Driving Forces and Pathways for China's Alumina Quality Upgrade

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Abstract

Alumina, the key raw material in aluminium production, directly determines the purity of primary aluminium and also influences the energy efficiency of the electrolysis process. As the world's largest producer of alumina, China's efforts to improve product quality are influenced by multiple factors, including resource characteristics, technological limitations, and policy promotion. Historically, due to China's bauxite resources being predominantly diaspore with high silica and low iron content, the production process relied heavily on the energy-intensive sintering process and parallel-series process. This resulted in alumina products being predominantly in floury form for an extended period. By the late 20th century, with the introduction of the Bayer process from Pechiney and the import of gibbsitic bauxite, China started to gradually achieve the production of sandy alumina. Nevertheless, due to various factors, China's alumina products remain primarily intermediate, hardly meeting the stringent requirements of the electrolytic aluminium industry for reduced energy consumption. In recent years, the Chinese government has introduced a series of policies requiring the aluminium industry to maximise energy consumption reduction, which in turn has driven improvements in the quality of alumina. However, in the alumina market, high-quality products have not received a corresponding price premium over the long term, leading some refineries to prioritize low quality and increased liquor productivity to boost profits. Looking ahead, the alumina industry needs to achieve breakthroughs in multiple aspects: First, leveraging the pressure from the aluminium industry for optimising energy consumption will promote the production of higher quality alumina. Second, addressing raw material supply bottlenecks through strategic overseas bauxite resource sourcing. Finally, establishing and refining a quality grading system for alumina to facilitate the industry's transition toward a quality-and-efficiency-driven model.

Keywords: Alumina, Bauxite, Electrolytic aluminium, Quality grading.

1. Introduction

Alumina, the key raw material for aluminium electrolysis, has a direct impact on the purity of primary aluminium and also influences the energy efficiency of the electrolytic process. Against the backdrop of the global green and low-carbon transition, the physical properties and chemical composition of alumina have become key constraints in upgrading electrolytic aluminium technology. As the world's largest producer of alumina and primary aluminium, China's evolution in product quality reflects the complex interplay of resource endowment, technological breakthroughs, and policy drivers.

China's alumina industry dated back in the 1950s. However, constrained by the characteristics of domestic bauxite resources where over 80 % are diasporic with high silica content [1], early alumina production relied on energy-intensive sintering process and parallel-series process. This resulted in alumina products being predominantly of the floury type for a long period, exhibiting defects such as high fine-particle content, poor flowability, and slow dissolution.

Since the 20th century, China's alumina industry has experienced significant development, with sandy alumina gradually being part of the industrial production landscape. However, influenced by market demand, China's products remain predominantly intermediate alumina. Key indicators such as the -45 µm content and α-Al_2O_3 proportion lag behind those of sandy alumina, making it difficult to meet the energy consumption reductions required from the aluminium industry.

In recent years, China has introduced a series of energy consumption limit standards and tiered electricity pricing policies for aluminium production, aiming to further reduce energy consumption in the aluminium industry. Given that the technology level of Chinese aluminium smelters has already reached the world's leading level, improving the quality of alumina can help achieving the goal of energy consumption reduction.

2. Development History of China's Alumina Quality

The quality of alumina, both physical properties and chemical composition, significantly impacts the quality of aluminium. Physical properties include particle size, attrition index, specific surface area, bulk density, α-Al_2O_3 content, angle of repose, etc. Chemical composition (purity) is a major factor, influencing the quality of primary aluminium and also affecting the technical and economic indicators of the aluminium electrolysis process. Since the establishment of China's first alumina refinery in 1954, the country's alumina industry has achieved significant development, with production technologies progressing through stages including the sintering process, Bayer-sintering series process, and Bayer process. The quality of alumina products has also evolved through three phases: an early stage dominated by floury alumina, a middle stage marked by the exploration and improvement of sandy alumina technology, and the most recent phase featuring further quality enhancement of alumina, driven by two-stage precipitation technology by mainly using imported bauxite.

The floury alumina contains over 20 % fine particles smaller than 45 µm, with α-Al_2O_3 accounting for 60–70 % of its composition. It exhibits a specific surface area of 50–60 m^2/g but weak adsorption capacity. Additionally, the floury alumina has an angle of repose > 40°, resulting in low particle strength and severe dust losses during electrolysis [2].

Sandy alumina typically exhibits superior physical and chemical properties. It has an average particle size of 80–100 µm, a fine particle content (- 45 µm) of less than 12 %, a high γ-Al_2O_3 proportion (and conversely an α-Al_2O_3 content lower than 20 %), and a specific surface area of 50–60 m^2/g. Additionally, sandy alumina demonstrates high flowability (angle of repose of 30–35°) and a low attrition index (< 20 %) [2].

The intermediate alumina exhibits properties between sandy and floury alumina, with a fine particle content (- 45 µm) of 12–20 %, a high α-Al_2O_3 proportion (40–50 %), and an angle of repose of 35–40° [2].

Table 1. Quality classification of SGA products [2].

