Life Cycle Energy Consumption and Greenhouse Gas Emissions Analysis of Primary and Recycled Aluminum in China

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Keywords: primary and recycled aluminum, Life Cycle Analysis, energy consumption, greenhouse gas emissions

Abstract:

Aluminum production is a major energy consumer and important source of greenhouse gas (GHG) emissions globally. Estimation of the energy consumption and GHG emissions caused by aluminum production in China has attracted widespread attention because China produces more than half of the global aluminum. This paper conducted life cycle (LC) energy consumption and GHG emissions analysis of primary and recycled aluminum in China for the year 2020, considering the provincial differences on both the scale of self-generated electricity consumed in primary aluminum production and the generation source of grid electricity. Potentials for energy saving and GHG emissions reductions were also investigated. The results indicate that there are 157,207 MJ of primary fossil energy (PE) consumption and 15,947 kg CO2-eq of GHG emissions per ton of primary aluminum ingot production in China, with the LC GHG emissions as high as 1.5?3.5 times that of developed economies. The LC PE consumption and GHG emissions of recycled aluminum are very low, only 7.5% and 5.3% that of primary aluminum, respectively. Provincial-level results indicate that the LC PE and GHG emissions intensities of primary aluminum in the main production areas are generally higher while those of recycled aluminum are lower in the main production areas. LC PE consumption and GHG emissions can be significantly reduced by decreasing electricity consumption, self-generated electricity management, low-carbon grid electricity development, and industrial relocation. Based on this study, policy suggestions for China’s aluminum industry are proposed. Recycled aluminum industry development, restriction of self-generated electricity, low-carbon electricity utilization, and industrial relocation should be promoted as they are highly helpful for reducing the LC PE consumption and GHG emissions of the aluminum industry. In addition, it is recommended that the central government considers the differences among provinces when designing and implementing policies.

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Article

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1. Introduction

China has the largest aluminum production capacity in the world. In 2020, 37.08 million tons of primary aluminum and 6.0 million tons recycled aluminum were produced in China, sharing more than half of the world's aluminum output [1,2]. As an energy- and GHG emissions-intensive industry, aluminum production puts tremendous pressure on China's energy conservation and greenhouse gas (GHG) emissions reduction. Aluminum smelting is one of the largest energy-consuming sectors of China's non-ferrous metal industry, which accounted for about 6.5% of China's total electricity consumption in 2020 [3,4]. GHG emissions from primary aluminum ingot production were as high as 426 mt (megaton) $CO_{2\text{-eq}}$ in 2020, accounting for approximately 5% of China's total GHG emissions [5]. China is now making great efforts to promote energy efficiency, capacity utilization, and the adoption of advanced technologies in the aluminum industry to realize the potential of energy saving and GHG emissions reduction towards its carbon peaking and carbon neutrality target. However, the production of aluminum is a complex and multi-process industrial activity. Therefore, it is necessary to assess the GHG footprint of the entire aluminum production process using the life cycle (LC) approach, instead of focusing solely on the smelting process.

Many academic and industrial institutions have carried out research on the GHG emissions of aluminum from the perspective of LC [6–13]. For example, the International Aluminum Institute (IAI) established a general process-based calculating tool to estimate the energy input, material flow, and environmental emissions from primary aluminum production worldwide. The LC inventory data and environmental metrics of the global primary aluminum industry in 2019 were published recently in which China's quantitative results were of poor quality due to the lack of statistics data [6]. Argonne National Laboratory developed the annually updated GREET model to investigate the LC energy input, water consumption, and air emissions of multiple materials used in vehicle manufacturing, with the ability to evaluate the performance of American aluminum products [7]. The Aluminum Association (TAA) released a report on the environmental footprint of aluminum products in North America based on operational data for the year of 2016 [8]. Aluminum for Future Generation (AFG) and the European Aluminum Association (EAA) [9] jointly built the LC inventory data for aluminum production and transformation processes in Europe according to the data for the year 2010. Liu et al. [10] reviewed the status and application of the life cycle assessment method in the aluminum industry, providing the strength and weakness of the method to address sustainability in the aluminum industry.

The energy consumption and GHG emissions of China's aluminum industry have also received extensive attention from researchers and have been widely analyzed in previous studies [14–23], in which LC analysis is an important perspective. Gao et al. [18] assessed the LC GHG emissions of primary aluminum in China in comparison with the global average level and estimated the reduction potentials in detail. Du et al. [19] evaluated the reduction potentials for LC GHG emissions and energy use from aluminum-intensive vehicles in China and found that the reduction potentials were insignificant because of the high LC intensities of energy consumption and GHG emissions. Ding et al. [20] quantitatively analyzed the energy consumption and GHG emissions caused by primary aluminum and recycled aluminum production in China in 2008 and compared this with 2003. Guo et al. [21] calculated the national average LC energy consumption and GHG emissions for primary aluminum production in China in the years of 2003, 2006, 2008, and 2010, and conducted correlation analysis between GHG emissions and key factors. Liu et al. [22] investigated the features, trajectories, and driving forces of the energy-related GHG emissions of China's primary and recycled aluminum industry from the LC analysis perspective in the period 2004–2013.

Electricity generation has a significant impact on energy consumption and GHG emissions for aluminum production. However, both the scale of self-generated electricity associated with primary aluminum production and the generation mix of grid electricity have significant regional variations in China. Therefore, its necessary to carry out provincial LC analysis on primary and recycled aluminum production considering the individual or regional actual power consumption to make the estimation more accurate and policy recommendations more effective. Several studies have assessed the provincial variations in the LC GHG emissions of China's aluminum industry [24–26]. For example, Hao et al. [24] explored the national and provincial average-level GHG emissions intensity of China's primary aluminum production in 2013 and 2020, considering the impact of provincial disparity in the electricity generation system based directly on GHG emissions factors of each process from other studies. Zhang et al. [25] assessed the LC environmental footprint of primary aluminum and recycled aluminum production in China based on a bottom-up approach with statistical data, and simply analyzed the provincial aluminum production density and environmental impacts in different provinces.

However, significant shortcomings still exist in the literature: (1) Most of these previous studies only focused on primary aluminum but neglected recycled aluminum; (2) very few studies considered the substantial impacts of self-generated electricity on primary aluminum production at both the national and provincial levels; (3) the characterization of the aluminum production process was not sufficiently comprehensive and detailed, with a failure to examine the potentials for energy saving and GHG emissions reduction of aluminum production in some studies; and (4) key data and assumptions need to be updated periodically based on the latest information and technologies.

This study aimed to fill the gaps by performing a comprehensive LC analysis of China's aluminum industry in 2020 based on a process-based approach. It focused on the following innovative aspects: (1) Both primary and recycled aluminum were studied using the same method and tool; (2) detailed investigation of the national and provincial self-generated electricity and grid mix was conducted to reflect the real electricity system of Chinese aluminum production; (3) the system boundary was extended to cover the upstream end-use energy production, main raw and auxiliary materials, and all related processes; (4) up-to-date data on the energy input and material flows were used; and (5) potentials for energy saving and GHG reductions were estimated and comparative analysis with international levels was conducted.

The structure of this paper is organized as follows: Section 2 explains the system boundary and research methodology and introduces the key data acquisition process and basic assumptions. Section 3 details the results and discussions. Section 4 concludes this paper and proposes policy implications.

2. Methodology

2.1. System Boundary

Figure 1 shows the research boundary of this study and the material flow of aluminum production. This study covers the main processes of primary and recycled aluminum production. The former includes bauxite mining, bauxite transport, alumina production, anode production, fluoride salt production, aluminum electrolysis, and ingot casting, and the latter contains aluminum scrap collection/transportation, pre-treatment, smelting, and ingot casting. Fuel inputs in aluminum production processes cover all key end-use energy types, including coal, natural gas (NG), oil, gasoline, diesel, electricity, and coke. Upstream production stages of process fuel are within the system boundary, which means that primary fossil energy (PE) consumption and GHG emissions occurring in resource exploitation, resource transportation, fuel production, fuel transportation, and distribution are covered. It should be pointed out that facilities construction and maintenance are excluded in this study. The process fuel consumed in all these stages is sourced in the form of three main types of PE: raw coal, raw NG, and petroleum. Three key types of GHGs, including CO_2, CH_4, and N_2O, and the perfluorocarbons (CF_4 and C_2F_6) emitted from the anode effect in the electrolysis process are taken into consideration, and they are measured in CO_2 equivalents ($CO_{2\text{-eq}}$) according to the global warming potential (GWP) factor.

