



# The Development Scenarios and Environmental Impacts of China's Aluminum Industry: Implications of Import and Export Transition

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## Abstract

Aluminum is widely used in buildings, transportation, and home appliances. However, primary aluminum production is a resource, energy, and emission-intensive industrial process. As the world's largest aluminum producer, the aluminum industry (ALD) in China faces tremendous pressure on environmental protection. This study combines material flow analysis and scenario analysis to investigate the potential of resource conservation, energy saving, and emission reduction for China's ALD under the import and export trade transition. The results show China's per capita aluminum stock will follow a logistic curve to reach 415 kg/capita by 2030. However, unlike the continued build-up of stocks, domestic demand for aluminum will peak at 44 million tons (MT) in 2025 and fall to 36 MT in 2030. The scenario analysis reveals that China's primary aluminum output could peak in 2025 at around 52 MT if the restrictions are not implemented (Scenario A). Compared to Scenario A, demand for primary aluminum is effectively limited in Scenarios B and C where exports of aluminum products are reduced. Correspondingly, both scenarios also have obvious benefits in reducing the environmental load of China's ALD. Besides, if hydropower used in aluminum electrolysis increases to 25% by 2030, the total GHG emissions in 2030 will be reduced by 12%. Therefore, promoting import/export and energy mix transformation can become an essential means for the sustainable development of China's ALD.

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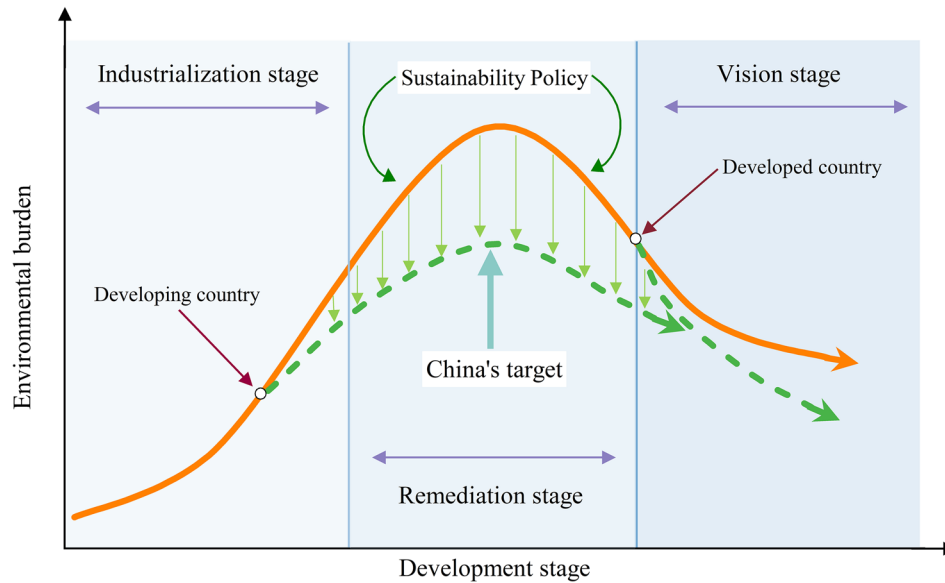
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## Graphical Abstract



**Keywords** Material flow analysis · Life-cycle assessment · Scenario analysis · Aluminum · China

## Introduction

Aluminum is the third most abundant element in the earth's crust, after oxygen and silicon. Due to its excellent physical and chemical properties, metallic aluminum is regarded as a critical primary material for social and economic development. Since 1990, China has ushered in an explosion of primary aluminum production. At present, China's primary aluminum output accounts for more than 50% of the world's total output, reaching about 40 MT. However, the primary aluminum production is one of the most energy- and emission-intensive industrial processes. Therefore, the subject of investigating the future resource and environmental impact of China's ALD has aroused intense interest from national and global stakeholders.

Some studies have been developed to investigate the flows and stocks of aluminum. Among them, the issue of aluminum flows on the global level has been widely concerned [1–4]. There are also some studies that have conducted national-level material flow analysis, such as the United States [5, 6], Austria [7–9], and Italy [10]. In particular, the material flow analysis of aluminum in China has also been deeply reported [11–18]. For example, Chen et al. [14] developed a dynamic top-down model to assess the stocks and flows of aluminum in mainland China from 1950 to 2009. Also, they explored the driving forces of the rapid growth of aluminum production. Ding et al. [15] applied a static substance flow analysis to quantify the

indicators of flows, stocks, trades, and losses for China's aluminum production in 2013.

There are also some published studies investigating the environmental issues of aluminum production. Most of these studies are based on the LCA method to assess the environmental impact per ton of primary or secondary aluminum produced [19–24]. For example, Nunes et al. [21] used the LCA method to analyze the environmental impact of per ton primary aluminum production on the global as well as the global minus China (rest of world) levels. In references [20] and [24], the researchers used the LCA method to make detailed reports on China's environmental footprint per ton of aluminum production. Furthermore, some studies have explored the energy consumption and greenhouse gas (GHG) emissions of aluminum production [25–33]. It is worth noting that some of these studies predicted and analyzed the future trends of energy consumption and CO<sub>2</sub> emissions in China's ALD [27, 28, 31]. However, there is no research to examine the future development trend of the environmental impact from the perspective of the whole industry.

China's primary aluminum production boom began in the early 1990s. The primary aluminum output in China at an average annual growth rate of close to 15%, from 0.8 MT in 1990 to 36.8 MT in 2018. At present, China has become the country with the largest aluminum production and consumption in the world. The reasons for this prosperity can be attributed to two: robust domestic consumption and export demand [14]. However, the aluminum exports of China

may be weakened due to the global pandemic of COVID-19. Therefore, the new national development model of the “internal–external dual cycle” was proposed by the Chinese government [29]. China's ALD also needs to make matching adjustments, that is, moderately reduce aluminum exports and give priority to domestic demand. As a result, the feasible benefits of reducing aluminum exports to address the challenges of resource and environmental impacts should be presented clearly to the stakeholders.

