GHG emission reduction potential in PAS

Figure 5(a) depicts the GHG emissions of China's Al cycle from 2000 to 2020. Such GHG emission increased from 64.27 Mt CO_2 in 2000 to 517.38 Mt CO_2 in 2020. PAS was the major GHG emission stage. In 2000, 32.42 Mt of CO_2 was produced in the PAS stage, accounting for 50.44% of the total CO_2 from China's Al industry. The proportion generated from PAS to the total CO_2 reached 72.51% in 2020, indicating a great GHG emission reduction potential in PAS. Figure 5(b) illustrates the GEF of China's Al cycle. The GEF value (the mass ratio of carbon dioxide to Al, g-CO_2/g-Al) decreased from 23.15 in 2000 to 14.54 in 2020. The year 2008 is an important year on China's Al industry. In 2008, the GEF value was 21.74. The average annual reduction rate was 0.78% between 2000 and 2008, but such a figure was 3.30% between 2008 and 2020. The implementation of the *Circular Economy Promotion Law* released by the Standing Committee of the National People's Congress in 2008 was the major driving force for such a decreased GEF.

The GEF value decreased in the AR, M&F, and SAP stages, but remained unchanged in the PAS stage. The GEF value in the AR, M&F, and SAP stages was 5.30, 3.24, and 3.3 in 2000, respectively, and 2.30, 0.94, and 0.97 in 2020, respectively. Instead, such a figure in PAS was 10.85 in 2000 and 10.12 in 2020. In terms of energy consumption types, electricity was the only energy source in the PAS stage and coal was the main energy source in other stages. Consequently, it is critical to pay more attention to the electricity consumption from the PAS stage since the majority of GHG emission was generated in this stage.

3.2.3 Impact of electricity structure on GEF generated from PAS

It is clear that electricity structure affects the GEF value. The GEF of electricity decreased from 922.6 g/kWh in 2000 to 716.2 g/kWh in 2020 at the national level. Such a figure ranged from approximately 100 g/kWh to 1200 g/kWh at the provincial level, which is listed in Table S4. Shandong, Henan, Xinjiang, Inner Mongolia, Qinghai, Gansu, Yunnan, and Ningxia were the top eight provinces/regions in terms of accumulative PAP from 2000 to 2020, accounting for 77.58% of the national total PAP. Figure 6 illustrates the regional disparity of GEF from PAS and anode production (defined as the GEF of 1 g Al in electrolysis process, GEF-E, g-CO_2/g-Al). Inner Mongolia had the highest GEF-E in 2020 (16.38), while Yunnan had the lowest GEF-E in 2020 (1.87). This indicates that the corresponding GHG emission can be reduced by 88.58% if all the primary Al production in Inner Mongolia is transferred to Yunnan. Inner Mongolia highly relies on coal-burning power plants to generate electricity, in which the electricity proportion from coal-burning power plants reached 84.88% in 2020. Compared with Inner Mongolia, Yunnan has more diversified electricity sources, such as hydro-power, wind power, and solar power, in which the electricity proportion from coal-burning power plants was only 11.87% in 2020.

To meet the increasing Al consumption, Shandong, Xinjiang, and Inner Mongolia increased their primary Al production capacities although their GEF-E values are much higher than those of other provinces, indicating the imbalanced Al production distribution in China. Unfortunately, those provinces with lower GEF-E values did not increase their primary Al production, implying an urgent