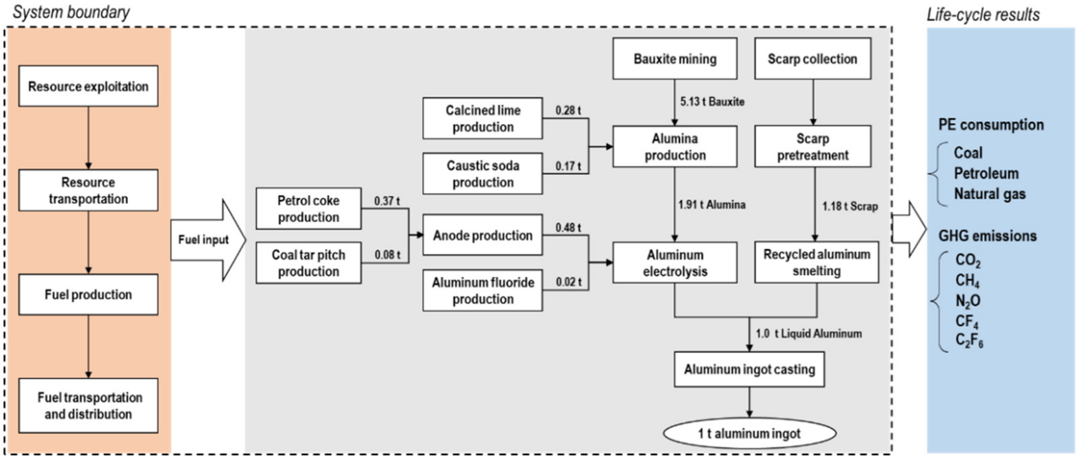

Figure 1. System boundary and material flow of primary and recycled aluminum production in China.

2.2. Calculation Method

The total direct energy consumption per ton of aluminum produced is the sum of the fuel consumption of each process, shown as Equation (1):

$$EN_{direct} = \sum_i \sum_j EN_{direct,i,j} \tag{1}$$

where EN_{direct} represents the total fuel consumed per ton of aluminum (MJ/t Al ingot); $EN_{direct,i,j}$ denotes the fuel type j consumed in the stage/process i (MJ/t Al ingot). The LC PE consumption is obtained with Equation (2):

$$EN_{LC} = \sum_i \sum_j EN_{direct,i,j} \cdot EN_j \tag{2}$$

where EN_{LC} is the LC PE consumption intensity of aluminum (MJ/t Al ingot); EN_j is the LC PE intensity of fuel type j (MJ/MJ fuel obtained and utilized). For electricity, EM_j can be defined as a weighted average intensity of all electricity generation sources using Equation (3):

$$EN_{electricity} = \frac{1}{1-\eta} \sum_k \left(EN_{electricity,k} \cdot SH_k \right) \tag{3}$$

where $EN_{electricity}$ is the average PE intensity of the electricity grid (MJ/MJ electricity generation and supply); η is the transmission loss of the electricity grid (%), $EN_{electricity,k}$ is the LC PE intensity of the electricity source k (MJ/MJ electricity generation and supply); and SH_k is the share of the electricity source k in the total electricity generation of the grid (%). Here, k represents coal, oil, NG, hydro, nuclear, solar, wind, biomass, and others, respectively.

The LC GHG emissions of primary aluminum are generated from four parts: (1) the combustion of fossil fuels; (2) CO_2 emitted from anode material consumption; (3) CO_2 emissions from the calcination of limestone; and (4) perfluorocarbons (PFCs) containing tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) from the anode effect in the electrolysis process. Equations (4)–(8) show the calculation principles for the total LC GHG emissions per ton aluminum:

$$EM_{LC} = EM_{LC,En} + EM_{AC} + EM_{AE} + EM_{Limestone} \tag{4}$$

$$EM_{LC,En} = \sum_i \sum_j \left(EN_{direct,i,j} \cdot EM_j / 1000 \right) \tag{5}$$

$$EM_{AC} = \frac{44}{12} P_A \cdot (1 - S_A - A_A) \tag{6}$$

$$EM_{AE} = 6500 EM_{CF_4} + 9200 EM_{C_2F_6} \tag{7}$$

$$EM_{Limestone} = P_{Limestone} \cdot EF_{Limestone} \tag{8}$$

where EM_{LC} is the LC GHG emissions intensity of aluminum (kg $CO_{2\text{-eq}}$/t Al ingot); $EM_{LC,En}$ represents the GHG emissions associated with fuel utilization (kg $CO_{2\text{-eq}}$/Al ingot); EM_{AC}, $EM_{Limestone}$, and EM_{AE} denote the GHG emissions intensities of anode consumption, calcining limestone, and the anode effect (kg $CO_{2\text{-eq}}$/t Al ingot), respectively; P_A is the carbon anode consumption per ton of primary aluminum (kg/ Al ingot); S_A is the average sulfur content of the carbon anode (%); A_A is the ash content of the carbon anode (%); EM_{CF_4} and $EM_{C_2F_6}$ are the CF_4 and C_2F_6 emissions per ton of primary aluminum (kg/t Al ingot); $P_{Limestone}$ is the limestone consumption per ton of primary aluminum (kg/t Al ingot); $EF_{Limestone}$ is the emission factor for calcining limestone (kg $CO_{2\text{-eq}}$/kg limestone); and EM_j is the LC GHG emissions intensity of fuel type j (kg $CO_{2\text{-eq}}$/MJ fuel obtained and utilized). In the case of electricity, EM_j can be defined as follows:

$$EM_{electricity} = \frac{1}{1-\eta} \sum_k \left(EM_{electricity,k} \cdot SH_k \right) \tag{9}$$

where $EM_{electricity}$ is the average GHG emissions intensity of the electricity grid (g $CO_{2\text{-eq}}$/MJ electricity generation and supply); $EM_{electricity,k}$ is the LC GHG emissions intensity of the electricity source k (g $CO_{2\text{-eq}}$/MJ electricity generation and supply).

GHG generated during recycled aluminum production comes from fuel utilization, which can also be estimated by Equation (5).

2.3. Key Data and Assumptions

2.3.1. Basic Process Data Collection

The material flow during LC of aluminum production is shown in Figure 1. The details of the basic data on the import rate of raw materials, fuel input in each process, and fuel structure of each process/material are based on the latest public official and industry statistics and reports, which reflect the average technological level of China's aluminum industry. There are three ways to collect these data: (1) The energy and feedstock input data was mainly obtained from the yearbooks of the non-ferrous metal sector [3] and the energy sector [4,27], and the LCA database of the International Aluminum Institution (IAI) [2,28]; (2) for the data of intermediate input products such as anode production, fluoride salt, etc., refer to commercial databases and literature research [7,29]; (3) for some processes or intermediate inputs for which it was difficult to obtain the data in the base year (2020) due to limited statistics and research, this study made corrections and assumptions on the basis of data from previous years [22,30–32]. China's bauxite resources are becoming increasingly scarce, and the limited domestic bauxite reserves are unable to meet the huge domestic demand, 54.6% of which needed to be imported from abroad in 2020, about 25.5% of aluminum scrap came from imports in 2020, and alumina was 4.9% [33]. It should be noted that the production process of imported materials occurs abroad, so this part is no longer included in China's analysis, but the transportation process from the exporter to China were taken into consideration in this study.

2.3.2. Data on Transportation

Data relating to the transportation of raw materials and intermediate products for aluminum production are shown in Table 1. Imported materials and scrap are assumed to be first transported to the port by ocean ships and then shipped to smelting plants by rail. The maritime transport distance is the value obtained by weighting the distance between the geographical location of the importing countries and the main ports of China according to the import volumes [3,34]. The domestic transport distance of imported bauxite and alumina refers to the average transport distance of metal ore while the data of aluminum scrap refers to that of non-ferrous metals. The average transport distance of domestic aluminum scrap is assumed to be 500 km by road to reach the smelting facilities from the main scrap distribution center [20,35]. Other materials, including caustic soda, calcined lime, fluoride salt, petrol coke, and coal bar pitch, are assumed to be directly transported by road from plants to the electrolytic aluminum refineries for use, with a distance of 176 km, which is the average distance of China's road freight transportation [35]. Table 2 presents China's energy intensity and fuel structure of multiple transport modes in 2020.

Table 1. Transportation parameters of the aluminum industry in China in 2020 [1,3,34,35].