Considering different import/export scenarios, Li et al. [29] have analyzed the development scenarios and GHG emissions in China's aluminum industry till 2030. However, their study used a flows-driven analysis method to simulate aluminum flows and stocks. The aluminum flows obtained by the linear regression analysis will always increase, which may weaken the reliability of this model. In metal flows and stocks forecasting research, the stocks-driven analysis is a more widely used method [34]. Some studies using the stocks-driven models suggested that China's future domestic aluminum demand and primary aluminum production may peak around 2025 [16]. In addition, their study only accounted for energy consumption and GHG emissions and did not assess several other important environmental impacts, including bauxite and fresh water consumption, as well as SO<sub>2</sub> dioxide and NO<sub>x</sub> emissions.

To fill this knowledge gap, this study firstly applied a stocks-driven model to forecast aluminum flows and stocks in China from 2017 to 2030. Second, based on the import/export scenario explored by Li et al. [29], aluminum demand and output were further projected for the period 2017 to 2030. Finally, the resource consumption and environmental emissions of each scenario were calculated under the accounting framework of the LCA. It is worth mentioning that the effect of energy mix restructuring is also considered in this paper in the environmental impact analysis. The conclusions of this study can provide some constructive suggestions for the sustainable development of the aluminum industry in China and the world.

## Methodology

### Modeling Aluminum Stocks and Flows

#### History of Aluminum Stocks and Flows

Based on previous researches [3, 35], an aluminum quantity balance equation was used to estimate the history of stocks and flows.

$$I_i(t) = I_i(t - 1) + D_i(t) + S_i(t), \quad (1)$$

where  $I_i(t)$  and  $I_i(t - 1)$  represent the aluminum stocks for the  $i$  sector in the year  $t$  and  $t - 1$ , respectively;  $D_i(t)$  is the inflows of aluminum for the  $i$  sector in the year  $t$  (i.e., domestic demand); and  $S_i(t)$  is the outflows of aluminum for the  $i$  sector in the year  $t$  (i.e., scrap generation); and  $i$  represents the end-use sector of aluminum, including construction, transportation, electrical, machinery, consumer durables, packaging, and others.

The amount of aluminum scrap produced can be calculated by multiplying the total consumption of aluminum-containing products by their lifetime distribution function. The calculation formula for aluminum scrap generation is as follows [29]:

$$S_i(t) = \sum_{\tau=a}^{b-1} D_i(t - \tau) * P(\tau), \quad (2)$$

where  $S_i(t)$  is the amount of aluminum scrap generation for the  $i$  sector in the year  $t$ ;  $D_i(t - \tau)$  is the amount of aluminum demand for the  $i$  sector in the year  $t - \tau$ ;  $P(\tau)$  is the lifetime distribution of the different aluminum-containing product, the normal distribution function; and  $a$  and  $b$  represent the upper and lower limits of the product life value, respectively.

#### Forecast of Aluminum Stocks and Flows

A dynamic stocks-driven model was developed to predict China's aluminum stocks and flows from 2017 to 2030 [16, 35]. The model assumes a logistic growth curve between per capita aluminum stocks and per capita GDP for each end-use sector. The details are described in Eq. (3).

$$IP_i(t) = \frac{IP_{i,\max}}{1 + e^{[\alpha - \beta * (g(t))]}}, \quad (3)$$

where  $IP_i(t)$  represents per capita aluminum stocks for the  $i$  sector in the year  $t$ ;  $IP_{i,\max}$  represents the saturation value of per capita aluminum stocks for the  $i$  sector;  $\alpha$  and  $\beta$  are the parameters defining the logistic curve; and  $g(t)$  represents per capita GDP in the year  $t$ .

This paper uses the current average per capita aluminum stocks in North America, Japan, and Europe as China's future saturation value ( $IP_{i,\max}$ ) of about 450 kg/capita [16] (Table S1 in the Supplementary Material). Parameters  $\alpha$  and  $\beta$  can be determined from the historical values of per capita aluminum stocks and GDP [35] (Table S1). Then, the future aluminum stocks and flows are calculated based on the future population and GDP projections.

$$I_i(t) = \text{POP}(t) * IP_i(t), \quad (4)$$

$$D_i(t) = I_i(t) - I_i(t - 1) + S_i(t), \quad (5)$$

$$D(t) = \sum_{i=1}^7 D_i(t), \tag{6}$$

$$S(t) = \sum_{i=1}^7 S_i(t), \tag{7}$$

where  $POP(t)$  represents the total population in China in the year  $t$ ;  $D(t)$  is the total inflows of aluminum the in the year  $t$  (i.e., domestic demand); and  $S(t)$  is the total outflows of aluminum in the year  $t$  (i.e., scrap generation).

### Scenario Setting

Similar to previous study [29], this study introduces  $R$  to describe the relationship between domestic consumption and the production of aluminum.  $R$  is the ratio of domestic aluminum demand to total output in a specific year, and its expression is as follows:

$$R(t) = \frac{D(t)}{O(t)}, \tag{8}$$

where  $R(t)$  is the ratio of the trade structure in the year  $t$ ;  $D(t)$  is the amount of aluminum flowing into the domestic in-use stocks in the year  $t$ ; and  $O(t)$  is the total output of aluminum in the year  $t$ , including primary aluminum and recycled aluminum.

The  $R$ -values of China, North America, and Europe from 1980 to 2017 are shown in Table 1. The  $R$ -value in North America and Europe gradually increased from 0.6 in 1980 to 1.4 in 2017. Correspondingly, these two regions have also changed from net exporters of aluminum to net importers. China has always been a net exporter of aluminum ( $R < 1$ ). Especially since 2010, the  $R$ -value has hovered around 0.6, indicating that over 30% of the aluminum produced in China is exported to foreign countries through trade. The experience of North America and Europe shows that the export volume of aluminum produced in China is likely to gradually decrease in the future with the upgrading of the industry. In addition, due to the global pandemic of COVID-19, China has proposed a new model of national development of the “internal–external

dual cycle.” China’s ALD also needs to make corresponding adjustments, that is, to moderately reduce aluminum exports to give priority to domestic demand. Three scenarios are established: the business as usual (Scenario A), the moderate reduction (Scenario B), and the enhanced reduction (Scenario C).