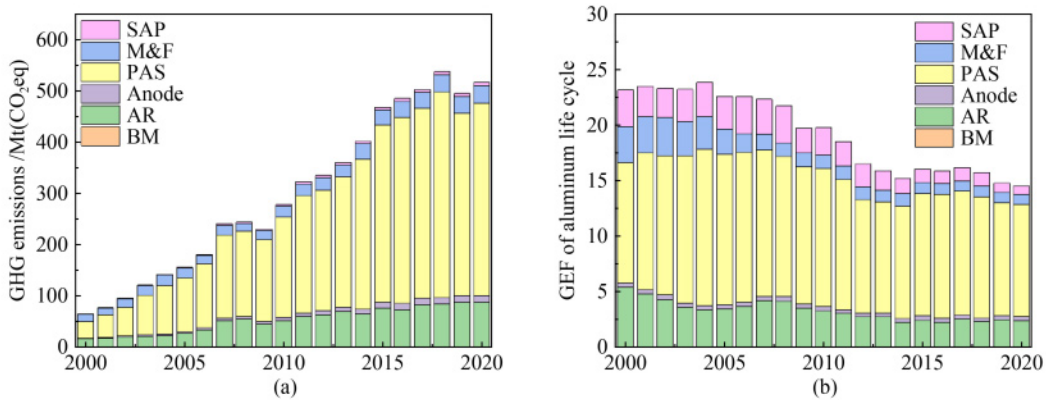

Fig. 5 GHG emissions of China's Al cycle from 2000 to 2020.
(a) GHG emissions; (b) GHG emission factors.

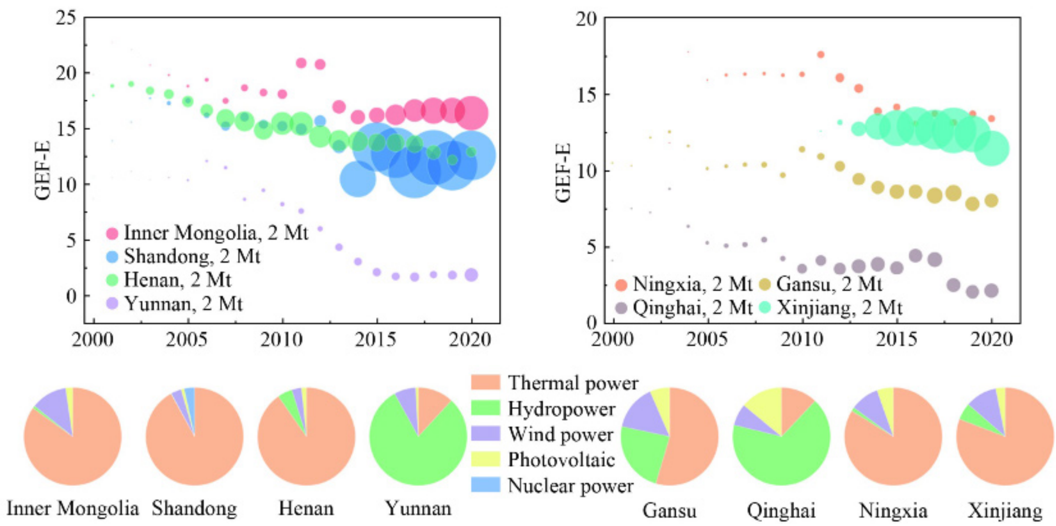

Fig. 6 GEF-E in Inner Mongolia, Shandong, Henan, Yunnan, Ningxia, Gansu, Qinghai, and Xinjiang (The bubble size denotes the primary Al production of each province while the pie chart represents the electricity structure of each province in 2020.)