Item	Transport Mode
Bauxite	Ocean shipping: 54.6% (15,755 km); Railway: 100% (670 km)
Alumina	Ocean shipping: 4.9% (8600 km); Railway: 100% (670 km)
Aluminum scrap	Ocean shipping: 25.5% (8033 km); Railway: 25.5% (500 km); Road: 70% (500 km)
Other	Road: 100% (176 km)

Note: The sum of the proportions of individual transport modes may exceed 100% because of intermodal transport.

Table 2. Energy intensity and fuel structure of various transport modes.

Item	Energy Intensity	Fuel Structure	Date Source
Ocean shipping [1]	$0.076\ \mathrm{MJ/t \cdot km}$	Fuel oil (100%)	[36]
Railway [2]	$0.129\ \mathrm{MJ/t \cdot km}$	Coal (2.5%), Diesel (23.0%), electricity (65%), others (9.0%)	[37]
Road	$0.498\ \mathrm{MJ/t \cdot km}$	Diesel (72%), gasoline (28%)	[36,38]

Note: [1] The fuel consumed in ocean shipping is fuel oil while other fuel types are not considered. [2] The fuel structure of railway was established according to a field survey and the literature [39].

2.3.3. Data on Electricity

As a high-energy consumption industry, the demand for electricity in primary aluminum production is huge. In order to obtain a stable electricity supply and reduce the cost of electricity, most electrolytic aluminum enterprises have built their own thermal power plants and purchase coal for electricity generation in addition to purchasing electricity from the national/regional grid. The electricity mix of the electrolytic aluminum industry does not necessarily match the grid mix found in aluminum-producing regions/nations due to the high proportion of self-generated electricity. According to AFG [40], about 30% of the electricity consumed in the electrolytic aluminum industry globally comes from a self-generated thermal power plant, with the rest being purchased as grid electricity. This ratio is higher in China, with about 65% estimated by market surveys [41,42]. The nationwide sources of electricity generation for electrolytic aluminum in China were assessed based on this data and China's grid mix in 2020 [27], as shown in Table 3. Coal power still dominates in the electricity mix of the electrolytic aluminum industry, the percentage of which is as high as 87.1%. The average transmission loss was 5.6% for grid electricity in China in 2020 [27]. This is negligible for self-generated electricity because the power plants are usually located close to electrolytic aluminum production facilities, avoiding long-distance transmission of electricity. In this study, we assumed that the grid electricity purchased is consumed in recycled aluminum production and the processes of primary aluminum production other than electrolysis. It should be noted that the diversity of electricity generation of primary aluminum production among provinces in China leads to significant regional differences in the results of the LC analysis, which is further discussed in Section 3.3.

Table 3. Nationwide sources of electricity generation for the grid mix and electrolytic aluminum mix.

Item	Coal	Oil	NG	Hydro	Nuclear	Solar	Other
Grid mix (%)	63.2	0.1	3.2	17.0	4.7	11.1	0.7
Electricity for aluminum electrolysis (%)	87.1	0.0	1.1	6.0	1.6	3.9	0.2

2.3.4. Data on Life Cycle Intensities of Each Process Fuel

Table 4 presents China's LC PE and GHG intensity of each process fuel in 2020. The definition of LC PE intensity is PE consumed to obtain and utilize 1 MJ fuel over the whole LC stages, including resource exploitation, resource transportation, fuel production, fuel transportation and distribution, and fuel combustion. LC GHG emissions intensity is the total GHG emitted to obtain and utilize 1 MJ fuel. Here, we update the data based on the methodology from our previous study [38] and national energy statistics [4].

Table 4. LC PE and GHG emissions intensity of each fuel.

Item	EN_j	$EN_{j,Coal}$	$EN_{j,NG}$	$EN_{j,Oil}$	EM_j
Unit	**MJ/MJ**	**MJ/MJ**	**MJ/MJ**	**MJ/MJ**	**$gCO_{2,e}$/MJ**
Raw coal	1.068	1.065	0.001	0.002	98.0
Raw NG	1.135	0.035	1.052	0.048	67.0
Crude oil	1.093	0.024	0.036	1.033	78.8
Clean coal	1.083	1.067	0.002	0.014	99.1
Refined NG	1.139	0.036	1.056	0.048	68.8
Diesel	1.251	0.058	0.047	1.146	91.6
Gasoline	1.260	0.060	0.047	1.153	89.4
Fuel oil	1.190	0.046	0.042	1.102	90.1
Grid power	1.910	1.817	0.064	0.029	172.7
Coke [1]	2.172	1.236	0.002	0.015	105.9
Coal power	2.844	2.802	0.004	0.038	260.3
NG power	2.561	0.014	2.534	0.013	149.9
Oil power	3.899	0.157	0.145	3.597	295.4
Nuclear power	0.063	0.052	0.005	0.006	6.5
Other power [2]	0	0	0	0	5.0

Note: [1] Data on coker refers to the research results from Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences [43]; however, it should be noted that that the data was obtained based on the 2010 situation. In this paper, we assume it did not change in the short term. [2] The fossil energy consumption of other electricity sources with non-fossil energy as the raw material (such as hydro, biomass, and wind) are very low and often negligible [38].

2.3.5. Data on GHG Emissions from Anode Consumption, Calcining Limestone, and Anode Effect

The parameters of anode consumption, calcining limestone, and anode effect shown in Table 5 were obtained from the NDRC guideline [32]. The GHG emissions factor of anode consumption and calcining limestone are determined by the physical properties of the material, resulting in similar values among all studies. CF_4 and C_2F_6 are emitted in the primary aluminum reduction process because of the anode effect, and their emission factors are closely related to the type and technological level of the electrolytic bath. Currently, China's electrolytic aluminum production mainly adopts world advanced Point-center Feed Prebake (PFPB) technology. Therefore, the value referenced by the NDRC guideline is lower than that provided by IAI [28]. In addition, the updated GWP factors from the Intergovernmental Panel on Climate Change (IPCC) were employed in this study: 6500 for CF_4 and 9200 for C_2F_6 [44].

Table 5. The parameters of anode consumption, calcining limestone, and anode effect [28,32,44].

Item	Unit	Value
Average sulfur content of carbon anode	%	2
Average ash content of carbon anode	%	0.4
Emission factor for calcining limestone	kg CO_2/kg limestone	0.405
CF_4 emission factor of anode effect	kg /t Al ingot	0.034
C_2F_6 emission factor of anode effect	kg /t Al ingot	0.0034

3. Results and Discussions

3.1. Life Cycle Results of Primary Aluminum

Figure 2 shows the LC results of primary aluminum. In total, 77,547 MJ of direct energy and 157,207 MJ of LC PE are consumed to produce one ton of primary aluminum ingot, with the proportion of aluminum electrolysis exceeding more than 60% and 76%, respectively. The total LC PE consumption is 2.3 times as much as the total direct energy input. The difference between LC PE consumption and direct energy input at the aluminum electrolysis stage is apparently higher than that at other stages because the main fuel consumed in the electrolysis process is electricity and the energy conversion efficiency of transforming PE into electricity is lower than in other fuel types. As Figure 2b shows, coal contributes the most in the LC PE consumption and accounts for 90.53% of the total due to China's coal-dominated power structure. In the transportation of bauxite, the LC PE consumption associated with the transportation of imported bauxite accounts for about 95% due to China's massive dependence on overseas sources and the long ocean shipping distance.

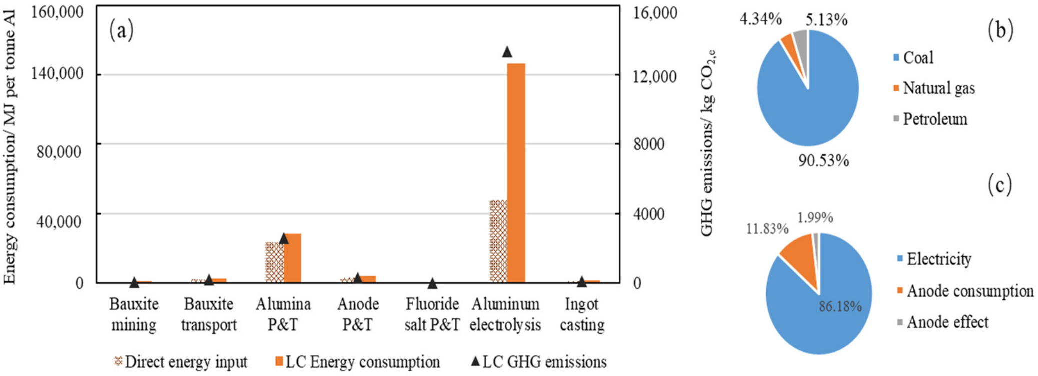

Figure 2. LC results of primary aluminum in mainland China in 2020: (**a**) Direct energy input, LC PE consumption, and GHG emissions of each stage/process; (**b**) Proportion of each primary fossil energy; (**c**) Breakdown of GHG emissions of aluminum electrolysis.