Types	**- 45 µm (%)**	**Average particle size (µm)**	**Angle of repose (°)**	**Specific surface area (m²/g)**	**LOI (%)**	**α-Al_2O_3 content (%)**
Floury	> 20	50	> 42	2 - 10	≤ 0.5	60 - 70
Intermediate	12 - 20	50 - 80	35 - 40	> 35	≤ 0.8	40 - 50
Sandy	< 12	80 - 100	< 30	50 - 60	≤ 1.0	< 20

2.1 Floury Alumina Phase

The majority of China's domestic bauxite reserves is diasporic, with discovered gibbsitic bauxite accounting for less than 1 % of the country's total bauxite resources [1]. These gibbsitic deposits are characterized by low grade and small scale, rendering them economically unviable for mining. The physico-chemical properties of diaspore determined the early production processes of alumina in China, thereby influencing product quality. The alumina monohydrate in diaspore is predominantly in the α-form, which is more crystallographically stable than the γ-form alumina trihydrate found in gibbsite, requiring a higher digestion temperature (260 °C). Nearly 80 % of China's diasporic bauxite has an aluminium-to-silica (A/S) ratio below 8, with overall characteristics of high alumina, high silica, and low iron content [1]. Given such bauxite resources, developing an alumina industry heavily reliant on them required the use of the sintering process, a process plagued by high energy consumption, high capital investment, and low product quality. This resulted in China's alumina products being predominantly in floury or intermediate forms for an extended period.

China's first alumina refinery, which commenced production on July 1, 1954, adopted the soda-lime sintering process. After assimilating and mastering the sintering process technology, China developed the parallel-series process tailored to its specific bauxite resources, which was applied in practice and in fact only used in China. Zhengzhou Alumina Refinery (predecessor of Chalco Henan), the second alumina refinery constructed and put into operation in 1965, pioneered the adoption of the parallel-series processes for alumina production. Its process demonstrated stable operation and advanced technical indicators, achieving sodium carbonate consumption below 70 kg per tonne of alumina and an overall alumina recovery rate exceeding 90 % [4]. The product quality was excellent. Production practice has proven that the parallel-series process is an effective method for treating high-silica, low-iron bauxite. Subsequently, China successively commissioned the Guizhou Alumina Refinery (predecessor of Chalco Guizhou) in 1978 and the Shanxi Alumina Refinery (predecessor of Chalco Shanxi) in 1987, both employing the parallel-series process.

The parallel-series process initially addressed the challenges of processing China's difficult-to-treat diasporic bauxite, but it subsequently led to quality issues in alumina products. Comparing China's early alumina quality standards with those of advanced international refineries during the same period, the indicators for Al_2O_3, SiO_2, Fe_2O_3, Na_2O, and loss on ignition (LOI) show little difference. However, most international alumina products had already adopted a sandy form, with controlled trace element content such as Ti, V, Zn, and K [5]. In contrast, constrained by processing technology and resource characteristics, China's alumina products were mostly floury, and thus the standards did not include requirements for particle size, trace element content, etc.

However, for the aluminium electrolysis process, the physical properties of floury alumina are problematic. It is mostly flaky and feathery, with fine particles, small specific surface area, and a large angle of repose (approximately 45°), along with high α-Al_2O_3 content. These characteristics resulted in poor fluidity and difficulty in dissolution during the electrolysis process. There was an urgent need to develop sandy alumina production technology.

Table 2. Requirements for alumina under different standards.

Standard	Grade	Al_2O_3 (%)	Chemical composition (%) ≤			
		≥	SiO_2	Fe_2O_3	Na_2O	LOI
GB 8178-1987(YS/T 274-1994) [6]	AO-1	98.6	0.02	0.03	0.55	0.8
	AO-2	98.5	0.04	0.04	0.66	0.8
	AO-3	98.4	0.06	0.04	0.65	0.8
	AO-4	98.3	0.08	0.05	0.7	0.8
	AO-5	98.2	0.1	0.05	0.7	1
YS/T 274-1998[7]	AO-1	98.5	0.02	0.02	0.5	1
	AO-2	98.4	0.04	0.03	0.6	1
	AO-3	98.3	0.06	0.04	0.65	1
	AO-4	98.2	0.08	0.05	0.7	1
Alcoa Australia Limited (1996)	-	98.4	0.025	0.02	0.55	0.9
Australia QAL	-	99.0	0.025	0.025	0.45	1
Greece AoG	-	98.5	0.016	0.015	0.38	1

2.2 Technical Exploration and Quality Improvement of Sandy Alumina

Globally, the rise of sandy alumina began in the 1970s, driven by the advent of dry purification technology and the development and application of large point-feeding prebaked electrolytic cells. This prompted advanced international aluminium smelters to demand higher standards for alumina's physical properties, requiring sandy alumina with coarse particle size, high strength, fast dissolution rate, good flowability, and strong HF adsorption capacity in dry gas scrubbing systems.

In the 1980s, China began to recognize the necessity of producing sandy alumina and initiated related researches. At that time, global production technologies for sandy alumina were primarily divided into two major systems: The low-soda concentration, low-αk sandy precipitation technology represented by Alcoa and Alcan; and the high-soda concentration, relatively high-αk sandy alumina production technology represented by Pechiney and Alusuisse.