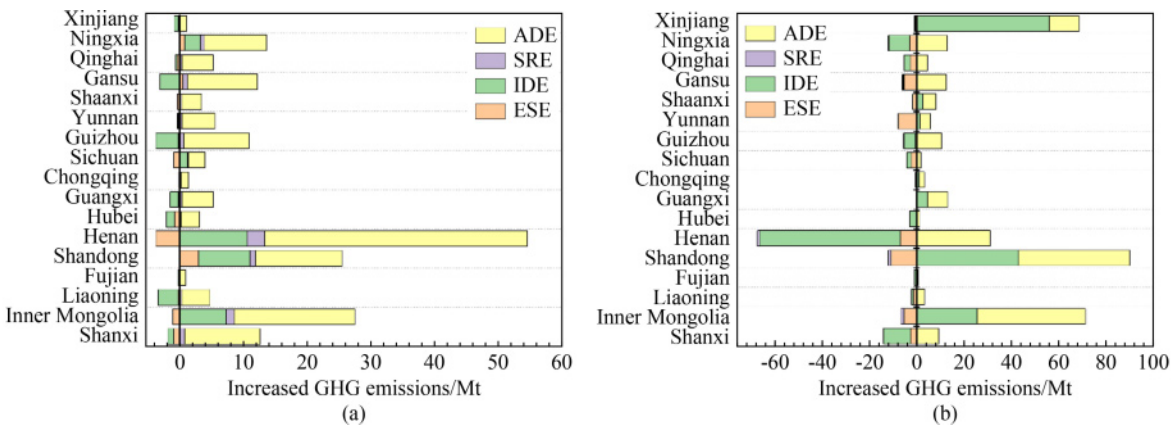

Fig. 7 LMDI results.
(a) 2000–2010; (b) 2010–2020.

need to transfer such primary Al production from those provinces with higher GEF-E values to such provinces.

3.3 Driving factors of Al-related GHG emissions

Figure 7 displays the LMDI results. The key driving factors for this LMDI study include the electricity structure effect (ESE), the industrial distribution effect (IDE), the SAP ratio effect (SRE), and the Al demand effect (ADE). Among these four driving factors, ADE is a factor inducing high GHG emissions, while other three factors represent different impacts in different periods and provinces. In 2000–2010, the ESE was reduced by 3.81 Mt CO_2, while other three factors induced more GHG emissions, with an IDE of 14.91 Mt CO_2, an SRE of 9.91 Mt CO_2, and an ADE of 147.36 Mt CO_2, respectively. Henan, Inner Mongolia and Shandong, were the top three provinces/regions with the most GHG emissions from PAP. In addition, ADE induced the highest GHG emissions in the two provinces and the one autonomous region. Such results indicate that China's Al industry was mainly focused on meeting the increasing Al demand in this period, without paying adequate attention to climate change.

In 2011–2020 both ESE and SRE factors mitigated the overall GHG emissions, with 50.86 Mt of CO_2 and 5.69 Mt of CO_2, respectively, while IDE and ADE induced more GHG emissions in the same period, with 39.82 Mt of CO_2 and 211.6 Mt of CO_2, respectively. Different from the period of 2000–2010, SRE became a mitigation factor although its impact was still marginal, indicating that the Al recycling had not been fully promoted and there is a great potential to further enhance the Al recycling. ESE was a major mitigation factor in all the investigated provinces and regions. For instance, the reduced GHG amount induced by ESE was higher than that increased by ADE in Yunnan, reflecting that the optimization of electricity power system can contribute to the carbon neutrality target of the Al industry. Shandong, Xinjiang, and Inner Mongolia were the top regions in terms of GHG emissions from PAP in this period. Similarly, IDE induced the highest GHG emissions in the said regions, further verifying that the said regions relied on increasing their production scales to meet the increasing Al demands. However, IDE mitigated GHG emissions in Henan and Shanxi, partly reflecting the fact that reasonable Al industrial distribution can contribute to the carbon neutrality targets the Al industry.

When accounting Al material flows, relevant data could be categorized into direct data and indirect data. Direct data refer to the data collected from governmental reports, literatures, and other public sources. Coefficients of variation (CV) of the direct data were set as 2% from governmental reports, 5% from literatures, and 10% from other public sources. Indirect data were the data calculated from the direct data, in which the CV values were calculated from Gauss's law of error propagation. The results of uncertainty analysis are listed in Fig. S1, indicating that they have marginal impacts on the accounting results of GHG emissions.

4 Policy implications

The above results show that increasing the secondary production ratio (SPR), reducing the GEF value of electricity, and transferring the primary production to provinces and regions with lower GEF values can help reduce the Al-related GHG emissions in China. Based upon such findings, several policy implications are proposed to help Al industries meet their carbon neutrality challenges.