The process of primary aluminum production will generate 15,947 kg $CO_{2\text{-eq}}$ GHG emissions from the LC perspective, in which the aluminum electrolysis shares the most at 80.0% (12,704 kg $CO_{2\text{-eq}}$), presented as Figure 2c. The overall emission structure is similar to that of energy consumption. The GHG emissions from electricity consumption contribute the most in the total GHG emissions of aluminum electrolysis, with a share of 86.18%, followed by that of anode consumption, which is estimated to be 1503 kg $CO_{2\text{-eq}}$, 11.83% of the total GHG emissions in this stage. At 2400 kg $CO_{2\text{-eq}}$, the GHG emissions from alumina P&T are the second largest emissions source, with a share of 15.05%. In total, 113 kg $CO_{2\text{-eq}}$ of GHG are generated from calcium carbonate decomposition, with a proportion of 4.73% of the alumina P&T stage, while the rest is generated by fuel combustion.

3.2. Life Cycle Results of Recycled Aluminum

The result of each process/stage in descending order is aluminum smelting, scrap pretreatment, ingot casting, and scrap collection/transportation, shown as Figure 3. In total, 8612 MJ of direct energy is consumed for per ton of recycled aluminum ingot production (only 11.1% of primary aluminum ingot), which are dominated by aluminum smelting with a share of 53.19%. In total, 11,730 MJ of LE PE is consumed per ton of recycled aluminum production, only 7.46% of primary aluminum, with the contribution from each process similar to those of direct energy input. Up to 25.5% of the scrap aluminum is imported from abroad, which leads to a large amount of energy input in the ocean shipping of imported scarp aluminum, which accounts for 36% of the whole transport stage. Compared to primary aluminum production, the structure of LC PE consumption changes significantly (shown as the sub-graph of Figure 3): coal accounts for 35.74% and is no longer the dominant energy while NG contributes the most, with a share of 54.31%.

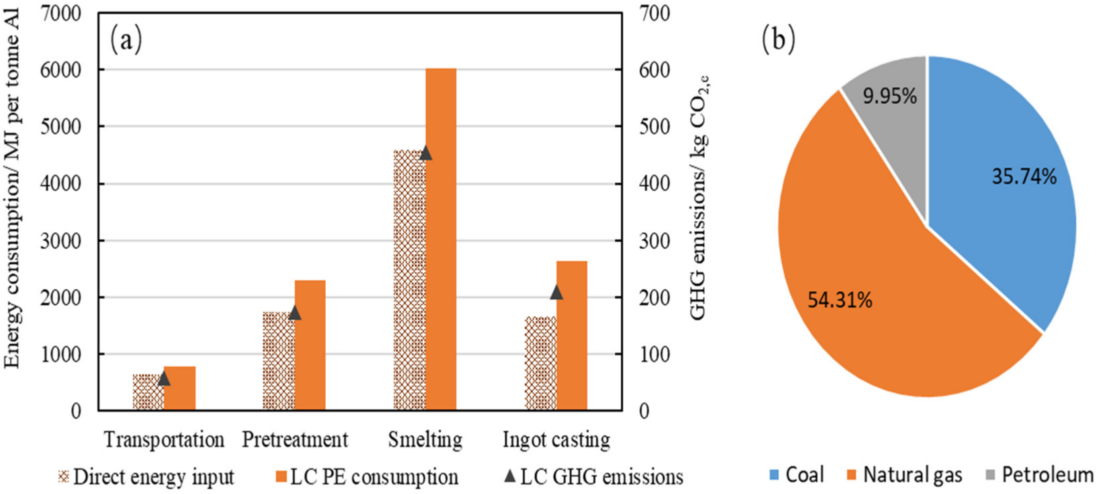

Figure 3. LC results of recycled aluminum in mainland China in 2020 (**a**); and the proportion of each primary fossil energy (**b**).

The process of recycled aluminum production will generate 845 kg $CO_{2\text{-eq}}$ GHG emissions, only 5.40% of those of primary aluminum ingot. The GHG emissions from the process of collection/transportation, pretreatment, smelting, and ingot casting are 57, 161, 424, and 203 kg $CO_{2\text{-eq}}$, representing 6.80%, 19.03%, 50.12%, and 24.05% of the total emissions, respectively.

Compared with primary aluminum, recycled aluminum shows obvious advantages in energy consumption and GHG emissions. It should be pointed out that the fuel of smelting furnaces in modern recycled aluminum factories is mostly fuel oil or NG. However, there are few official statistics on the nationwide average energy data, which makes it difficult to explore the fuel structure of recycled aluminum. In this study, we adopted the data of NG from [25]. If the smelting furnace is fueled by fuel oil, the LC PE and GHG emissions will increase due to the fact that the LC intensities of fuel oil are higher than those of NG.

3.3. Regional Disparity of LC Results

This part shows the provincial differences among 31 provinces in mainland China. Hong Kong, Macao, and Taiwan in China are excluded in this study due to the lack of sufficient data.

The spatial distribution of primary and recycled aluminum production in mainland China in 2019 are shown in Figure 4a,b, respectively (data of aluminum production in 2020 has not been published). The production capacity of China's primary aluminum is highly concentrated, mainly distributed in 17 provinces in the north and central west regions. Shandong and Xinjiang are the two most important primary aluminum production provinces in China currently, accounting for more than 40% of the national production [3]. Recycled aluminum production is distributed in all provinces of mainland China except Jilin, Guangxi, Hainan, Tibet, and Ningxia. The southeastern coastal provinces are major production areas, particularly the three coastal provinces of Jiangsu, Shandong, and Guangdong, accounting for more than 35% of the national production [3].