The previously mentioned Guizhou Alumina Refinery attempted to adopt the Bayer process with two-stage precipitation. However, due to issues such as excessively low product temperature in the second stage during production, they had to abandon the two-stage precipitation approach and revert to one-stage precipitation. The precipitated product is screened, with the underflow for sandy alumina and the overflow for floury alumina after settling.

In 1992, the second phase of Shanxi Alumina Refinery attempted to adopt the parallel-series process with a two-stage precipitation technology to produce sandy alumina. However, due to mechanical failures and changes in production conditions, the pilot production of sandy alumina ultimately failed, and the refinery switched to producing intermediate alumina instead.

In 1990, Pingguo Alumina Refinery introduced the Bayer process using Pechiney technology, initiating China's industrial-scale production of sandy alumina. The refinery was completed and put into operation in 1995, adopting French tubular preheating and digestion technology and equipment, becoming China's first pure Bayer process alumina refinery. Its technical and economic indicators reached internationally advanced levels, holding significant importance in the development history of China's alumina industry.

After long-term technological assimilation, absorption, and independent innovation, China ultimately established a production technology system for sandy alumina based on the Bayer process using diasporic bauxite. However, as indicated by the particle size indicators of the sandy alumina produced with this technology (-45 µm content at 12–14 % and Al_2O_3 attrition index at 20–30 %), the sandy alumina derived from diaspore only met the threshold level of the sandy alumina standard, still falling short of fully meeting the requirements for sandy alumina.

During this phase, the national standard *Alumina* (GB/T 24487-2009) replaced the industry standard *Alumina* (YS/T 274-1998). While making minor adjustments to chemical composition requirements, the new standard began emphasizing trace elements and physical performance indicators, though without specifying definitive limits. The industry standard *Smelter Grade Alumina* (YS/T 803-2012) shows little difference in chemical composition from GB/T 24487-2009 but adds physical performance indicators such as particle size distribution, angle of repose, attrition index, α-Al_2O_3 content, and bulk density, etc. [9].

Table 3. Requirements for alumina in GB/T 24487-2009 [8].

Grade	**GB/T 24487-2009**				
	Chemical composition (mass fraction), %				
	Al_2O_3 ≥	**Impurity content, ≤**			
		SiO_2	Fe_2O_3	Na_2O	LOI
AO-1	98.6	0.02	0.02	0.5	1
AO-2	98.5	0.04	0.02	0.6	1
AO-3	98.4	0.06	0.03	0.7	1

Table 4. Requirements for *Smelter Grade Alumina* (YS/T 803-2012) [9].

Grade	**Physical properties**					
	Particle size distribution (%)		**Angle of repose**	**Attrition index**	**a-Al_2O_3 content**	**Bulk density**
	-20 µm	+ 150 µm	(°)	(%)	(%)	(g/cm^3)
	≤	≤	≤	≤	≤	—
YAO-1	2	3	35	25	10	0.95–1.10
YAO-2	5	6				

2.3 Improvement of Alumina Quality Under the Dominance of Imported Bauxites

In the 21st century, as China's bauxite resources have become increasingly depleted, the country has imported some alumina while also sourced gibbsite from Australia and Guinea to vigorously expand production of sandy alumina by the Bayer process. Alumina output has sustained a rapid growth. As shown in Figure 1, by 2023, China's alumina output reached 82.51 million tonnes, accounting for approximately 58.15 % of the global output (141.9 million tonnes) [10]. Concurrently, the quality of China's alumina has further improved, with high-quality products achieving a controlled particle size distribution of -45 µm content in the range of 8–12 %.

The rapid growth of alumina production between 2000 and 2011 was primarily attributed to the peculiarity of the period. In the early 21st century, China joined the WTO and became the "world's factory", with rapid national economic growth and foreign trade expansion propelling a surge in both production and consumption of primary aluminium. This, in turn, fuelled soaring demand for alumina. The supply-demand balance tilted sharply, causing alumina prices to skyrocket from 2.93 kRMB/t in 2003 (approx. 414 USD/t) to nearly 6.5 kRMB/t by 2006 (approx. 924 USD/t), while profit margins surged from around 30 % to nearly 200 %, making the alumina industry highly lucrative. The substantial profits attracted massive capital inflows, leading to the construction of many private alumina refineries and driving rapid growth in alumina output [23].