First, it is critical to increase Al recycling efforts through the implementation of circular economy [41]. Local governments and Al companies should work together to establish end-of-life Al products collection systems. ACPs are mainly consumed in the east part of the Hu line, indicating that this region is the key place for Al scraps. Currently, such Al scraps are collected by informal vendors and refined by unqualified private firms. Most of these firms do not have advanced Al recycling technologies and energy efficient equipment, leading to lower Al recycling rates, secondary pollution issues, and low quality. To solve such problems, the central government should establish secondary Al products standards and make appropriate policies to formalize those vendors, while local governments should improve their enforcement abilities to make sure that all the Al scraps can be collected more efficiently and all the Al recycling firms can operate their businesses under strict environmental regulations. As such, large Al production companies should consider preparing and upgrading their Al recycling production lines and seek technological help from research institutions or universities so that those unqualified recycling firms can be phased out.

Next, the central government should make a national Al industry relocation plan by considering local realities. One key finding of the study described in the present paper is that the local electricity structure has significant impacts on Al-related GHG emissions. Therefore, it would be rational to relocate such Al industries to those provinces with rich renewable and clean power endowments. Carbon tax is a useful economic instrument since it can address environmental externalities by incorporating climate change considerations into the overall Al products costs. Fortunately, the national carbon market has been operated since July 2021, indicating that such an economic instrument may help promote such industrial relocations. The collected tax can be used to facilitate the related research and development activities so that more advanced Al production and recycling technologies will be available and applied by more Al companies. Moreover, besides such a relocation recommendation, all the Al-relevant regions should strive to optimize their electricity structure by encouraging more applications of winder power, solar power, hydro-power, geothermal power, and other clean energy sources, which eventually will contribute to their carbon neutrality targets.

Finally, capacity-building activities should be promoted across the whole country so that all the relevant stakeholders can understand the significance of achieving carbon neutrality in the Al industry. The central government should formulate national Al-related GHG accounting standards and educate all the stakeholders so that they can learn how to accurately calculate the related GHG emissions from their operations. Likewise, the central government should establish a national information platform so that all the stakeholders can share their data, information, technologies, and expertise. In addition, local governments should initiate various efforts, such as regular workshops, internet promotions, and pamphlets. The more developed eastern provinces should also transfer their advanced technologies and equipment to their western counterparts and send technical secondments to help local stakeholders. Moreover, such capacity building efforts should cover all the Al products consumers so that they can realize the significance of the Al industry to the national carbon neutrality target. With improved understanding and awareness, they may change their consumption behaviors by extending the life cycles of their Al products, selling their end-of-life Al-containing products to official vendors, purchasing the Al products produced in those provinces and regions with a much cleaner electricity structure, and avoiding irrational consumption of Al products.

5 Conclusions

Al has become a strategical metal due to its great physical and chemical features. However, Al production is very energy and GHG emission intensive and has become a key barrier for different countries to achieve their carbon neutrality targets. As the world's largest Al production and consumption country, China is facing a great challenge to mitigate its overall GHG emission from the Al industry. Al recycling can significantly reduce such emissions by 93.73%. However, the study described in the present paper found that less than 20% of Al demand was supplied by secondary Al in China. Barriers do exist for further promoting Al recycling, such as insufficient collections, backward technologies and equipment. Thus, it is crucial to promote Al recycling through implementing circular economy.

In terms of GHG emissions from China's Al industry, PAS and anode production contributed to 73.47% of the accumulated GHG emission from China's Al industry for the period of 2000–2020 because electricity was the main energy source of PAS and anode production. The Hu line divides primary Al production and consumption regions. More primary Al production firms were transferred to the west of the Hu line. Although several western provinces, such as Yunnan and Qinghai, has applied more clean energy sources, key Al production province and regions, such as Shandong, Xinjiang, and Inner Mongolia, still rely on coal-burning power plants to provide electricity for their Al production, leading to a high GEF-E value (about 12 during 2000–2020). Therefore, it is important to transfer such Al firms to those provinces and regions with rich renewable and clean power endowments. During this process, economic leverage, such as carbon tax, can effectively facilitate such actions. In addition, capacity building efforts should be initiated so that all the stakeholders can improve their awareness and change their behaviors.