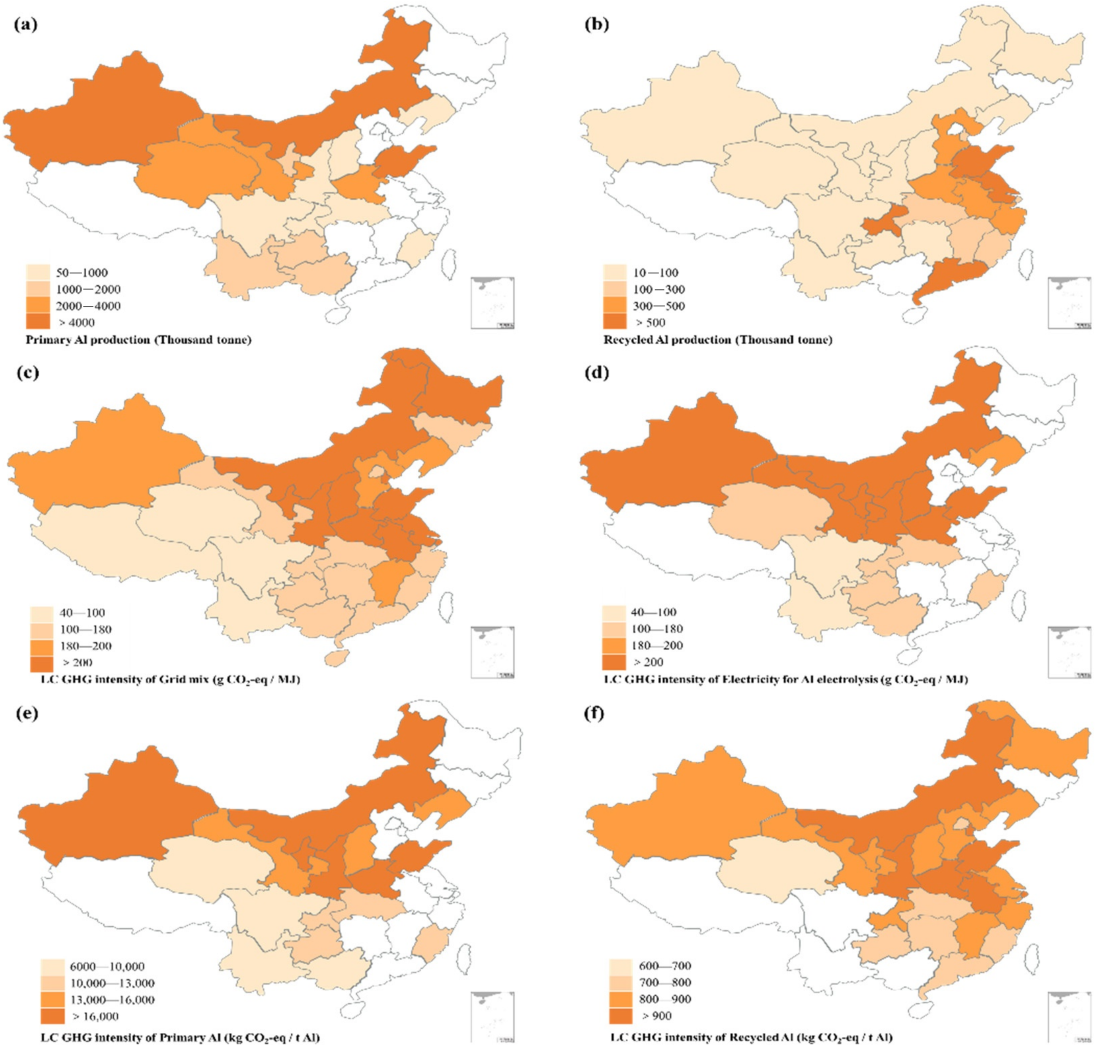

Figure 4. Provincial aluminum industry data in mainland China: (**a**) Primary aluminum and (**b**) recycled aluminum production in 2019; (**c**) LC GHG emissions intensity of the grid mix; (**d**) LC GHG emissions intensity of electricity for aluminum electrolysis; (**e**) GHG emissions intensity of primary aluminum; and (**f**) GHG emissions intensity of recycled aluminum in 2020.

Some previous studies [24,45,46] estimated the grid mix and LC GHG emissions intensity at the provincial level in China, considering the inter-province power transmissions for the provincial grid mix. Here, we recalculated the LC emissions intensity of electricity (see Figure 4c) based on their estimations [46]. The LC intensity shows a downward trend from northeast to southwest. Shannxi, Shandong, and Inner Mongolia show the highest intensity, with more than 250 g $CO_{2\text{-eq}}$/MJ, which is about 1.1 times that of the nationwide average level. Due to the differences in the regional policy and self-generated electricity cost, the proportion of self-generated electricity in the electrolytic aluminum industry varies from province to province. Based on the industry survey and literature review, we obtained the provincial self-generation rate (as shown in Table A1). Combining the provincial grid mix, GHG emissions intensity of different power generation sources, and proportion of self-generated electricity, we estimated the provincial GHG emissions intensity of electricity for aluminum electrolysis, as shown in Figure 4d. The distribution of GHG emissions intensity basically coincides with primary aluminum production, particularly those in

Shandong, Xinjiang, and Inner Mongolia, as these provinces have an intensity of more than 255 g $CO_{2\text{-eq}}$/MJ.

We assume that, apart from provincial electricity diversity, no other differences exist among provinces, such as production technology, energy efficiency, fuel input and mix, and other factors. For primary aluminum, there is a geographical mismatch between the raw materials production processes (such as bauxite mining, alumina production, and anode) and electrolytic aluminum production process. As a result, raw materials in many provinces need to be purchased across provinces or imported from other countries. However, there are no reliable data on the interprovincial flows of raw materials, making it impossible to analyze the LC supply chains in certain provinces. Therefore, we only consider the provincial electricity mix disparity in the aluminum electrolysis process, and still used the nationwide average data for other processes.

The LC GHG emissions per ton of primary aluminum ingot are shown in Figure 4e and Table A1. Generally, the LC GHG emissions intensity of primary aluminum is positively correlated with the production volume and shows significant provincial disparity. The provinces with larger production volumes, such as Shandong and Xinjiang, also have higher emissions intensities. The five provinces (Inner Mongolia, Shandong, Shaanxi, Xinjiang, and Ningxia) with GHG intensities exceeding the national average intensity account for 59.2% of China's total production. The GHG emissions intensity of the southwest provinces is lower than that of the northern provinces. For instance, the GHG emissions intensities of Yunnan and Sichuan are 39.2% and 37.2% that of Shandong (17,540 kg $CO_{2\text{-eq}}$), respectively. Provinces with low GHG emissions intensities share two characteristics: (1) relatively high proportions of renewable electricity in the grid mix; and (2) low proportions of self-generated electricity for primary production. Figure 4f and Table A1 show the LC GHG emissions per ton of recycled aluminum ingot. Generally, the LC GHG emissions intensities show a negative correlation with the spatial distribution of recycled aluminum production, indicating that the provinces with lower emissions intensities tend to have higher production volumes. As shown in Figure 4f, the LC GHG emissions intensities of the southeastern coastal provinces are lower than those of the northern provinces. Shannxi shows the highest GHG emissions intensity with 927 kg $CO_{2\text{-eq}}$, about 1.1 times that of the national average level and 1.6 times that of Yunnan. This is mainly attributed to the high proportion of coal power in northern China's grid mix.

3.4. Potential for Energy Conservation and GHG Emissions Reduction

3.4.1. Decrease in Electricity Consumption of Electrolytic Aluminum

The overall electricity consumption per ton of electrolytic aluminum in China has been steadily declining in recent years due to the improvement in aluminum smelting technology, reaching 13,244 kWh/t Al in 2020 [1]. This is below the global average level (see Figure 5). According to the specification of the aluminum industry [30], the electricity consumption of newly built and reformed electrolytic aluminum liquid must be less than 12,750 kWh/t Al liquid, and the overall electricity consumption of aluminum ingot must be less than 13,200 kWh/t Al ingot. For existing facilities, if the electricity consumption decreases by 100 kWh, the LC PE and GHG emissions per ton of primary aluminum ingot will decrease by 906 MJ and 86 kg $CO_{2\text{-eq}}$, respectively.

3.4.2. Self-Generated Electricity Management

Self-generated electricity plays an important role in China's primary aluminum industry. Compared with many other countries, China has a high proportion of self-generated electricity in the electrolytic aluminum industry. China has implemented relevant policies to strengthen the management of coal-fired power plants for self-generation in order to control the scale of their development and improve their energy efficiency. A 10% decrease in the proportion of self-generated electricity for the electrolytic aluminum industry will reduce the LC PE consumption and GHG emissions by 4504 MJ and 274 kg $CO_{2\text{-eq}}$, respectively. The LC PE and GHG emissions intensities under different proportions of self-generated electricity for the electrolytic aluminum industry are presented in Figure 6. When all the electricity consumed is purchased from the grid, the LC PE consumption and GHG emissions per ton of aluminum ingot are 127,931 MJ and 13,203 kg $CO_{2\text{-eq}}$, a decrease of 18.6% and 16.3% compared to those of 65% self-generation in 2020, respectively.

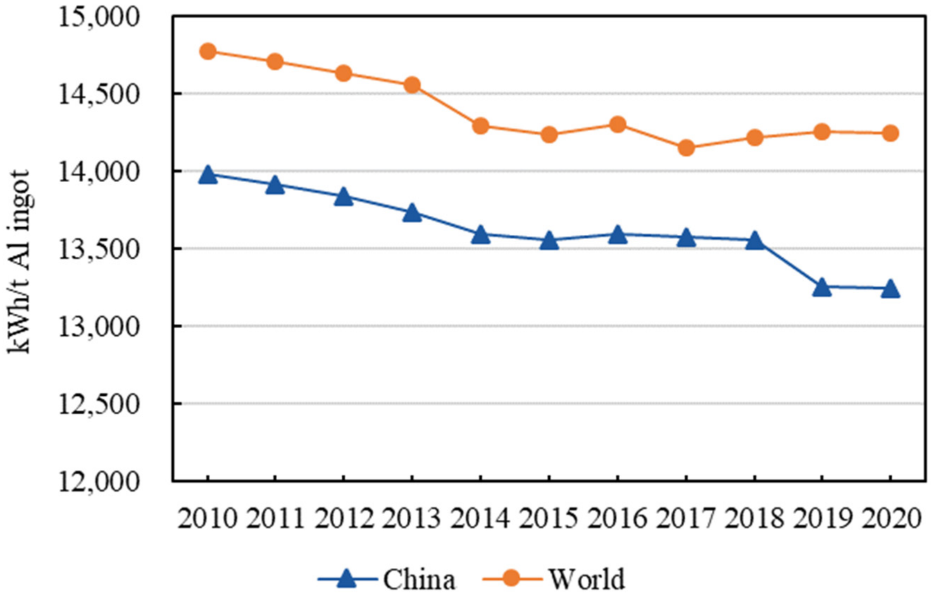

Figure 5. Overall electricity consumption per ton of primary aluminum ingot 16.