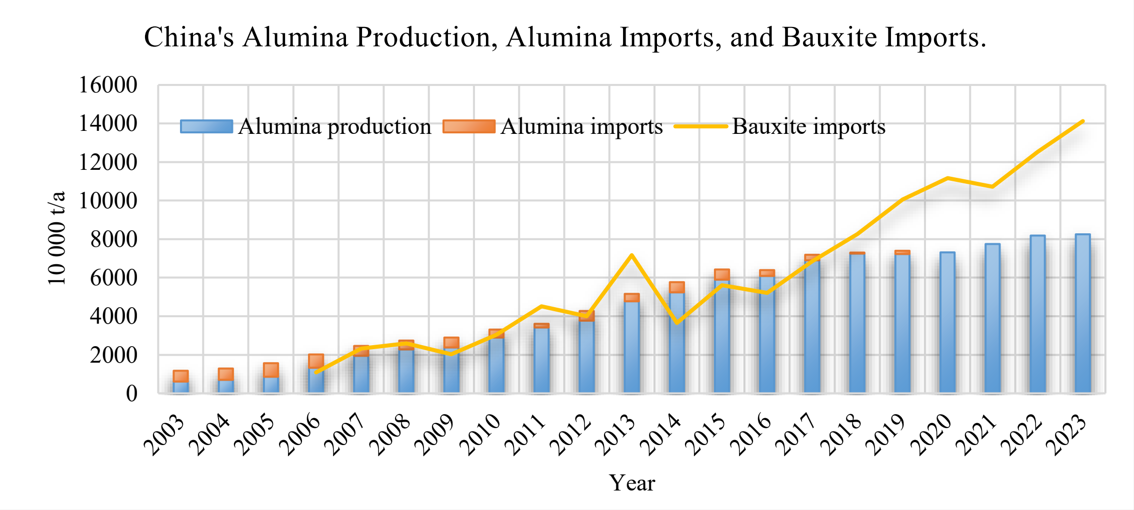

Figure 1. China's alumina production, alumina imports, and bauxite imports [15].

Since 2012, after the 18th National Congress of the CPC, the Party Central Committee introduced new economic development directives, shifting the focus from high-speed growth to high-quality development. In 2018, the National Development and Reform Commission (NDRC) issued the *Notice on Promoting the Orderly Development of the Alumina Industry* to regulate the alumina industry's growth. From 2012 to the present, the alumina industry has exhibited two major trends: deepening reliance on imported bauxite alongside simultaneous improvements in alumina quality and quantity. On one hand, as domestic high-grade bauxite reserves dwindled, imports surged, increasing the competitive edge of coastal alumina refineries. China has strategically constructed a number of Bayer process alumina refineries in port cities such as Fangchenggang and Beihai in Guangxi, as well as Caofeidian in Hebei, including large-scale projects like the Guangxi Huasheng Alumina Refinery Phases I and II and the Hebei Wenfeng Alumina Project. These initiatives leverage port logistics and the advantages of imported bauxite. On the other hand, technological upgrades and the application of new technologies have led to rapid improvements in alumina output and product quality. For example, the traditional and relatively complex two-stage precipitation process, requiring two-stage hydrocyclone classification, results in higher investment and operating costs. Based on the conventional two-stage precipitation, Guiyang Aluminium and Magnesium Design & Research Institute has developed a pre-purification two-stage precipitation technology. This innovation not only reduces construction and operational costs but also ensures that the particle size of alumina product meets a higher standard, with the particle size of -45 µm controlled at ≤ 9 %.

To meet the demand for primary aluminium, as shown in Figure 1, China once imported large quantities of high-quality alumina, with imports peaking in 2004 at 7.02 million tonnes [11], even exceeding domestic alumina production at the time. However, as China began large-scale imports of bauxite for the production of sandy alumina, both the volume and proportion of alumina imports declined rapidly. By 2019, alumina imports had become so negligible that they were no longer included in China's statistical yearbooks. This fact strongly demonstrates that China's alumina production can provide sufficient and reliable raw material support for primary aluminium production [12].

With the overall improvement in the quality of China's alumina products, the national standard *Alumina* (GB/T 24487-2022) has replaced *Alumina* (GB/T 24487-2009). The new standard introduces physical indicators such as specific surface area and particle size, while limiting the content of -45 µm particles to no more than 20 % [13]. In contrast, the industry standard YS/T 803-2023 sets the -45 µm content for Grade 1 products at no more than 18 % [14]. This shows that even the highest-grade alumina products under China's current national and industry standards only need to meet the requirements for intermediate alumina, without more detailed quality grading.

Table 5. Smelter Grade Alumina (YS/T 803-2023) [14].

Grade	**Chemical composition (mass fraction) %**						**Physical properties**	
	Al_2O_3	**SiO_2**	**Fe_2O_3**	**Na_2O**	**CaO**	**LOI**	**Specific surface area**	**Content of particle size ≤ 45 µm no more than %**
	≥	≤					**m^2/g**	
YAO-1	98.6	0.02	0.02	0.45	0.03	1	70–120	18
YAO-2	98.5	0.04	0.02	0.55	0.04	1		25

Table 6. Alumina (GB/T24487-2022) [13].

Main chemical composition							**Main physical properties**	
Grade	**Al_2O_3 (%)**	**SiO_2 (%)**	**Fe_2O_3 (%)**	**Na_2O (%)**	**CaO (%)**	**LOI (%)**	**Specific surface area (m^2/g)**	**Content of particle size ＜45 µm (%)**
	≥	≤					≥	≤
AO-G	98.6	0.018	0.015	0.35	0.03	1	60	20
AO-1	98.6	0.02	0.02	0.45	0.03	1	60	20
AO-2	98.5	0.04	0.02	0.55	0.04	1	60	25

However, while China's alumina production has seen substantial growth, its quality has not improved at the same pace. In the primary aluminium industry, the successful development and application of large-scale electrolytic cell technologies, such as the 500 kA and 600 kA cells, have elevated China's technical prowess to internationally leading levels, achieving a current efficiency of 94.6 % and a power consumption of 12 443 kWh/t Al (NEUI600) [15]. Data from the International Aluminium Institute (IAI), as shown in Table 7, indicate that China's aluminium electrolysis performance ranks among the world's best when measured by the industry-wide average power consumption [16]. However, the quality of SGA supply remains suboptimal.

