Supplementary Materials

This study focuses on modeling the flows and stocks of aluminum in six main categories, namely construction, electricity, consumer durables, transport, machinery, and packaging. Therefore, in the supporting information, this study is similarly divided into six sections to illustrate the number of products containing aluminum and the information on aluminum intensity.

Population size is the main driver of aluminum consumption [18]. Since 2014, China has loosened its grip on the one-child policy, gradually implementing "two children alone" and "two children across the board" to encourage population growth (https://www.gov.cn/gongbao/content/2014/content_2561278.htm). Currently, China remains one of the most populous countries in the world, with more than 1.4 billion people. The size of GDP is another factor that affects aluminum consumption [18]. Previous articles on the future demand for metals have often cited it as a driving indicator.

Table S1. Future population, Urbanization rate, and GDP growth rate in China [16, 46, 47].

Year	2020	2025	2030	2035	2040	2045	2050
Population	14.12	14.35	14.50	14.49	14.45	14.30	14.00
Urbanization rate, %	60.48	64.69	68.45	71.90	75.18	78.44	81.80
Year	2018-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
GDP growth rate, %	6.5	5.5	4.5	3.5	3.5	2.5	2.5

This study also looks at the level of urbanization as an important indicator that will drive future consumption of aluminum metal [18]. Previous studies have shown significant differences in metal stocks between urban and rural areas [40, 58]. In calculating the stock of aluminum metal for consumer durables, this study first estimates the total number of urban and rural households based on the total population, the level of urbanization rate, and the size of urban and rural households[18]. The total aluminum metal stock in the consumer durables sector was then calculated on the basis of the number of consumer durables per household in rural and urban areas, the aluminum metal content of the final product, and the total number of households in urban and rural areas [18]. The data on the future level of China's urbanization rate used in this study comes from a research report by the Development Research Centre of the State Council of China (https://www.drc.gov.cn/DocView.aspx?chnid=379&leafid=1339&docid=2894327). Table S1 shows the future population, GDP, and urbanization rate data used in this study.

(1) Construction

In construction, aluminum is mainly found in non-removable fixtures and fittings including, windows, doors, cables, pipes, ceilings, signage, light fittings, etc [33]. The stock of aluminum metal in the building sector is generally calculated by using data on the total floor area of the building and the aluminum content per square meter of floor area. Based on the literature [59], this study firstly divides the buildings into two sub-systems: urban and rural buildings, and then within these two sub-systems into residential and non-residential buildings. Finally, the aluminum stock is calculated for each of the four sub-systems: urban residential, urban non-residential, rural residential, and rural non-residential buildings.