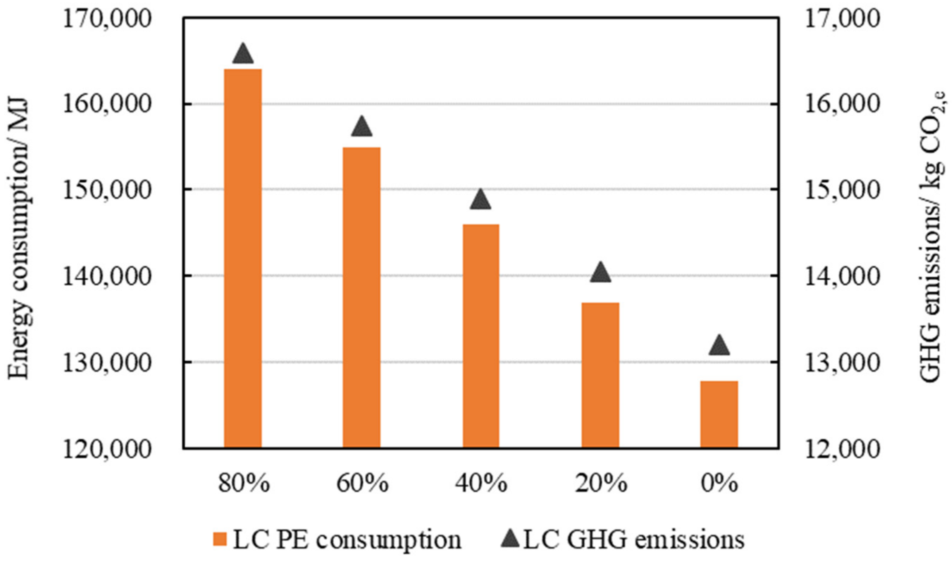

Figure 6. LC PE and GHG emissions intensities under different proportions of self-generated electricity in the electrolytic aluminum industry.

The LC PE and GHG emissions intensities of coal power used in this study were estimated by the method from Peng et al. [38] based on the national average net coal consumption rate at 305 g of coal equivalent/kWh in 2020 [4]. However, the net coal consumption of self-generated power plants is generally higher than this value as the capacities of coal-fired units in self-generation power plants are smaller than those of large-scale thermal power plants [41]. A decrease in the net coal consumption of self-generation power plants by 10 g of coal equivalent/kWh will reduce the LC PE consumption and GHG emissions by 3747 MJ and 425 kg $CO_{2\text{-eq}}$, respectively.

3.4.3. Low-Carbon Electricity Development

China's electricity grid is currently dominated by coal power, with a proportion of 63.2% in 2020, resulting in high LC PE and GHG emissions intensities. China has introduced many measures to vigorously promote the development of renewable electricity and the proportion of coal power in the electricity grid is expected to gradually decrease in the future. Scenario analysis was conducted to estimate the LC PE and GHG emissions intensities of primary and recycled aluminum with different proportions of coal power in the electricity mix (50%, 40%, and 30%). Here, we assume that the proportion of self-generated electricity in the electrolytic aluminum industry is 50% and is the same under different scenarios. For primary aluminum, the LC PE intensities in the 50%, 40%, and 30% coal power scenarios drop by 7.06%, 11.64%, and 16.21% compared with the baseline (2020) while the LC GHG emissions intensities decrease by 7.07%, 11.12%, and 15.18%, respectively. The LC PE intensities for recycled aluminum are reduced by 7.22%, 11.90%, and 16.58% under the 50%, 40%, and 30% coal power scenarios while the LC GHG emissions intensities decline by 11.80%, 17.60%, and 23.41%, respectively. Therefore, decarbonization of grid electricity can play an important role in promoting energy conservation and GHG emissions reduction of the aluminum industry.

3.4.4. Industrial Relocation

The LC GHG emissions intensity is high in provinces with concentrated production of primary aluminum, resulting in the high GHG emissions of China's aluminum production. The southwest provinces are rich in hydropower and therefore have natural advantages in hosting the electrolytic aluminum industry. The appropriate relocation of the primary aluminum industry from north China to the southwest will help reduce PE consumption and GHG emissions. For example, relocating half of Shandong's production to Qinghai and Sichuan will reduce the production-weighted average LC GHG emissions intensity of Chinese aluminum by 6.42% and 15.31%, respectively. The relocation of the primary aluminum industry shows great potential in GHG emissions reduction. However, other key factors such as the consumer market, production cost, and environmental protection should be taken into account holistically in any industrial relocation. This is a topic worth exploring in detail in future studies.

3.5. Comparative Analysis with Similar Studies

Table 6 presents a comparative analysis with other studies focusing on China and other regions. The results for China show significant differences among studies, most of which are lower than those of this study mainly because: (1) we extended the system boundary to include both fuel acquisition and aluminum production, taking into consideration fuel conversion efficiencies that are usually neglected by other studies; and (2) in primary aluminum production, the proportion of thermal power in the electricity mix for electrolytic aluminum is higher than that of the grid electricity mix due to coal-fired self-generation, leading to higher LC PE and GHG emissions intensities.

The results for China tend to be worse than those for the U.S. and Europe, which are mainly attributed to the coal-dominated energy structure. The LC GHG emissions intensity of primary aluminum for China is 1.5–3.5 times that of other regions, respectively. The U.S. is taken as an example for analysis. The power consumption for China's per ton aluminum production has been almost close to advanced economies [7]; however, its LC PE consumption and GHG emissions are about two times as much as that in the U.S. This is mainly attributed to two reasons: (1) the fuels consumed for primary aluminum production in the U.S. are mainly fuel oil and natural gas in addition to electricity while this is dominated by coal in China; and (2) coal shares a proportion of more than 60% in China's grid mix [27] while this figure is 14.3% in the U.S. [7].

Table 6. LC results from different studies.

Item	Year	Scope	LC PE Intensity (MJ/t Al Ingot)		LC GHG Emissions Intensity (kg $CO_{2\text{-eq}}$/t Al Ingot)	
			Primary	Recycled	Primary	Recycled
This study	2020	China	157,207	11730	15,947	845
Hao et al., 2016 [24]	2013	China			16,500	
Hao et al., 2016 [24]	2020	China			14,300	
Ding et al., 2012 [20]	2010	China			17,000	715
Ding et al., 2021 [26]	2017	China			14,500	930
Zhang et al., 2016 [25]	2012	China	167,847	7875	15,800	722
He et al., 2020 [23]	2016	China			19,500	350
Anna M K 2014 [11]	2013	Europe			9503	
Anna M K 2014 [11]	2013	Iceland			5560	
IAI 2022 [6]	2018	Global			16,100	
World Aluminum 2018 [12]	2015	Global	166,000		18,000	
Nunez et al. 2016 [13]	2010	Global	163,000		16,500	
Nunez et al. 2016 [13]	2010	RoW *	109,000		10,800	
TAA 2013 [8]	2010	North America			8973	670
GREET 2021 [7]	2020	the U.S.	115,780		7282	

Note: * RoW: the world excluding China (rest of world).

3.6. Limitation and Future Work

Although this study has carried out several extensive works compared to previous similar studies, it still faces three limitations: (1) the average data of the energy efficiency and fuel consumption industry used in the current study cannot reflect the more specific technical characteristics of China's aluminum industry, especially the situation of advanced enterprises; (2) this study failed to assess the GHG emissions contribution of the entire aluminum industry to China's carbon emissions; and (3) it is necessary to explore the low-carbon transition pathway of the aluminum industry in the context of China's carbon peaking and carbon neutrality targets.

4. Concluding Remarks

This study estimated China's national average LC PE consumption and GHG emissions of the aluminum industry in 2020 based on the process-based LC analysis method and proposed several policy recommendations for China's aluminum industry. In view of the different GHG emissions factors of the electricity mix for the aluminum industry, the disparity of the GHG emissions intensity of aluminum production among provinces was estimated. In addition, comparative analysis with other studies was conducted. The following specific conclusions are drawn from this study:

(1) LC PE consumption and GHG emissions per ton of primary aluminum ingot in 2020 were 157,207 MJ and 15,947 $CO_{2\text{-eq}}$, respectively, with the aluminum electrolysis stage being the largest contributor. There are multiple sources of GHG emissions in the LC chain of aluminum production, among which fuel generation and utilization contribute the most, accounting for 88.28% of the total emissions.