China's aluminium electrolysis technology generally imposes lower quality requirements on metallurgical-grade alumina compared to international standards. This relative leniency in quality standards for SGA came from the challenges posed by China's reliance on diasporic bauxite in early stage [1]. From the arduous beginnings of self-reliance to the exploration of sandy alumina technology, issues such as high digestion temperature, high precipitation concentrations, yet low precipitation temperatures due to diaspore have persistently constrained the quality improvement of China's alumina products. For nearly five decades, these factors made the products difficult to meet the standards of sandy alumina. It was not until the 21st century, when China began large-scale imports of bauxite for alumina production, that the overall product quality showed a trend of significant improvement.

Table 7. Global average power consumption in electrolytic aluminium production [16].

Year	Africa	North America	South America	Asia	Europe	Oceania	Gulf Region	China	Global average
				(Excluding China)					
2012	14 774	15 458	15 912	14 939	15 699	14 911	14 480	13 844	14 638
2013	15 534	15 584	15694	14 749	15 528	14 643	14 817	13 740	14 561
2014	14 569	14 933	15 038	14 766	15 494	14 770	14 889	13 596	14 292
2015	14 550	15 130	15 751	14 891	15 522	14 667	14 497	13 562	14 239
2016	14 280	15 613	15 944	14 767	15 513	14 613	14 868	13 599	14 305
2017	13 892	14 738	15 159	14 751	15 141	14 624	15 252	13 579	14 161
2018	14 512	14 927	15 919	14 914	15 468	14 517	15 094	13 555	14 221
2019	14 527	15 499	15 510	14 900	15 474	14 501	15 126	13 531	14 255
2020	14 567	15 008	17 169	14 888	15 499	14 515	15 129	13 543	14 243
2021	14 499	14 634	16 708	14 669	15 146	16 513	16 513	13 519	14 209
2022	14 463	14 944	15 572	14 739	15 481	15 027	14 833	13 448	14 103

However, the advancement of China's aluminium electrolysis technology has far outpaced that of the alumina industry. The successful development of the 320 kA extra-large aluminium reduction cell technology in 2000 marked China's entry into the global forefront of aluminium electrolysis technology [18]. Yet in the same year, among China's six alumina refineries, only Pingguo Alumina Refinery and Shandong Alumina Refinery (which adopted the Bayer process after its expansion in 1993) utilized relatively advanced methods; while the other refineries still employed parallel-series or sintering processes [19], making it difficult for them to produce sandy alumina. This industrial landscape resulted in relatively low raw material quality requirements for aluminium electrolysis. Furthermore, since neither national nor industry standards imposed additional requirements or grading for alumina, high-quality alumina failed to command premium prices or generate sufficient profits due to the lack of product differentiation and weak market demand. Without profit incentives or clear market demand, the sustained progress and development of China's alumina product quality faced significant challenges.

3. Maximum Energy Consumption Reduction in Aluminium Electrolysis and Quality Requirements for Alumina

In the 21st century, the electrolytic aluminium industry has experienced explosive growth. As shown in Figure 2, China's primary aluminium (electrolytic aluminium) output was only 2.79 million tonnes in 2000 but surged to 41.98 million tonnes by 2023, accounting for 56.8 % of the global total and securing its position as the world's largest producer [10]. Thanks to the widespread adoption of large-scale aluminium reduction cells, China has achieved a global leading position in average power consumption for aluminium production. Given the increasing national emphasis on energy efficiency in high-energy consumption industries like primary aluminium, China has introduced a series of policies requiring the aluminium industry to maximise energy consumption reduction. Beyond improving its own processes and equipment, achieving this goal also necessitates enhanced alumina product quality.