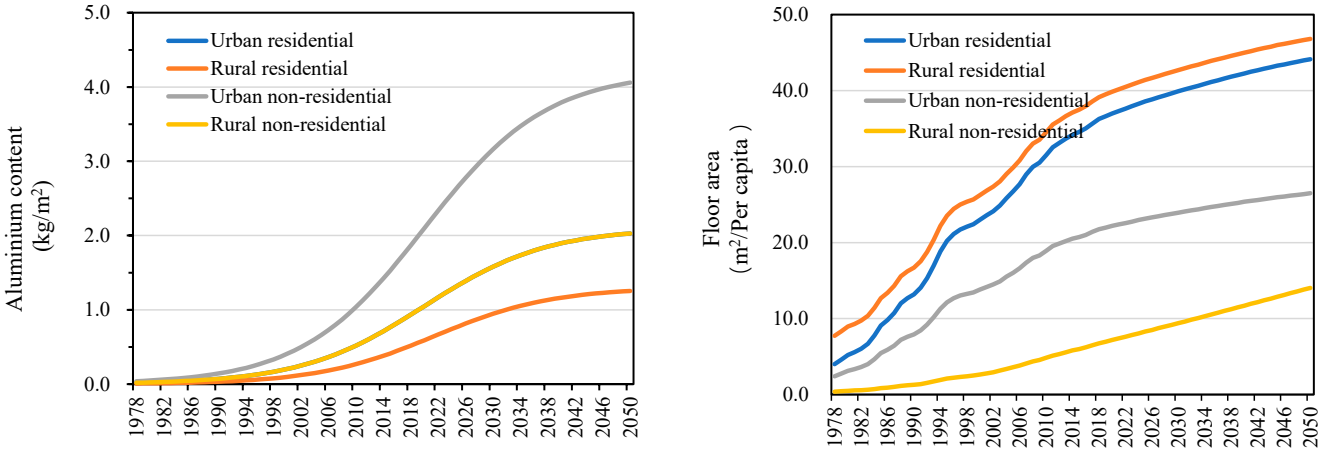


Figure S1. Aluminum contents for different buildings in China, 1978-2050 (Based on literature (Liu et al., 2019; Wang and Graedel, 2010)) (left); Floor space per capita in different buildings in China, 1978-2050 (right).

Data on per capita residential space in urban and rural areas from 1978 to 2018 are from the China Statistical Yearbook. For the years 2018 to 2050, data on urban and rural per capita residential areas are derived from projections of previous studies [16, 59-62]. It is assumed that there is the following functional relationship between per capita living space and per capita GDP, as shown in Equation (S1).

$$Y=A+B\times \mathrm{LN}(GDPC) \quad \text{(S1)}$$

Here, Ydenotes urban or rural per capita housing floor space; $GDPC$ denotes GDP per capita; and A and B represent two model parameters.

Specific values of model parameters A and B can be calculated from historical values of per capita living space and per capita GDP. The results of this paper show that the per capita housing floor space in both urban and rural areas will be about 44 m^2 and 47 m^2 by 2050 (Figure S1), which is in general agreement with the findings of the literature [39, 61, 63]. Based on the literature [59], it is assumed that the ratio of urban residential floor area to non-residential floor area increases gradually from 0.45 to 0.8, and the ratio of rural residential floor area to non-residential floor area increases from 0.05 to 0.2, between 1978 and 2050.

Previous studies have come to different conclusions regarding data on aluminum content in buildings [18, 33-36, 39]. Two previous studies [39, 64] modeled the growth of floor space in China up to 2050 and its impact on building materials and energy demand. Both studies assumed that the aluminum intensity of residential and commercial buildings in China is projected to increase from 2.02 kg/m^2 and 4.9 kg/m^2 in 2010 to 2.20 kg/m^2 and 5.34 kg/m^2 in 2025 and to remain constant thereafter. Using a bottom-up approach, Wang and Graedel [33] examined China's aluminum stocks in 2000 and 2005, and they used data on the aluminum intensity of buildings, as shown in Table S2. Liu, et al. [18] investigated the patterns, drivers, and implications of product and metal inventory accumulation in Chinese megacities from 1980 to 2016, and the aluminum intensity data they used for buildings were 0.5 kg/m^2 for urban dwellings, 0.5 kg/m^2 for rural dwellings, and 4 kg/m^2 for non-residential buildings. Chen [34] estimated the product-level in-use stocks of aluminum in the USA for the period 1960–2009 (and in some cases even longer), and the aluminum strength of residential and commercial buildings increased from 0.04 kg/m^2 and 0.69 kg/m^2 in 1949 to 0.59 kg/m^2 and 4.65 kg/m^2 in 2010. In addition, previous the study [8] have shown that China's consumption of aluminum products was small before 1990, after which it exploded. For these reasons, in this study, it is assumed that the aluminum content of buildings obeys an exponential growth model [34] and that the

aluminum content of urban residential and rural industrial buildings is equal [33], as shown in Figure S1.

Table S2. Aluminum contents for different buildings in China (kg/m²).