- (1) Scenario A assumes that the  $R$ -value remains unchanged at 0.62 until 2030; this means that China maintains the current high export situation of aluminum products unchanged.
- (2) Scenario B assumes that the  $R$ -value will increase from 0.62 in 2017 to 0.80 in 2030; this means that China is still a net exporter of aluminum, but the net export volume of aluminum is smaller than Scenario A.
- (3) Scenario C assumes that the  $R$ -value will increase from 0.62 in 2017 to 1.0 in 2030; this means that the export volume of aluminum will be further reduced compared to Scenario B, and China’s aluminum net export volume will decrease to 0 by 2030.

## Modeling Aluminum Production

### Total Output of Aluminum

The total amount of aluminum produced under various scenarios in the future can be calculated, as follows:

$$O(t) = D(t) \div R(t) \tag{9}$$

these parameters are the same as above.

### Recycled Aluminum Output

The mathematical formula of recycled aluminum production is as follows:

$$O_r(t) = NS(t) + IS(t) + OS(t), \tag{10}$$

**Table 1** The  $R$ -value of China, North America, and Europe

Year	1980	1985	1990	1995	2000	2005	2010
China	0.77	0.91	0.86	0.94	0.77	0.74	0.66
North America	0.62	0.86	0.73	1.10	0.96	1.31	1.17
Europe	0.60	0.72	0.86	1.01	1.00	1.12	1.26
Year	2011	2012	2013	2014	2015	2016	2017
China	0.63	0.62	0.61	0.61	0.55	0.61	0.62
North America	1.18	1.29	1.28	1.36	1.41	1.42	1.43
Europe	1.25	1.23	1.20	1.28	1.24	1.31	1.36

*Data Sources* International Aluminum Institute [36]. North America: Canada, Mexico, USA. Europe: EU28, Iceland, Macedonia, Moldavia, Norway, Serbia-Montenegro, Switzerland, Turkey, Ukraine

$$NS(t) = O(t) * 10\%, \quad (11)$$

$$OS(t) = S(t) \times 0.75, \quad (12)$$

where  $O_r(t)$  represents the total output of recycled aluminum in the year  $t$ ;  $NS(t)$ ,  $IS(t)$ , and  $OS(t)$  represent the amount of recycled aluminum produced from new scrap, and imported scrap, domestic old scrap in the year  $t$ , respectively; 10% is the rate of new scrap generation during the manufacturing of finished and semi-finished aluminum products; and 0.75 is the conversion rate of recycled aluminum produced from aluminum old scrap.

### Primary Aluminum Output

According to the law of conservation of quality, the calculation formula of primary aluminum output is as follows.

$$O_p(t) = O(t) - O_r(t), \quad (13)$$

where  $O_p(t)$  represents the output of the primary aluminum in the year  $t$ .

### Resource Consumption and Environmental Emission

From the perspective of LCA, primary aluminum production is mainly composed of five production units, namely bauxite mining, alumina refining, carbon anode production, aluminum smelting, and ingot casting (Fig. 1). On the contrary, the resource input and environmental emissions in the secondary aluminum production process will be greatly reduced. Recycled aluminum mainly includes collection, selection, transportation, pretreatment, smelting, and casting processes of scrap (Fig. 1).

For simplicity, we directly use output multiplied by its life-cycle input–output coefficient to calculate resource consumption and environmental emissions [37]. It is worth noting that the source of electricity in the aluminum electrolysis process has a massive impact on the environmental emissions, including primary energy consumption as well as GHG,  $SO_2$ , and  $NO_x$  emissions [20]. Currently, about 90% of the electricity used in the aluminum electrolysis process is coal-fired thermal power, and only 10% is hydroelectric. To illustrate the impact of the change in the energy mix, we divided the environmental impact of primary aluminum production into two types: Primary Al-based coal-fired thermal power and Primary Al-based hydropower (Table 2).