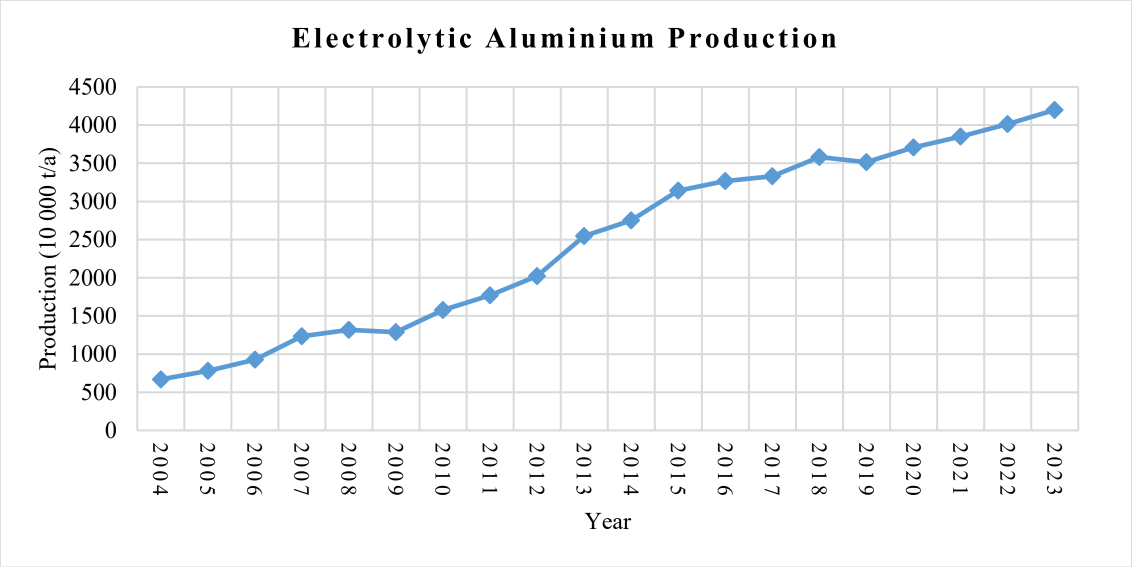

Figure 2. China's aluminium production [10, 11, 12].

3.1 Maximum energy consumption reduction requirements for aluminium industry

The *Notice on Improving the Tiered Electricity Pricing Policy for the Electrolytic Aluminium Industry* (FGJG [2021] No. 1239) stipulates that the tiered standards for comprehensive AC power consumption per tonne of molten aluminium in the aluminium industry will be progressively tightened: 13 650 kWh/t in 2022, reduced to 13 450 kWh/t (excluding power consumption of desulfurization) in 2023, and further lowered to 13 300 kWh/t by 2025. For aluminium smelters that exceed the prescribed energy consumption standards, a progressive electricity surcharge mechanism will be applied. Specifically, for every 20 kWh beyond the tiered threshold, the electricity price for molten aluminium production will be increased by RMB 0.01/kWh (approx. 1.383 USD/MWh). If the excess consumption is less than 20 kWh, it will be rounded up to 20 kWh for calculation purposes. Furthermore, if the proportion of non-hydro renewable energy used by a smelter exceeds 15 % – and is not lower than the provincial incentive benchmark – for every additional percentage point, the surcharge rate can be reduced by 1 %.

The *Norm of Energy Consumption per Unit Product of Electrolytic Aluminium and Alumina* (GB 21346-2022) stipulates that the comprehensive AC power consumption per tonne of molten aluminium in existing aluminium smelters shall not exceed 13 700 kWh, while for newly constructed or expanded smelters, the limit is no more than 13 350 kWh/t.

According to the *Notice on Issuing the Energy Efficiency Baseline and Benchmark Levels in Key Energy Intensive Industries* (2023 Edition) (No. 723 [2023]) issued by the NDRF and other departments, electrolytic aluminium, as a defined key sector (with a benchmark AC power consumption of 13 000 kWh/t Al and a baseline level of 13 350 kWh/t Al for molten aluminium), needs to be upgraded by classification. Planned and under-construction projects must align with the benchmark levels; existing projects with energy efficiency between the benchmark and baseline levels are encouraged to undergo upgrades; while those below the baseline must define a timeline for retrofitting or phase-out, in principle, by the end of 2025. Additionally, the *Action Plan for Energy Conservation and Carbon Reduction in the Electrolytic Aluminium Industry* imposes strict restrictions on the addition of new capacity. In key areas for air pollution prevention and control, no new capacity will be permitted. By 2025, the proportion of production capacity meeting or exceeding the energy efficiency benchmark level shall reach 30 %. Moreover, pre-baked anode electrolytic cells with a capacity below 200 kA will be gradually phased out, and the capacity replacement policy must be rigorously enforced.

3.2 Improvement of Alumina Quality Under the Dominance of Imported Bauxites

3.2.1 Requirements for Physical Properties

In terms of physical properties, modern aluminium reduction cells require that the alumina used should contain less than 5 % of particles larger than 150 µm and less than 12 % of particles smaller than 45 µm. A high content of coarse particles (> 150 µm) adversely affects the dissolution rate of alumina in the electrolyte, while an increased proportion of fine particles (< 45 µm, especially those < 20 µm), often accompanied by elevated α-Al_2O_3 content, can lead to higher dust generation during electrolysis, compromising the precision of timed and targeted feeding. Additionally, it reduces alumina solubility and easily leads to alumina sludge at the cell bottom.

The particle size distribution of sandy alumina is 80–100 µm, with the content of fine particles of -45 µm being less than 12 %. For intermediate alumina, the proportion of -45 µm particles exceeds 20 %, while floury alumina even surpasses 50 %. This difference in particle size directly affects the dissolution rate: sandy alumina dissolves completely in the electrolyte in just 240–250 seconds, producing relatively little sediment, which helps maintain the thermal equilibrium stability of the electrolytic cell, with current efficiency generally reaching 94–95 %. In contrast, intermediate and floury alumina, due to their higher proportion of -45 µm particles, require over 300 seconds to dissolve, leading to the accumulation of undissolved particles at the cell bottom, forming sludge and causing localized overheating. This results in a 1–2 % drop in current efficiency. For example, after a smelter switched to intermediate alumina, alumina sludge at the cell bottom increased significantly, causing uneven current distribution, higher cathode voltage, and a 2.1 % decrease in current efficiency [17].