Category	High	Medium	Low
Urban residential	2.00	1.10	0.20
Urban nonresidential	3.60	1.95	0.30
Rural residential	1.30	0.70	0.10
Rural nonresidential	2.00	1.10	0.20

(2) Transportation

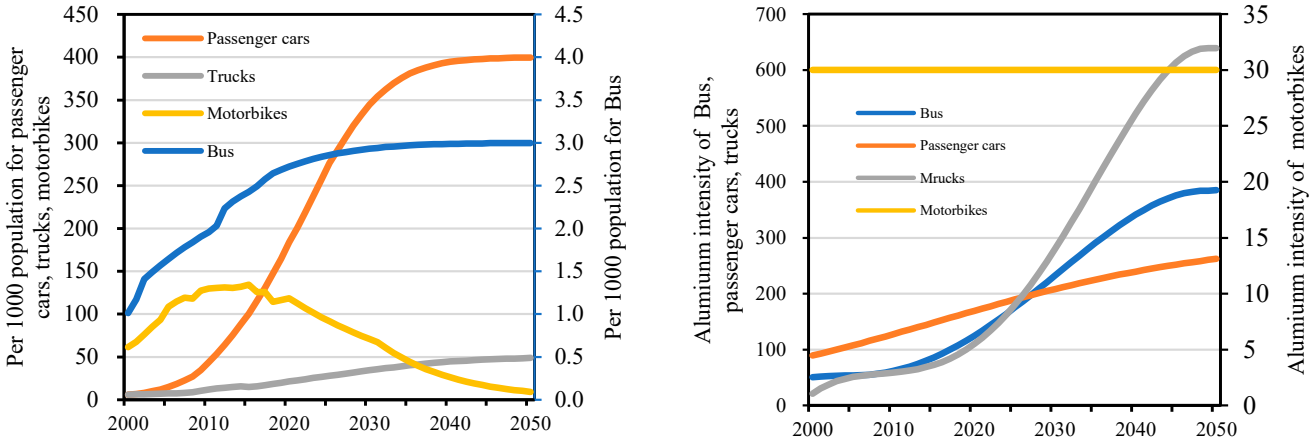


Figure S2. Per thousand population for passenger cars, trucks, motorbikes, and buses (left); Aluminum intensity for passenger cars, trucks, motorbikes, and buses (right).

Eleven aluminum-containing end-products in the transport sector were considered in this study, including passenger cars, trucks, buses, motorbikes, metro, trains, and planes. Historical ownership data for these products are mainly from the China Statistical Yearbook and the China Traffic Statistical Yearbook. Future holdings of passenger cars, trucks, buses, and motorbikes are mainly based on the methodology provided in the literature [44]. Specifically, it is assumed that by 2050 these four vehicle types will have a total of about 460 per thousand population, i.e. 400 for cars, 48 for trucks, 3 for buses, and 9 for motorcycles, as shown in Figure S3. Aluminum intensity for passenger cars, trucks, buses, and motorbikes is mainly based on data provided in previous literature [34], as shown in Figure S2.

For metro, trains, and planes, the amount of aluminum in-use stock is relatively small, so this study simplifies the process. Assuming there is a functional relationship between their quantity and GDP (Figure S3), a fitting equation can be derived using historical data, and their future quantity can be calculated using future GDP. In addition, assuming that the aluminum content of trains, subways, and airplanes remains unchanged, and based on their future quantity data, aluminum in-use stocks up to 2050 can be obtained. The aluminum content is set at 6,500 kg per subways vehicle; 7,000 kg per locomotive train, 12,600 kg per passenger train and 3,000 kg per goods train; and 910 kg per small aircraft and 28,000 kg per medium and large aircraft [32, 34, 58].