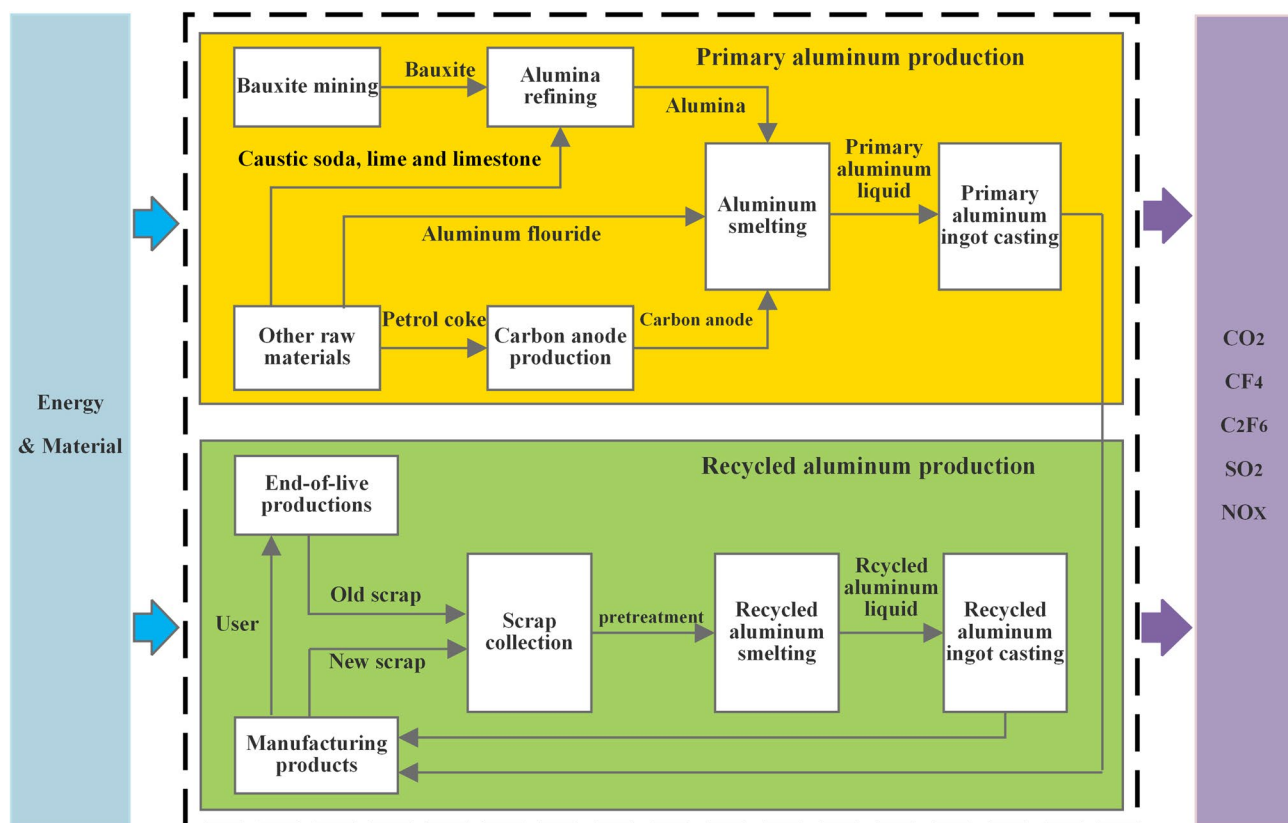


Fig. 1 Production flow chart of primary aluminum and secondary aluminum

**Table 2** Environmental impact of aluminum production

Environmental impact	Primary Al-Coal-fired thermal power	Primary Al-Hydro power	Recycled Al	References
Bauxite consumption (t/t-Al)	4.6	4.6	0	[20, 24]
Water use (m <sup>3</sup> /t-Al)	10.1	10.1	0.9	[20, 24]
Primary energy demand (MJ/t-Al)	263,000	106,000	9212	[20, 24]
GHG emissions (kg CO <sub>2</sub> -eq/t-Al)	21,800	4910	665	[20, 24]
SO <sub>2</sub> emissions (kg/t-Al)	4.8	2.1	1.2	[20, 24, 40]
NO <sub>x</sub> emissions (kg/t-Al)	6.4	3.6	0.2	[20, 24, 40]

The value of environmental impacts on China's ALD can be obtained by the following equations:

$$RS_j(t) = O_p(t) \times CP_j + O_r(t) \times CR_j, \quad (14)$$

$$WE_i(t) = O_p(t) \times [PE(t) \times ETP_i + (1 - PE(t)) \times EHP_i] + O_r(t) \times ER_i, \quad (15)$$

where  $RS_j(t)$  is the consumption of the  $j$ -th resource in the year  $t$ ;  $CP_j$  represents the consumption factor of  $j$ -th resource of primary aluminum production;  $CR_j$  represents the consumption factor of  $j$ -th resource of recycled aluminum production;  $j$  represents the bauxite and fresh water;  $WE_i(t)$  represents the consumption (or emission) of the  $i$ -th substance in the year  $t$ ;  $ETP_i$  represents the consumption (or emission) factor of  $i$ -th substance in primary Al-based coal-fired thermal power;  $EHP_i$  represents the consumption (or emission) factor of  $i$ -th substance in primary Al-based hydropower;  $ER_i$  represents the consumption (or emission) factor of  $i$ -th substance in recycled aluminum production;  $i$  represents the primary energy, GHG, SO<sub>2</sub>, and NO<sub>x</sub>; and  $PE(t)$  the percentage of electrolytic aluminum produced based on coal-fired thermal power generation in the year  $t$ .

## Data Sources

The datasets required for this study can be divided into two levels: calculation of aluminum stocks and flows, and assessment of the environmental impact.

First, the historical inflow ( $D_i(t)$ ) for each end-use sector of aluminum can be obtained by multiplying the total domestic demand by the consumption proportion in each end-use sector. The historical data of domestic aluminum consumption were obtained from the International Aluminum Institute (IAI) [36]. The proportion of consumption of aluminum in each end-use sector was acquired from the IAI [38] (Fig. A1). The historical information of population and GDP per capita was obtained from the China Statistical Yearbook (Table S2) [39]. The data for future forecasts of population and GDP are obtained from previous studies [16, 29] (Table S3). Besides, the life distribution data of aluminum products are needed to calculate the amount