(2) China's recycled aluminum shows significant advantages in energy consumption and GHG emissions in comparison with primary aluminum. The LC PE consumption and GHG emissions per ton of recycled aluminum ingot in 2020 were 11,730 MJ and 845 $CO_{2\text{-eq}}$, only 7.46% and 5.30% of those for primary aluminum ingot, respectively. Promotion of the recycled aluminum industry will contribute to energy saving and emission reduction in China's aluminum industry.

(3) Obvious provincial disparity exists in the LC results of China's aluminum industry. In general, the LC PE and GHG emissions intensities of primary aluminum are higher in the main production areas while those of recycled aluminum are lower in the main production areas.

(4) China's aluminum industry has significant potential for energy saving and GHG emissions reduction by decreasing electrolysis electricity consumption, improving the electricity structure (particularly the share of self-generated electricity), reducing the net coal consumption rate of self-generated electricity, and optimizing the geographical distribution of the production capacity.
(5) GHG emissions of China's primary aluminum production are 1.5–3.5 times that of developed economies mainly because China's electricity source and process fuels are both dominated by coal.

The following policy suggestions for China's aluminum industry are made based on this study:

(1) To boost the utilization of renewable electricity in the aluminum industry to improve the performances of the electricity mix in LC PE consumption and GHG emissions.
(2) To restrict new capacities and phase out inefficient capacities of self-generated electricity to limit the scale and reduce the overall net coal consumption rate.
(3) To improve the domestic aluminum scrap recovery system to provide sufficient and stable raw materials for the development of the recycled aluminum industry.
(4) To promote the relocation of the primary aluminum production capacity from the north to the south-west to optimize the spatial distribution of the primary aluminum industry.
(5) To consider the differences among provinces when relevant policies are implemented by the central government in order to make policies more effective nationwide.

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Abbreviations/Nomenclature

AFG	Aluminum for Future Generation
Al ingot	aluminum ingot
CF_4	tetrafluoromethane
C_2F_6	hexafluoroethane
$CO_{2\text{-eq}}$	CO_2 equivalents
GHG	greenhouse gas
GWP	global warming potential
IAI	International Aluminum Institute
IPCC	Intergovernmental Panel on Climate Change
LC	life-cycle
mt	megaton

NG	natural gas
NDRC	National Development and Reform Commission
PE	primary fossil energy
PFCs	perfluorocarbons
PFPB	Point-center Feed Prebake
P&T	production and transportation
RoW	the world excluding China (rest of world)
t	tonne
TAA	The Aluminum Association
A_A	the average ash content of carbon anode
EM	greenhouse gas emissions intensity
EM_{LC}	life-cycle greenhouse gas emissions intensity
EN_{direct}	direct energy consumption
EN_{LC}	life-cycle primary fossil energy intensity
P	specific material consumption per tonne of primary aluminum
SH_k	the share of electricity source in the electricity generation of the grid
S_A	the average sulfur content of carbon anode
η	transmission loss of the electricity grid
i	aluminum production process
j	process fuel type
k	electricity source

Appendix A

Table A1. Provincial and nationwide GHG intensity of electricity and aluminum production.

	Grid Mix	Electricity for Al Electrolysis		LC GHG Emissions Intensity (kg $CO_{2\text{-eq}}$/t Al)	
	g $CO_{2\text{-eq}}$/MJ Electricity	Share of Self-Generated Power	LC GHG Intensity (g $CO_{2\text{-eq}}$/MJ Electricity)	Primary Aluminum	Recycled Aluminum
Beijing	142.3	- -	- -	- -	753.9
Tianjin	227.0	- -	- -	- -	921.6
Hebei	198.4	- -	- -	- -	865.1
Shanxi	216.0	0%	216.0	15,443.6	899.9
Inner Mongolia	217.7	89%	255.6	17358.4	923.6
Liaoning	188.5	0%	188.5	14020.1	845.4
Jilin	178.3	- -	- -	- -	0.0
Heilongjiang	206.8	- -	- -	- -	881.7
Shanghai	222.7	- -	- -	- -	913.1
Jiangsu	201.4	- -	- -	- -	871.0
Zhejiang	167.0	- -	- -	- -	802.8
Anhui	222.1	- -	- -	- -	911.9
Fujian	135.8	0%	135.8	11290.4	741.1
Jiangxi	194.7	- -	- -	- -	857.6
Shandong	216.9	98%	259.4	17539.7	924.5
Henan	219.0	60%	243.8	16793.0	919.2

Table A1. *Cont.*

	Grid Mix	Electricity for Al Electrolysis		LC GHG Emissions Intensity (kg $CO_{2\text{-}eq}$/t Al)	
	g $CO_{2\text{-}eq}$/MJ Electricity	Share of Self-Generated Power	LC GHG Intensity (g $CO_{2\text{-}eq}$/MJ Electricity)	Primary Aluminum	Recycled Aluminum
Hubei	122.5	0%	122.5	10604.3	714.9
Hunan	144.8	- -	- -	- -	758.9
Guangdong	160.6	- -	- -	- -	790.2
Guangxi	121.2	30%	162.9	8026.8	0.0
Hainan	136.2	- -	- -	- -	- -
Chongqing	166.6	0%	166.6	12886.6	802.1
Sichuan	43.9	0%	43.9	6533.5	559.2
Guizhou	154.3	0%	154.3	12249.5	777.8
Yunnan	50.4	0%	50.4	6872.5	572.2
Tibet	40.6	- -	- -	- -	- -
Shaanxi	218.4	100%	260.3	17586.9	927.1
Gansu	154.8	70%	228.7	15835.5	818.6
Qinghai	53.3	23%	100.9	9317.3	603.6
Ningxia	206.0	50%	233.1	16233.6	894.7
Xinjiang	199.4	94%	256.6	17343.4	897.9
Nationwide	172.7	65%	229.0	15,947	844.9

Note: "- -" represents there is no primary/recycled aluminum industry capacity in the province.

References

1. China Nonferrous Metals Industry Association. China Nonferrous Metals Industry 2020 Economic Operation Report. 2021. Available online: http://lwzb.stats.gov.cn/pub/lwzb/tzgg/202205/W020220511403032411542.pdf (accessed on 12 October 2021). (In Chinese)
2. International Aluminum Institute (IAI). Statistics of Global Primary Aluminum Production. 2021. Available online: http://www.world-aluminium.org/statistics/ (accessed on 10 November 2021).
3. Editorial Board of the Yearbook of Nonferrous Metals Industry of China. *The Yearbook of Nonferrous Metals Industry of China 2020*; China Nonferrous Metals Industry Association: Beijing, China, 2021. (In Chinese)
4. Bureau of Statistics of China. *China Energy Statistical Yearbook 2021*; China Statistics Press: Beijing, China, 2022.
5. Hu, B. The change of electrolytic aluminum industry under carbon neutrality target. *China Nonferrous Met News*. 2021. Available online: https://acin.org.cn/6772.html (accessed on 19 May 2021). (In Chinese)
6. International Aluminium Institute (IAI). 2019 Life Cycle Inventory (LCI) Survey Global Summary. 2022. Available online: https://international-aluminium.org/resource/life-cycle-inventory-lci-data-and-environmental-metrics/ (accessed on 16 July 2022).
7. Argonne National Laboratory (ANL). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET). 2021. Available online: https://greet.es.anl.gov/greet_excel_model.models (accessed on 12 August 2022).
8. The Aluminum Association (TAA). The Environmental Footprint of Semi-Finished Aluminum Products in North America. 2022. Available online: https://www.aluminum.org/sites/default/files/2022-01/2022_Executive-Summary_Semi-Fab_LCA.pdf (accessed on 16 May 2022).
9. European Aluminum Association. Life Cycle Inventory Data for Aluminum Production and Transformation Processes in Europe. 2013. Available online: http://ec.europa.eu/DocsRoom/documents/13762/attachments/5/translations/en/renditions/pdf (accessed on 14 November 2021).
10. Liu, G.; Müller, D.B. Addressing sustainability in the aluminum industry: A critical review of life cycle assessments. *J. Clean. Prod.* **2012**, *35*, 108–117. [CrossRef]
11. Anna, M.K. *A Cradle-To-Gate Life Cycle Assessment of Primary Aluminum Production at Norðurál*; University of Iceland: Reykjavik, Iceland, 2014.