Additionally, sandy alumina exhibits a low attrition index (below 20 %) and high particle strength, with minimal flying losses during transportation, which is only 0.28 kg/t Al. In contrast, intermediate alumina, characterized by fine, fragmented particles and a large angle of repose (> 40°), incurs significantly higher dust losses (up to 10 kg/t Al). This not only increases raw material waste but also exacerbates potroom pollution [17].

Meanwhile, the high specific surface area (60–80 m^2/g) of sandy alumina and its γ-Al_2O_3-dominated crystal structure significantly enhance its HF adsorption capacity, achieving an adsorption efficiency of over 95 %. In contrast, intermediate and floury alumina, due to their high α-Al_2O_3 content (30–95 %) and low specific surface area, exhibit an adsorption efficiency below 70 %, leading to increased consumption of aluminium fluoride.

The high fluidity of sandy alumina ensures the efficient operation of automated feeding systems, reducing manual intervention and operational failures. Long-term operational data indicate that the use of sandy alumina extends the service life of electrolytic cells by 15–20 % and reduces cathode failure rates by 30 %, further lowering maintenance costs [21].

3.2.2 Requirements for Chemical Composition

In terms of chemical composition, as shown in Figure 3, the contents of Al_2O_3, SiO_2, Fe_2O_3, and ZnO in alumina directly affect the proportions of Al, Si, Fe, and Zn elements in aluminium ingots. An increase in the content of these components leads to a corresponding rise in the content of the associated elements in the aluminium ingots. For example, a slight increase in the iron content of alumina (from 0.005 % to 0.007 %) results in a rise in the iron content of electrolytic aluminium from 0.065 % to 0.139 %, as iron ions are preferentially electrolyzed. In practical production, a similar case occurred in an aluminium smelter in Guangxi. The use of alumina with a ZnO content of 0.018 % resulted in the zinc content of aluminium ingots rising to 0.0268 %, exceeding the limit of ≤ 0.025 % specified in the *Primary Aluminium Ingots* (GB/T 1196-2023) for Al 99.85. Sandy alumina, with its low and controllable impurity content, is crucial for both primary aluminium quality and the economic efficiency of the electrolytic process. The Na_2O content in sandy alumina is typically below 0.4 %, whereas that in intermediate or floury alumina can reach 0.6–0.8 %. During electrolysis, Na_2O reacts with AlF_3 to form NaF, destabilizing the electrolyte molecular ratio. This necessitates additional AlF_3 supplementation to maintain production stability. For every 0.1 % increase in Na_2O content in alumina, the AlF_3 consumption per tonne of aluminium increases by 3.56 kg, directly raising production costs [22].