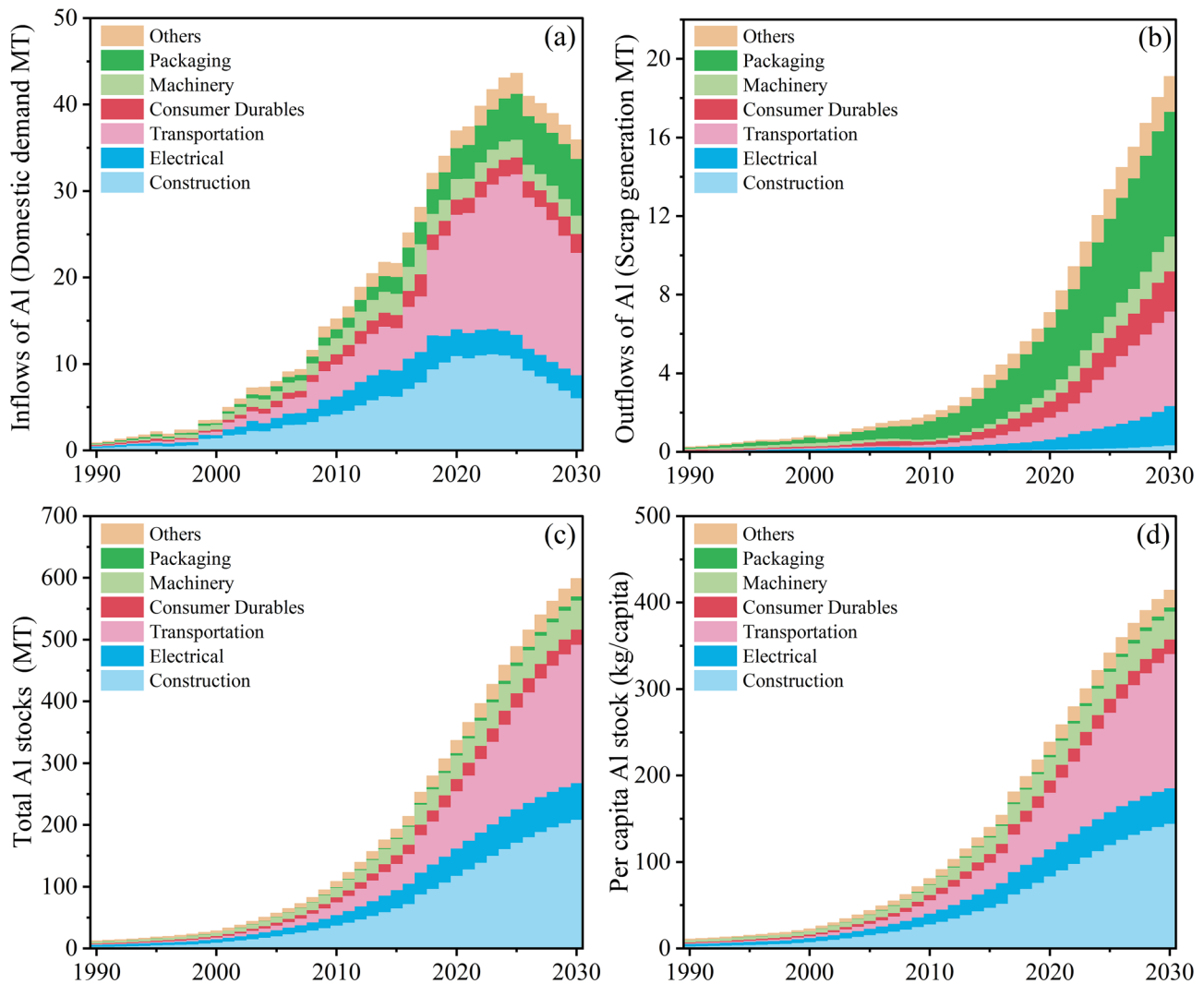
of aluminum scrap generated. These data were obtained from previous literature [2, 3, 5–7]. Second, the life-cycle input–output coefficients of resource consumption and environmental emissions were obtained by reviewing previous LCA studies on aluminum production, as shown in Table 2 [20, 24, 40].

## Results and Discussion

### Aluminum Stocks and Flows

The stocks and flows of aluminum in China are shown in Fig. 2. For nearly 30 years, China's domestic aluminum consumption has been overgrowing, from 0.9 MT in 1990 to 28.7 MT in 2017, with an average annual growth rate of 13.7%. The simulations in this paper show that China's domestic aluminum demand will maintain its growth trend until 2025, peaking at 44 MT. Subsequently, it will decrease to about 36 MT in 2030 (Fig. 2a).

Along with the increase in aluminum consumption, the total aluminum stocks are also accumulating rapidly, about 600 MT in 2030 (Fig. 2c). China's per capita aluminum stock could follow a logistic curve, reaching 415 kg/capita by 2030. Most aluminum stocks are deposited in the construction and transportation sectors, accounting for more than 70% of the total. Specifically, aluminum stock per capita in construction and transportation will be 144 and 155 kg/capita in 2030. Of particular note is the transportation sector. In the United States and Japan, car ownership has exceeded 500 cars per 1000 people, while China only has about 180 vehicles per 1000 people. Moreover, the development trend of lightweight automobiles makes the use of aluminum in the transportation sector also increasing rapidly (Fig. 2a). Therefore, transportation will replace construction as the sector with the most robust aluminum consumption in the next decade. The remaining five sectors account for less than 30% in 2030, including electrical (10%), machinery (8%), consumer durables (4%), packaging (1%), and others (5%). The aluminum stock per capita of electrical, machinery, consumer durables, packaging, and other sectors was 41, 33, 17, 4.6, and 20 kg/capita, respectively.