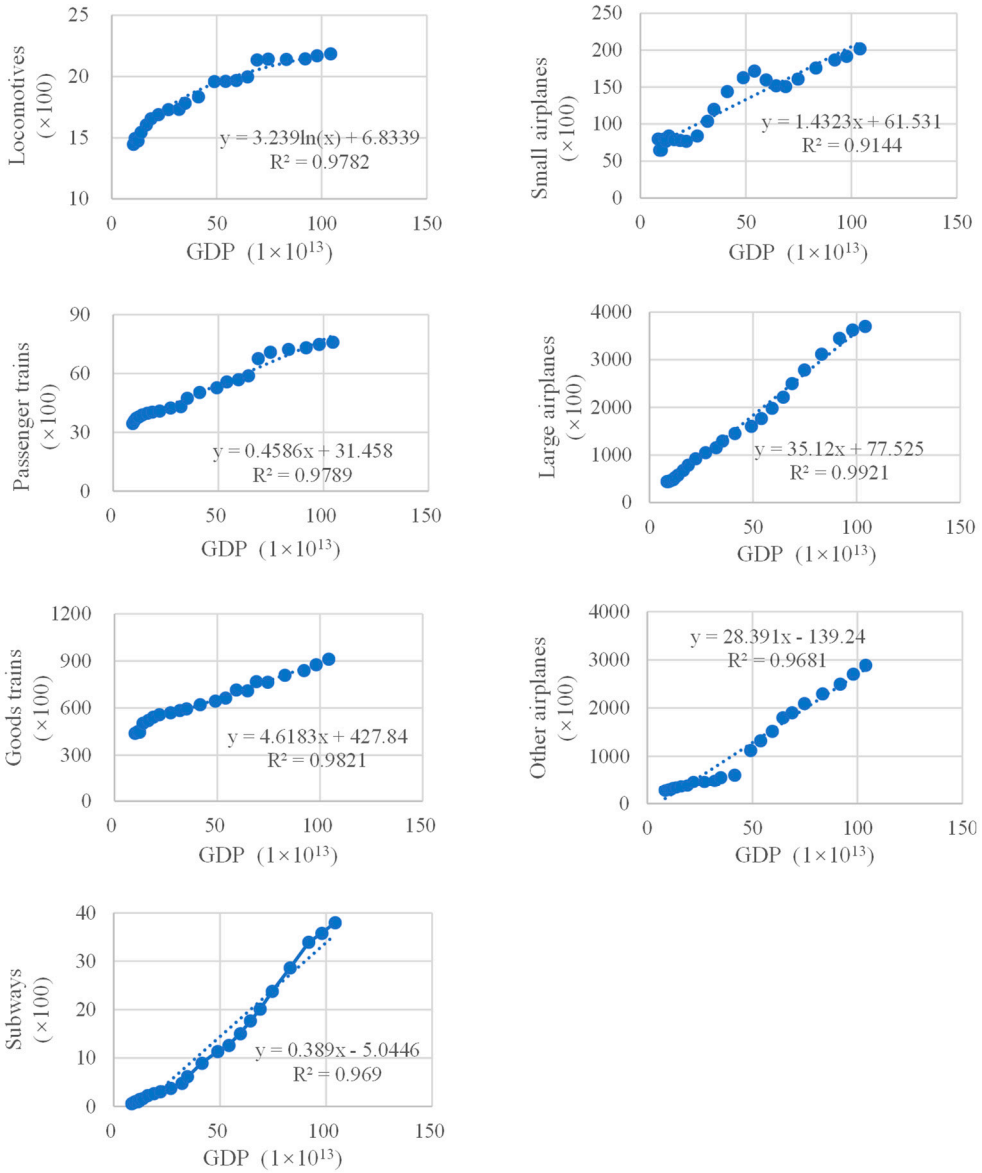


Figure S3. Fitting results of historical numbers of trains, subways, and airplanes with GDP.

(3) Electricity

The aluminum in-use stocks accumulated in the electricity sector can be mainly divided into three categories: power production, power transmission, and power distribution. For power production, this study assumes that the aluminum content of each power generation method remains unchanged, with the specific values shown in the literature [38], specifically: thermal power (990 kg/MW), hydropower (200 kg/MW), solar power (730 kg/MW), wind power (430 kg/MW), nuclear power (200 kg/MW) and other power generation modes (430 kg/MW). As long as the installed capacity of each power generation method in the future is obtained, the aluminum in-use stocks for power production can be calculated.