12. World Aluminum. Aluminum Carbon Footprint Technical Support Document. 2018. Available online: http://www.world-aluminium.org/media/filer_public/2018/02/15/carbon_footprint_technical_support_document_v1_published.pdf (accessed on 12 September 2019).
13. Nunez, P.; Jones, S. Cradle to gate: Life cycle impact of primary aluminum production. *Int. J. Life Cycle. Assess.* **2016**, *21*, 1594–1604. [CrossRef]
14. Yue, Q.; Wang, H.; Gao, C.; Du, T.; Liu, L.; Lu, Z. Resources saving and emissions reduction of the aluminum industry in China. *Resour. Conserv. Recycl.* **2015**, *104*, 68–75. [CrossRef]
15. Lin, B.; Xu, L. Energy conservation of electrolytic aluminum industry in China. *Renew Sustain. Energy Rev.* **2015**, *43*, 676–686. [CrossRef]
16. Li, M.; Mi, Z.; Coffman, D.M.; Wei, Y.M. Assessing the policy impacts on non-ferrous metals industry's CO_2 reduction: Evidence from China. *J. Clean. Prod.* **2018**, *192*, 252–261. [CrossRef]
17. Li, Q.; Zhang, W.; Li, H.; He, P. CO_2 emission trends of China's primary aluminum industry: A scenario analysis using a system dynamics model. *Energy Policy* **2017**, *105*, 225–235. [CrossRef]
18. Gao, F.; Nie, Z.; Wang, Z.; Li, H.; Gong, X.; Zuo, T. Greenhouse gas emissions and reduction potential of primary aluminum production in China. *Sci. China Ser. E Technol. Sci.* **2009**, *52*, 2161–2166. [CrossRef]
19. Du, J.; Han, W.; Peng, Y.; Gu, C. Potential for reducing GHG emissions and energy consumption from implementing the aluminum intensive vehicle fleet in China. *Energy* **2010**, *35*, 4671–4678. [CrossRef]
20. Ding, N.; Gao, F.; Wang, Z.; Gong, X. Comparative analysis of primary aluminum and recycled aluminum on energy consumption and greenhouse gas emission. *Chin. J. Nonferr. Met.* **2012**, *22*, 2908–2915.
21. Guo, J.; Gao, F.; Wang, Z.H.; Liu, Y.; Hu, J.Y.; Li, Z. Correlation Analysis between Emission and Impact Factors of Greenhouse Gases Caused by Production of Primary Aluminum. *Mater. Sci. Forum* **2014**, *787*, 135–143. [CrossRef]
22. Liu, Z.; Geng, Y.; Adams, M.; Dong, L.; Sun, L.; Zhao, J.; Dong, H.; Wu, J.; Tian, X. Uncovering driving forces on greenhouse gas emissions in China' aluminum industry from the perspective of life cycle analysis. *Appl. Energy* **2016**, *166*, 253–263. [CrossRef]
23. He, X.; Kim, H.C.; Wallington, T.J.; Zhang, S.; Shen, W.; De Kleine, R.; Wu, Y. Cradle-to-gate greenhouse gas burdens for aluminum and steel production and cradle-to-grave GHG benefits of vehicle lightweighting in China. *Resour. Conserv. Rec.* **2020**, *152*, 104497. [CrossRef]
24. Hao, H.; Geng, Y.; Hang, W. GHG emissions from primary aluminum production in China: Regional disparity and policy implications. *Appl. Energy* **2016**, *166*, 264–272. [CrossRef]
25. Zhang, Y.; Sun, M.; Hong, J.; Han, X.; He, J.; Shi, W.; Li, X. Environmental footprint of aluminum production in China. *J. Clean. Prod.* **2016**, *133*, 1242–1251. [CrossRef]
26. Ding, N.; Liu, N.; Lu, B.; Yang, J. Life cycle greenhouse gas emissions of aluminum based on regional industrial transfer in China. *J. Ind. Ecol.* **2021**, *25*, 1657–1672. [CrossRef]
27. China Electricity Council (CEC). *National Power Industry Statistics 2020*; China Electricity Council: Beijing, China, 2021; Available online: https://www.cec.org.cn/upload/1/editor/1640595481946.pdf (accessed on 12 July 2022).
28. IAI. Global Data on Perfluorocarbon (PFC) Emissions. 2018. Available online: http://www.world-aluminium.org/statistics/perfluorocarbon-pfc-emissions/#bubble (accessed on 26 May 2019).
29. Integrated Knowledge for our Environment (iKE). Chinese Life Cycle Database. Available online: http://www.ike-global.com/products-2/chinese-lca-database-clcd (accessed on 26 May 2019).
30. Ministry of Industry and Information Technology(MIIT). Standard Regulations for Aluminum Industry. 2013. Available online: http://www.gov.cn/gzdt/2013-07/24/content_2454273.htm (accessed on 25 May 2019). (In Chinese)
31. Zhang, Z. Energy saving of carbon anode enterprises. *Carbon Technol.* **2012**, *31*, B29–B32.
32. National Development and Reform Commission (NDRC). Guideline for accounting GHG emissions from the aluminum smelter. Beijing. 2013. Available online: http://qhs.ndrc.gov.cn/zcfg/201311/W020131202589518801729.pdf (accessed on 25 May 2019). (In Chinese)
33. General Administration of Customs of China. Import statistics of aluminum ore and concentrate in 2020. Available online: http://www.customs.gov.cn/eportal/ui?msgDataId=78ec17e885704f22b552e7cfe4e4002b (accessed on 12 July 2021).
34. International Trade Statistics Database. Available online: https://comtrade.un.org/data/ (accessed on 21 July 2022).
35. National Bureau of Statistics of China. National Data on the Average Distance of Cargo Transportation. 2020. Available online: http://data.stats.gov.cn/easyquery.htm?cn=C01 (accessed on 25 May 2021). (In Chinese)
36. Ministry of Transport. Statistical Bulletin of Transportation Development. 2020. Available online: http://www.gov.cn/xinwen/2020-05/12/content_5510817.htm (accessed on 15 May 2020). (In Chinese)
37. National Railway Administration. Statistical Bulletin of the Railway in 2020. Available online: http://www.nra.gov.cn/xwzx/zlzx/hytj/202204/P020220902306794538609.pdf (accessed on 25 April 2021). (In Chinese)
38. Peng, T.; Zhou, S.; Yuan, Z.; Ou, X. Life Cycle Greenhouse Gas Analysis of Multiple Vehicle Fuel Pathways in China. *Sustainability* **2017**, *9*, 2183. [CrossRef]
39. State Railway Administration. *Completion of National Railway Energy Consumption and Conservation Indicators (2015–2019)*; State Railway Administration: Beijing, China, 2020. (In Chinese)
40. Aluminum for Future Generation (AFG). Energy & Water Consumption for Primary Aluminum Production. Available online: http://primary.world-aluminium.org/aluminium-facts/energy-water/ (accessed on 16 May 2019).

41. China Bond Rating Co., Ltd. Guide to Regional and Enterprise Competitiveness of Electrolytic Aluminum in 14 Provinces of China. 2017. Available online: http://finance.sina.com.cn/stock/hkstock/hkstocknews/2017-05-24/doc-ifyfkkme0318771.shtml (accessed on 16 May 2019).
42. Antaike. The Proportion of Self-Generated Power Capacity in China's Electrolytic Aluminum Industry Shows a Downward Trend. 2020. Available online: https://news.cnal.com/2020/12-02/1606872807561727.shtml (accessed on 20 January 2021). (In Chinese)
43. Ding, N.; Yang, J. Life cycle inventory Analysis of Fossil Energy in China. *China Environ. Sci.* **2015**, *35*, 1592–1600.
44. IPCC. *Climate Change 2014: Mitigation of Climate Change Chapter 10: Industry*; Cambridge University Press: Cambridge, UK, 2014.
45. IAI. Life Cycle Model of Chinese Grid Power and Application to the Aluminum Industry. 2017. Available online: http://www.world-aluminium.org/publications/ (accessed on 10 November 2021).
46. Zhuo, Z.; Du, E.; Zhang, N.; Nielsen, C.P.; Lu, X.; Xiao, J.; Wu, J.; Kang, C. Cost increase in the electricity supply to achieve carbon neutrality in China. *Nat. Commun.* **2022**, *13*, 1–13. [CrossRef] [PubMed]