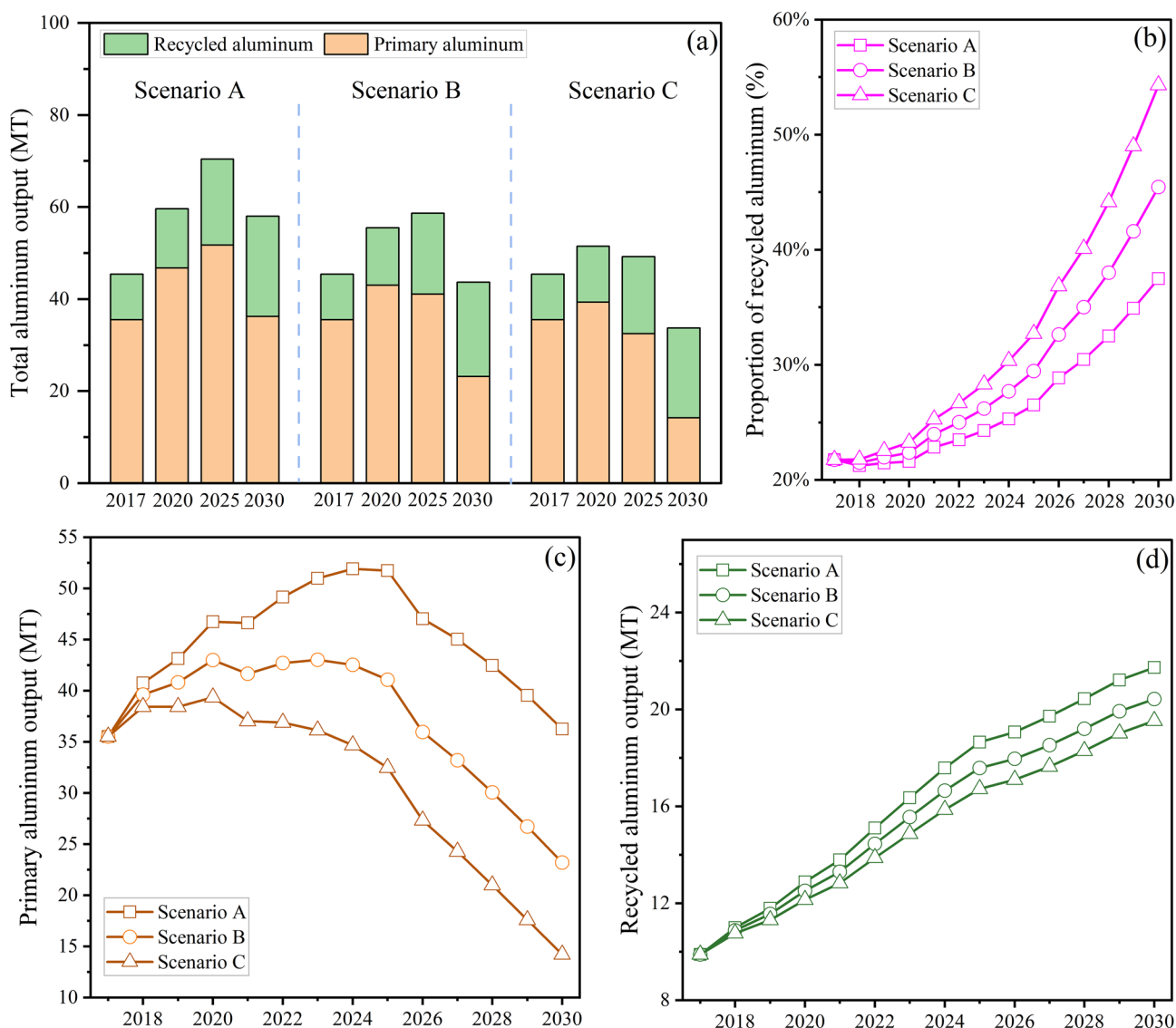
**Fig. 2** The stocks and flows of aluminum in China from 2017 to 2030

In addition, the results also show that the amount of aluminum scrap will increase from 5 MT in 2017 to 19 MT in 2030 at an average annual growth rate of about 11% (Fig. 2b). The apparent difference from in-use stock is that the construction sector does not generate much aluminum scrap, accounting for only 1% of the total in 2030. The aluminum scrap produced in the transportation and packaging sectors accounted for a large proportion of 29% and 25%, respectively. The remaining four sectors had almost the same amount of aluminum scrap. The electrical, consumer durables, machinery, and other sectors accounted for 11%, 14%, 9%, and 11%, respectively. The generated scrap depends mainly on the historical flow of aluminum, and its amount in this paper is consistent with the results of Li et al. [29]. However, the aluminum inflows predicted in this paper are far from previous results [29]. This difference mainly comes from the systematic difference between the flows-driven

and stocks-driven models. Currently, most studies use the stocks-driven model to predict future metal flows and stocks [16, 34]. Furthermore, the results of this study are closer to those of the references [16, 35]. Therefore, it is reasonable to believe that the results of this paper may be more in line with the future development expectations of China's ALD.

### Aluminum Output

Figure 3 shows the production of primary aluminum and secondary aluminum under those three scenarios. In any scenario, China's total aluminum demand and primary aluminum production will peak before 2025. Specifically, China's total aluminum demand will increase to 70 MT by 2025 in Scenario A if restrictions are not taken. The measures of reducing China's aluminum exports can effectively decrease the total aluminum demand (Fig. 3a). In Scenario B and C,



**Fig. 3** The production of primary aluminum and secondary aluminum in 2017–2030

China's total aluminum demand will peak in 2025 (60 MT) and 2020 (52 MT).

The reduction in China's total aluminum demand will be directly transmitted to the production of primary aluminum, which is the shrinking of its output capacity (Fig. 3c). In Scenario A, China's primary aluminum output will climb from 36 MT in 2017 to 52 MT in 2025. In the moderate reduction scenario (Scenario B), China's primary aluminum output increased slower and eventually remained around 40–43 MT during 2020–2025. In the enhanced reduction scenario (Scenario C), China's primary aluminum production will peak at 39 MT in 2020, and be reduced to 14 MT by 2030. It is worth noting that the production of secondary aluminum will increase rapidly no matter which scenario (Fig. 3d). In Scenario C, the proportion of recycled aluminum in total

production will increase from approximately 22% in 2017 to 55% in 2030. Even in the least optimistic scenario (Scenario A), the proportion of recycled aluminum in 2030 will be close to about 38% (Fig. 3b). Therefore, the collection and recycling of aluminum scrap in the future should attract the attention of policymakers.