Reference [46] shows that China's installed power capacity in 2020 is about 1.8 billion kilowatts, of which fossil energy accounts for about two-thirds of the installed capacity, and non-fossil energy sources such as hydropower, nuclear power, and wind power account for about one-third of the installed capacity; The installed capacity of power in 2030 is 2.5-2.8 billion kilowatts, with fossil energy accounting for about 50% -60% and non-fossil energy accounting for about 40% -50%; The installed capacity of power in 2050 is approximately 3.2-3.4 billion kilowatts, of which fossil energy accounts for about 47% and

non-fossil energy accounts for about 53%. Reference [47] indicates that the development scenario of the high proportion of renewable energy electricity can be used as a realistic path for the future development of electricity in China. In this scenario, the total installed capacity of national power in 2050 will reach 7.36 billion kilowatts, including 1.32 billion kilowatts of thermal power, 100 million kilowatts of nuclear power, 550 million kilowatts of hydropower, 2.4 billion kilowatts of wind power, 2.7 billion kilowatts of solar power, and 310 million kilowatts of other power generation. In the current context of carbon neutrality policies, this study chooses the installed capacity of electricity in reference [47] to calculate the future aluminum in-use stocks.

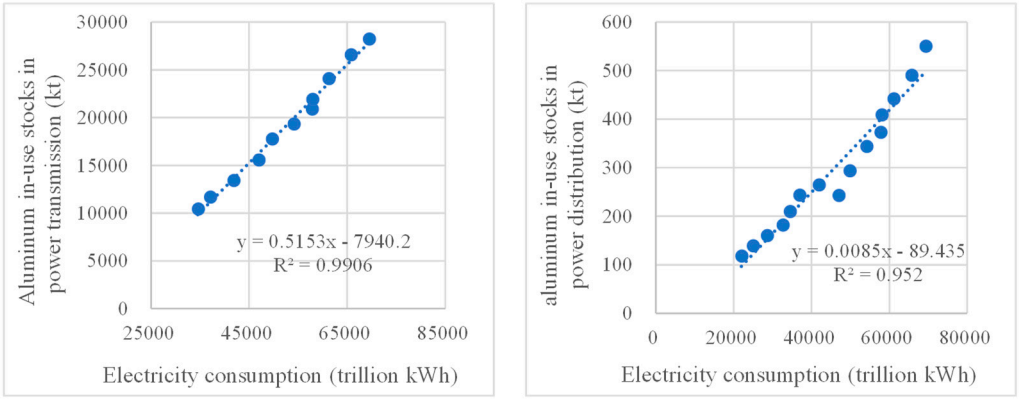


Figure S4. Historical numbers for aluminum in-use stocks of power transmission and power distribution with electricity consumption.

It is difficult to predict the future development trends of aluminum in-use stocks in various categories for power transmission and power distribution [16]. Figure S4 shows the fitting relationship between the aluminum in-use stocks in the two categories of power transmission and power distribution and the total national electricity consumption. Reference [47] provides predicted electricity consumption data for China by 2050, which is 11.8 trillion kWh in 2030 and 15.2 trillion kWh in 2030.

(4) Machinery

The mechanical department involves a wide variety of aluminum-containing products, making it difficult to calculate and predict the aluminum in-use stocks in the department. Previous studies typically used the electricity consumption of the agricultural and industrial sectors to calculate and predict the aluminum in-use stocks [16, 18], and this study also draws on this method. First, this study calculated the aluminum in-use stocks of six types of agricultural machinery, namely, medium and large tractors (20 kg/unit), small tractors (10 kg/unit), combine harvesters (5 kg/unit), motorized threshers (5 kg/unit), irrigation machinery (5 kg/unit), and pumps (1 kg/unit). Based on their historical quantities and aluminum content, the aluminum in-use stock of agricultural machinery was calculated. Next, the aluminum in-use stock of industrial machinery was calculated using the ratio of electricity consumption in the agricultural and industrial sectors. Then, the historical data of electricity consumption and its aluminum in-use stock were fitted using the agricultural and industrial sectors **(Figure S5)**, respectively. Finally, the projected aluminum in-use stock is solved using future data on electricity consumption in the agricultural and industrial sectors. The research results of reference [47] show that the total electricity consumption demand in China will be 11.8, 13.9, and 15.2 trillion kWh in 2030, 2040, and 2050, respectively. Compared to the historical development experience of developed countries, the research results in reference [47] indicate that the proportion of electricity consumption in China's agricultural sector will gradually decrease from 2.2% in 2013 to 1% in 2050. The proportion of electricity consumption in the industrial sector has gradually decreased from approximately 75% in 2013 to 40-45% by 2050. The electricity consumption in the tertiary industry has gradually increased from 11% in 2013 to

approximately 33% by 2050. Figure S5 shows the fitting results between the electricity consumption of the industrial and agricultural and their aluminum in-use stocks.