Regional distribution of the secondary Al industry is not investigated in the study described in the present paper due to the lack of relevant data and information. In the future, it would be necessary to further study such an issue so that more valuable insights can be obtained for formulating relevant policies.

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References

1. Rabinovich D. The allure of aluminium. Nature Chemistry, 2013, 5(1): 76
2. Kvande H. Aluminum production in the times of climate change: the global challenge to reduce the carbon footprint and prevent carbon leakage. Journal of Metals, 2020, 72: 296–308
3. USGS. National minerals information center: aluminum statistics and information. 2020, available at website of United States Geological Survey
4. Das S. Achieving carbon neutrality in the global aluminum industry. Journal of Metals, 2012, 64(2): 285–290
5. NBSC. China Statistical Yearbook (2000–2020). 2021, available at website of National Bureau of Statistics of China
6. IAI. Primary Aluminum Production 2000–2020. 2021, available at website of International Aluminum Institute
7. Hao H, Geng Y, Hang W. GHG emissions from primary aluminum production in China: regional disparity and policy implications. Applied Energy, 2016, 166: 264–272
8. Li S, Zhang T, Niu L, et al. Analysis of the development scenarios and greenhouse gas (GHG) emissions in China's aluminum industry till 2030. Journal of Cleaner Production, 2021, 290: 125859
9. CEADs. China CO_2 inventory 2016–2018 (IPCC Sectoral Emissions). 2021, available at website of Carbon Emission Accounts and Datasets
10. Zhang X, Geng Y, Shao S, et al. How to achieve China's CO_2 emission reduction targets by provincial efforts? —an analysis based on generalized Divisia index and dynamic scenario simulation. Renewable & Sustainable Energy Reviews, 2020, 127: 109892
11. Zhang X, Geng Y, Tong Y, et al. Trends and driving forces of low-carbon energy technology innovation in China's industrial sectors from 1998 to 2017: from a regional perspective. Frontiers in Energy, 2021, 15(2): 473–486
12. Chen W Q, Shi L, Qian Y. Aluminium substance flow analysis for mainland china in 2005. Resources Science, 2008, 30(9): 1320–1326 (in Chinese)
13. Chen W Q, Shi L, Qian Y. Substance flow analysis of aluminium in mainland China for 2001, 2004 and 2007: exploring its initial sources, eventual sinks and the pathways linking them. Resources, Conservation and Recycling, 2010, 54(9): 557–570
14. Wang J, Graedel T E. Aluminum in-use stocks in China: a bottom-up study. Journal of Material Cycles and Waste Management, 2010, 12(1): 66–82
15. Chen W Q, Shi L. Analysis of aluminum stocks and flows in mainland China from 1950 to 2009: exploring the dynamics driving the rapid increase in China's aluminum production. Resources, Conservation and Recycling, 2012, 65: 18–28
16. Ding N, Yang J, Liu J. Substance flow analysis of aluminum industry in mainland China. Journal of Cleaner Production, 2016, 133: 1167–1180
17. Li Y, Yue Q, He J, et al. When will the arrival of China's secondary aluminum era? Resources Policy, 2020, 65: 101573
18. Dai M, Wang P, Chen W Q, et al. Scenario analysis of China's aluminum cycle reveals the coming scrap age and the end of primary aluminum boom. Journal of Cleaner Production, 2019, 226: 793–804
19. Song X, Geng Y, Li K, et al. Does environmental infrastructure