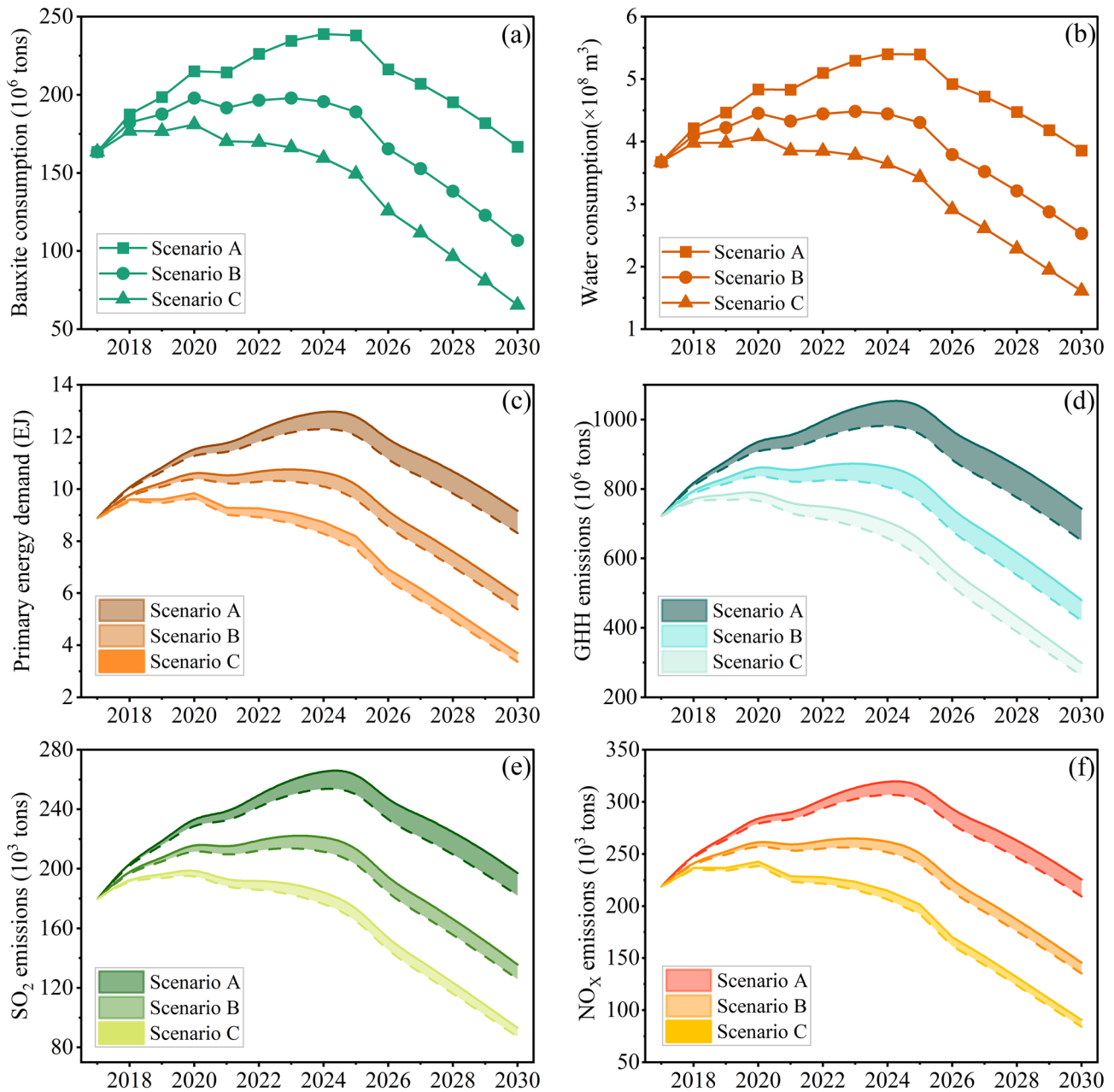
**Resource Consumption and Environmental Emission**

At present, more than 50% of the bauxite required for alumina production in China needs to be imported. However, the overuse of bauxite has tremendous implications for resource utilization and environmental management. The results of this paper indicate that the bauxite consumption of China's ALD will reach about 240 MT by 2025 under



Scenario A and then decrease to 167 MT in 2030. Compared with Scenario A, the demand for bauxite under Scenario B and C would be reduced by 35% and 61% in 2030, respectively. Besides, Scenarios B and C save a cumulative 496 MT and 890 MT of bauxite consumption during 2017–2030 compared to Scenario A. On the premise of giving priority to meeting China's domestic demand, a moderate reduction in aluminum exports is an important measure to alleviate the shortage of bauxite resources. The conservation of water

resources has been highlighted as a critical pillar in shaping the aluminum industry toward sustainable development [37]. The development trend of water resource consumption and bauxite consumption is same for each scenario. This paper assesses the water resources saving benefits brought by reducing aluminum exports for China's ALD. In 2030, the freshwater consumption is  $3.9 \times 10^8$ ,  $2.5 \times 10^8$ , and  $1.6 \times 10^8$  m<sup>3</sup> under Scenario A, Scenario B, and Scenario C, respectively (Fig. 4).



**Fig. 4** Environmental impacts of China's aluminum industry under different scenarios. In **c–f**, the solid line at the top represents the environmental burden when the energy structure of aluminum electrolysis does not change (90% coal-fired thermal power and 10% hydro-

power). The lower dashed line represents the environmental burden when the energy structure of aluminum electrolysis is improved (the proportion of hydropower gradually increases from 10% in 2017 to 25% in 2030 [32])

On the whole, the trends of the other four environmental impacts are similar to those of primary aluminum under each scenario, including primary energy demand, GHG emissions, SO<sub>2</sub> emissions, and NO<sub>x</sub> emissions. They will peak in 2025 in Scenario A and B. However, unlike bauxite and new water consumption, these four environmental impacts are influenced by the energy mix. In Fig. 4c–f, the shaded part represents the benefits of primary energy savings and emission reductions of GHG, SO<sub>2</sub>, and NO<sub>x</sub> from the adjustment of the energy structure. In Scenario A, these four environmental impacts will also be reduced by about 12% if hydropower used in aluminum electrolysis increases to 25% by 2030. In the other two scenarios, the reduction effect from the energy mix is somewhat diminished by the decrease in primary aluminum production, but it still exceeds 6%. Therefore, besides reducing the export of aluminum products, optimizing the energy mix in the aluminum electrolysis process is also a meaningful way to reduce the environmental impact.