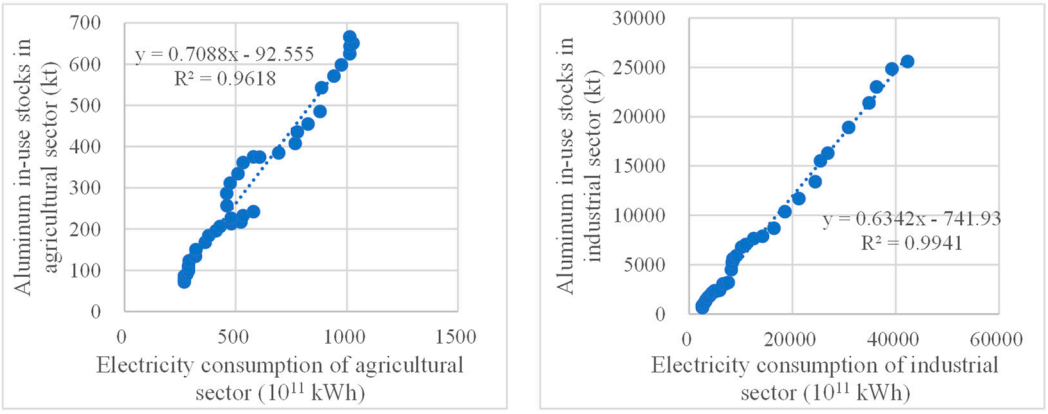


Figure S5. Results of the fitting of electricity consumption and its aluminum in-use stock for the agricultural and industrial sectors.

(5) Consumer durables

The growth trend of durable consumer goods follows the shape of the S-curve. The saturation values of household durable consumer goods set in this study are shown in Table S3. Equation (S2) is used to calculate the future quantity of aluminum-containing durable consumer goods.

$$CD_{i,t} = \frac{K_i}{1+\beta\times\exp(-\alpha\times t)} \quad \text{(S2)}$$

Where $CD_{i,t}$ represents the ownership of the i product in the year t in the year t; t represents year; K_i represents the saturation value of of the i product; and α and β represent the parameters defining the logistic curve.

Table S3 Saturation value of household durable consumer goods ownership in urban and rural areas (units/100 households).

	References	Cameras	Electric bicycles	Water heaters	Refrigerators	Air conditioners	Range hood	Microwave ovens	Washing machines	Computers	Phones	Color TVs
Urban	This study	10	120	110	110	250	95	100	110	140	280	160
	[59]				107	207			102			
	[62]				107	210		100	102			
	[65]				100-110	240-260			100-110	120-140	250-280	140-160
	[16]			110	120	200	92	100	110	400		150
	[66]				102	223			102	99	250	141
Rural	This study	2	173	100	107	150	60	80	102	60	270	120
	[59]				107	147			101			
	[62]				107	150		100	101			
	[16]			70	100	100	45	80	100	250		100
	[66]				102	104			102	50	100	131
Aluminum content		0.02kg	10 kg	1.6 kg	2.1 kg	2.5 kg	1.9 kg	0.5 kg	1.4 kg	0.03kg	0.01 kg	0.2 kg

Table S4 Lifetimes for six sectors of aluminum products.

Lifetime (year)	Construction	Electrical	Transportation	Consumer durables	Machinery	Packaging
Low (a)	30	15	12	9	15	1
Mean (μ)	40	20	16	12	20	1
High (b)	50	25	20	15	25	1