investment contribute to emissions reduction? A case of China Frontiers in Energy, 2020, 14(1): 57–70
20. Xu Y, Geng Y, Gao Z, et al. Accounting greenhouse gas emissions of food consumption between urban and rural residents in China: a whole production perspective. Frontiers in Energy, 2021, online
21. Gao F, Nie Z, Wang Z, et al. Greenhouse gas emissions and reduction potential of primary aluminum production in China. Science in China, Series E. Technological Sciences, 2009, 52(8): 2161–2166
22. Ding N, Gao F, Wang Z H, et al. Comparative analysis of primary aluminum and recycled aluminum on energy consumption and greenhouse gas emission. Chinese Journal of Nonferrous Metals, 2012, 22: 2908−2915 (in Chinese)
23. Zhang W, Li H, Chen B, et al. CO_2 emission and mitigation potential estimations of China's primary aluminum industry. Journal of Cleaner Production, 2015, 103: 863–872
24. Yue Q, Wang H, Gao C, et al. Resources saving and emissions reduction of the aluminum industry in China. Resources, Conservation and Recycling, 2015, 104: 68–75
25. Liu Z, Geng Y, Adams M, et al. Uncovering driving forces on greenhouse gas emissions in China' aluminum industry from the perspective of life cycle analysis. Applied Energy, 2016, 166: 253–263
26. Li Q, Zhang W J, Li H Q, et al. CO_2 emission trends of China's primary aluminum industry: a scenario analysis using system dynamics model. Energy Policy, 2017, 105: 225–235
27. Zhang Y, Sun M, Hong J, et al. Environmental footprint of aluminum production in China. Journal of Cleaner Production, 2016, 133: 1242–1251
28. Geng Y, Wei Y M, Fischedick M, et al. Recent trend of industrial emissions in developing countries. Applied Energy, 2016, 166: 187–190
29. Rui X, Geng Y, Sun X, et al. Dynamic material flow analysis of natural graphite in China for 2001–2018. Resources, Conservation and Recycling, 2021, 173, 105732
30. Müller E, Hilty L M, Widmer R, et al. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environmental Science & Technology, 2014, 48(4): 2102–2113
31. Allesch A, Brunner P H. Material flow analysis as a tool to improve waste management systems: the case of Austria. Environmental Science & Technology, 2017, 51(1): 540–551
32. Shan Y, Liu J, Liu Z, et al. New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors. Applied Energy, 2016, 184: 742–750
33. Jiang H, Geng Y, Tian X, et al. Uncovering CO_2 emission drivers under regional industrial transfer in China's Yangtze River Economic Belt: a multi-layer LMDI decomposition analysis. Frontiers in Energy, 2021, 15(2): 292–307
34. Geng Y, Wang M, Sarkis J, et al. Spatial-temporal patterns and driving factors for industrial wastewater emission in China. Journal of Cleaner Production, 2014, 76: 116–124
35. Brunner P H, Rechberger H. Methodology of MFA. In: Brunner P H, Rechberger H, eds. Practical Handbook of Material Flow Analysis. Boca Raton: CRC Press, 2003
36. Cullen J M, Allwood J M. Mapping the global flow of aluminum: from liquid aluminum to end-use goods. Environmental Science & Technology, 2013, 47(7): 3057–3064
37. Yue Q, Du Y, Wang H M. Analysis of Al-contents in social stock and the regeneration. Journal of Northeastern University (Natural Science), 2015, 36(9): 1297–1301 (in Chinese)
38. Liu G, Müller D B. Centennial evolution of aluminum in-use stocks on our aluminized planet. Environmental Science & Technology, 2013, 47(9): 4882–4888
39. Liu S. Contribution analysis of recycled aluminum supply in China based on sustainable supply. IOP Conference Series. Materials Science and Engineering, 2018, 397: 012107
40. Li J, Lu D, Xu C, et al. Spatial heterogeneity and its changes of population on the two sides of Hu line. Acta Geographica Sinica, 2017, 72(1): 148–160 (in Chinese)
41. Geng Y, Sarkis J, Bleischwitz R. Globalize circular economy. Nature, 2019, 565(7738): 153–155