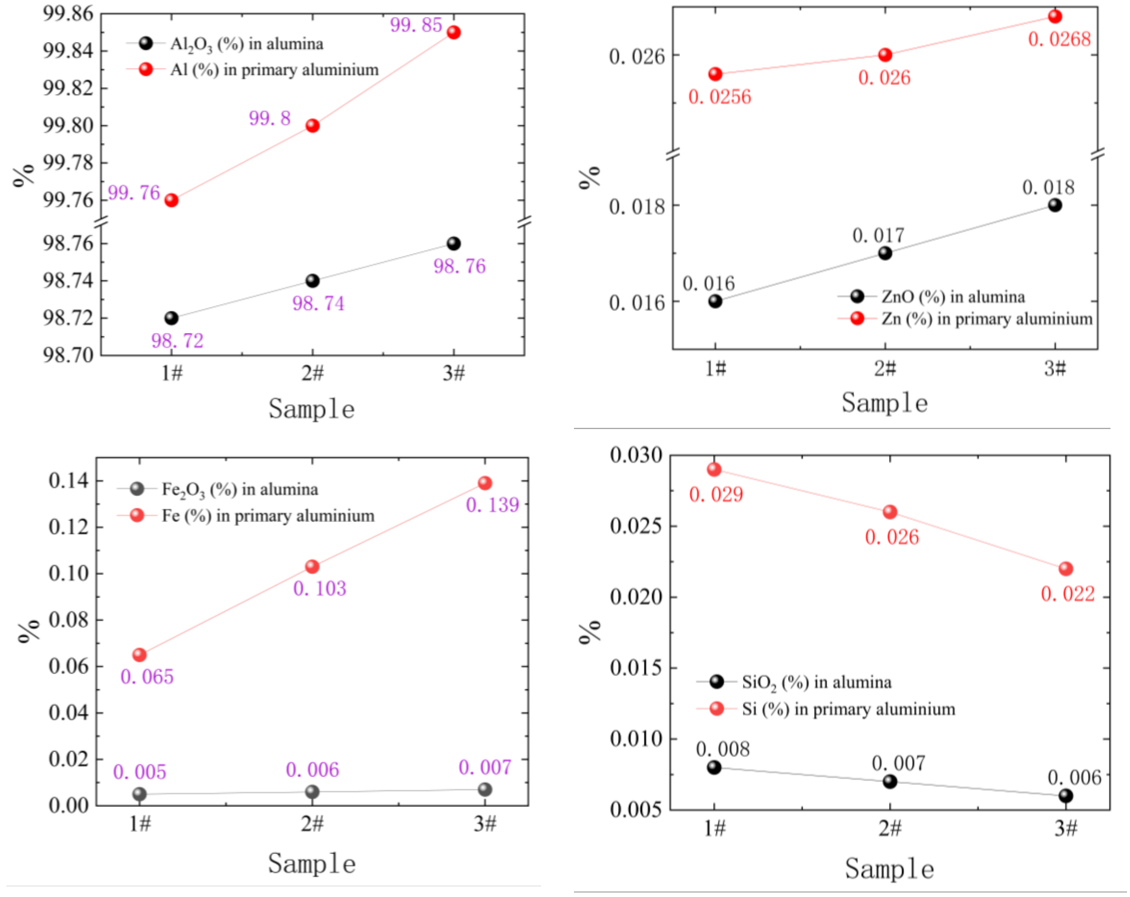

Figure 3. Effects of Al_2O_3, SiO_2, Fe_2O_3, and ZnO contents in alumina on elemental composition of electrolytic aluminium products. Top left: aluminium content; top right: zinc content; bottom left: iron content; bottom right: silicon content.

In addition, the content of Fe_2O_3 and SiO_2 in sandy alumina is less than 0.02 %, while that in intermediate alumina is generally 50–100 % higher. These impurities preferentially deposit at the cathode, leading to increased iron and silicon content in primary aluminium. For every 0.01 % increase in Fe_2O_3 and SiO_2 in alumina, the Fe and Si content in primary aluminium rises by 0.013 and 0.009 %, respectively, directly affecting the conductivity and corrosion resistance of aluminium ingots. For example, after a smelter switched to using intermediate alumina, the Fe content in primary aluminium increased from 0.08 to 0.12 % [21].

The low LOI of sandy alumina (< 1 %) helps reduce the reaction between moisture and fluoride salts, avoiding excessive HF generation. In contrast, intermediate alumina has a higher LOI (> 1.5 %), leading to increased HF emissions per tonne of aluminium, which raises environmental protection costs [17].

4. Conclusion and Outlook

4.1 The Pressure to Minimize Energy Consumption in Aluminium Industry Is Passed Up, Compelling Improvement in the Quality of Alumina Products

As the direct downstream industry of alumina, the development trend of electrolytic aluminium has a decisive impact on the alumina industry. With China's energy consumption policies for the electrolytic aluminium industry becoming increasingly stringent, aluminium smelters have been compelled to elevate their quality requirements for alumina raw materials in order to comply with energy consumption standards.

Currently, aluminium smelters are facing the challenge of increasingly stringent tiered standards for comprehensive AC power consumption of molten aluminium year by year. This pressure will be directly transmitted to the upstream alumina industry, compelling it to optimize processes and improve product quality to meet the consumption reduction needs of electrolytic aluminium. Sandy alumina, due to its superior physical properties and chemical composition, can significantly reduce energy consumption and maintenance costs in electrolytic cells. In the future, alumina refineries should further break through technical bottlenecks to improve product quality while supporting the electrolytic aluminium industry in achieving its energy-saving goals.

The improvement of alumina quality must be closely aligned with the actual needs of aluminium smelters. Currently, China's alumina products still lack control over trace elements (such as Zn, V, and Ti). In the future, alumina refineries should establish a comprehensive quality control system and strengthen their ability to remove impurities of the entire process.

4.2 Establishing Overseas Bauxite Mining Operations to Alleviate the Bottleneck in Raw Material Supply

As previously mentioned, in response to the dual challenges posed by the depletion and declining quality of China's domestic bauxite resources, developing overseas bauxite mining projects has become an essential strategy to overcome bottlenecks in raw material supply. Priority should be given to resource-rich countries such as Guinea, where long-term agreements can be established to secure access to high-quality mineral resources, thereby ensuring a stable and reliable supply of raw materials. By leveraging the advantages of high-quality imported gibbsite, production costs can be reduced and product performance will be enhanced. Additionally, the adoption of advanced, cost-effective two-stage precipitation technology with pre-purification processes will facilitate the production of premium alumina. Ultimately, the goal is to establish an aluminium industry ecosystem characterized by high quality, low consumption, stable supply chains, and circular low-carbon development.

4.3 Establish and Refine the Quality Grading System for Alumina to Drive the Industry's Transition Toward Higher Quality and Greater Efficiency

Establishing and improving a quality grading system for alumina is a key strategy for advancing the industry's transition from a focus on "quantity" to one on "quality." Moving forward, it is essential to develop a comprehensive grading standard that encompasses multiple parameters, including particle size, α-Al_2O_3 content, and trace elements. This standard should directly correlate key physical and chemical performance indicators—such as α-Al_2O_3 content, angle of repose, and abrasion index—with pricing mechanisms. By leveraging market-driven approaches, refineries can be guided toward enhancing product quality and operational efficiency, transforming technological inputs in high-quality alumina into tangible economic returns. This, in turn, will incentivize increased R&D investment and drive a substantial improvement in the overall quality standards of the industry.

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