## Discussion

### Role of Aluminum Produced in China in Meeting Global Demand

China's aluminum net export volume has been increasing since 1990, and it was about 18 MT in 2017. Correspondingly, the proportion of China's aluminum net exports to the world's total consumption (except China) is also increasing, from 0% in 1990 to 35% in 2017 [36]. Therefore, China's production of aluminum products is critical to meeting global aluminum demand. According to forecasts from IAI [36], the total market for aluminum in other regions of the world except China will reach about 65 MT in 2030. In scenarios A and B, aluminum exports may be reduced to 9 MT and 0 MT in China. If China reduces its net exports of aluminum, it may have a significant impact on the worldwide aluminum production chain. Compared with other parts of the world, China's primary aluminum production has a higher resource consumption and environmental waste discharge [21, 41, 42]. Reducing China's aluminum exports can promote the transfer of this part of the production capacity to regions rich in renewable energy (such as Norway, Iceland, and Australia) [43]. Therefore, from an industrial chain perspective, this shift can reduce the global aluminum industry's environmental burden associated with aluminum production.

### Impact of the Reduction Export on the Sustainable Development of China's ALD

For sustainable development, China's primary aluminum production capacity has begun to be restricted and set its

upper limit to about 45 MT. Suppose the previous development trend (Scenario A) is followed. China's primary aluminum production may reach 52 MT (Fig. 3c), which undoubtedly exceeds this limit set by China (45 MT). Therefore, it is a feasible measure to moderately reduce the export volume of aluminum products under China's policy of expanding domestic demand. For example, in Scenario B, the primary aluminum production capacity is maintained at around 45 MT, which meets the need for aluminum in China society and reduces environmental pollutants. This method strikes a good balance between economic development and environmental protection. Therefore, under the constraints of sustainable development, a moderate reduction in the proportion of China's primary aluminum exports is significant for energy conservation and emission reduction.

### Effect of Scrap Aluminum Reuse on China's Aluminum Resources

During the vital process of structural adjustment and developing a circular economy, a shift of aluminum production from bauxite based to scrap based is essential. Compared with bauxite based, the scrap-based method to produce aluminum has apparent advantages in resource input, energy consumption, and environmental emissions (Table 2). Under three scenarios, China would confront a substantial increase in domestic scrap during 2020–2030 due to the vast consumption of aluminum products since 1990. However, there are no well-established policies to manage and process such vast aluminum scrap. It takes 20–40 years for aluminum products to enter the in-use stocks to outflow. China's previous low aluminum consumption resulted in a small amount of aluminum scrap, so it was difficult to form a complete recycling system of aluminum scrap. Second, the aluminum scrap industry is poorly managed and uses backward techniques. For example, some scrapped vehicles are privately refitted to extend their lives. This unsafe practice may cause some loss of aluminum scrap. In addition, some aluminum scrap being processed by illegal small-scale factories in poor technological conditions, which reduces its recycling efficiency and quality. China's ALD should correctly resolve these problems to meet the upcoming boom in recycled aluminum.

### Policy Implications

Based on the above analysis, we have put forward some policy recommendations to promote the sustainable development of China's ALD.

- (1) Moderately reducing aluminum exports. In Scenario A, China's primary aluminum production will rise to 52 MT in 2025, which will pose a considerable challenge

to environmental protection. The total primary energy consumption and GHG emissions are as high as 9.2 EJ and 744 MT in this scenario, respectively. If the export volume of aluminum scrap is reduced (Scenario B), environmental pressure will be significantly reduced (energy consumption 5.9 EJ, GHG emissions 480 MT). In addition, while further reductions in aluminum exports could bring more substantial environmental benefits, it is a serious waste of the young and technologically advanced primary aluminum production facilities in China (Scenario C). Therefore, moderately reducing exports is a better choice for the sustainable development of China's ALD.

- (2) Optimizing the energy mix. The high GHG emission factor of primary aluminum production in China is mainly due to the predominantly coal-fired thermal power supply in the aluminum electrolysis process. In 2018, the proportion of clean energy in primary aluminum smelting was only about 10%, far lower than in other countries and regions (the United States, Australia, and Europe). If hydropower in aluminum electrolysis increases to 25% by 2030, total GHG emissions in 2030 will be reduced by 12%. Also, the refining and smelting energy densities in China were 12,054 MJ/t- $\text{Al}_2\text{O}_3$  and 13,579 kWh/t-Al in 2018, while the current world's advanced levels were 8938 MJ/t- $\text{Al}_2\text{O}_3$  and 13,200 kWh/t-Al [27]. Therefore, China's ALD should further reduce energy intensity and promote clean energy to reduce its environmental burden.
- (3) Improving the technical content and added value of aluminum products. In the past few decades, China's ALD has achieved certain economic benefits by relying on the growing export of aluminum products. However, this economic growth also comes with high environmental costs, which is not in line with the concept of sustainable development. If it wants to strike a balance between economic gains and environmental protection, China can learn from Japan's experience. By importing unprocessed aluminum and then processing it into aluminum-containing semi-finished and finished products (increasing added value), the Japanese aluminum industry reduces environmental burdens and increases economic returns. China's ALD needs to complete the transformation from the export of low-end raw materials to the manufacturing of high-end aluminum products. In order to achieve this goal, measures such as controlling product quality, strengthening worker training, and strict industrial standards should be considered.

## Conclusions

In this study, the scenario analysis was used to discuss the impact of reducing exports on the resource and energy consumption and pollution emissions of China's ALD. If there are no restrictions, China's total aluminum demand may exceed 70 MT by 2030. Although the output of aluminum scrap will gradually increase in the future, primary aluminum production will continue to rise to 53 MT by 2030 due to huge demand. The moderate reduction in exports is critical to the sustainable development of China's ALD. The upper limit of primary aluminum production capacity set by the Chinese government is 45 MT. In Scenario B, China's primary aluminum production is basically stable at 40–45 MT during 2020–2030. Therefore, it is a reasonable choice to control the ratio of aluminum net exports to total production at about 20%. In the future, the government should issue relevant policies to promote the development of China's aluminum processing industry to enhance the technological content and added value of aluminum products. At the same time, the promotion of energy mix transformation and the recycling of aluminum scrap are essential measures to reduce the environmental burden of China's ALD.

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## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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