Current Status of Carbon Emissions in the Aluminium Electrolysis Industry and Analysis of Carbon Reduction Pathways

Jiao Qingguo[1], Wang Huaijiang[2], Zhang Yanan[3], Li Changlin[4] and Bao Shengzhong[5]
1,4. Second Level Researchers - Professor Level Senior Engineers
2.Vice General Manager - Professor Level Senior Engineer
3.Director - Professor Level Senior Engineer
5.Vice Director - Professor Level Senior Engineer
Zhengzhou Non-ferrous Metals Research Institute of Chalco (ZRI), Zhengzhou, China
Corresponding author: *qg_jiao@chinalco.com.cn*
https://doi.org/10.71659/icsoba2025-al063

Abstract

Aluminium electrolysis is a highly energy-intensive and high-emission industry, generating substantial amounts of CO_2 greenhouse gases directly or indirectly during production, making it a key focus for global carbon emissions monitoring. In response to national carbon reduction requirements and targets for the aluminium industry, this paper analyses the mechanisms of greenhouse gas emissions in aluminium electrolysis, presents the current status of carbon emissions in the industry, and examines the technologies, approaches and potentials of greenhouse gas emission reduction from three key perspectives: power decarbonization, direct emission reduction, and PFC emission reduction, providing a reference for the aluminium industry to advance greenhouse gas emission reduction.

Keywords: Aluminium electrolysis, Carbon emission, Greenhouse gases, PFC, Anode effect.

1. Introduction

According to the Global Carbon Budget 2023 report released by the International Energy Agency (IEA) in March 2024, global energy-related carbon dioxide (CO_2) emissions increased by 410 million tonnes in 2023, rising by 1.1 % compared to 2022 and reaching a record high of 37.4 billion tonnes. China accounted for the largest share of global CO_2 emissions at 12.6 billion tonnes, representing approximately 34 % of the world's total [1]. As the world's leading producer in the aluminium industry, China's primary aluminium output reached 43.396 million tonnes in 2024, accounting for about 59.4 % of global output, according to International Aluminium Institute statistics. Estimates indicate that the total CO_2 emissions amounted to approximately 426 million tonnes, contributing roughly 5 % to the nation's net CO_2 emissions.

The aluminium electrolysis industry emits significant amounts of greenhouse gases due to the use of carbon anodes during production, while the substantial consumption of thermal power resources also indirectly generates considerable greenhouse gas emissions. As a result, the electrolytic aluminium industry has become one of China's key industries for carbon emissions control. On 22 September 2020, General Secretary Xi Jinping announced at the 75th General Assembly of the United Nations China's “dual carbon” goals: one to peak emissions before 2030, and the other to achieve carbon neutrality before 2060. This marks China's first explicit global announcement of the "carbon peak" and "carbon neutrality" targets, representing the most significant climate commitment by any nation to date in mitigating global warming [2–4]. In May 2024, the State Council issued a notice on the issuance of "2024–2025 Energy Conservation and Carbon Reduction Action Plan", requiring governments at all levels and ministries to implement energy conservation and carbon reduction initiatives by sector and industry. The electrolytic aluminium industry is required to strictly implement the replacement of production capacity quota.

By the end of 2025, the proportion of production capacity above the energy efficiency benchmark level in the electrolytic aluminium industry will reach 30 %, and the proportion of renewable energy use will reach more than 25 %. Therefore, gaining a comprehensive understanding of the carbon emission mechanism and the current situation of aluminium electrolysis industry, as well as applying new technologies and exploring innovative approaches for energy conservation and emission reduction, has become a critical task for the industry.

2. Mechanism of Carbon Emission in Aluminium Electrolysis

Carbon dioxide is referred to as a greenhouse gas due to its strong absorption and thermal insulation capacity. It can effectively absorb long-wave infrared radiation emitted from the earth's surface, thereby preventing the dissipation of heat and leading to a rise in earth's surface temperature. The greenhouse effect can trigger a series of environmental issues, such as rising sea levels, abnormal climate patterns, and increased extreme weather. Consequently, controlling greenhouse gas emissions has become a globally shared priority.

The carbon dioxide emissions in the aluminium electrolysis process primarily consist of three categories:
1) Direct CO_2 emissions from carbon anode consumption;
2) PFC greenhouse gas emissions generated during anode effects in the electrolysis process, expressed as CO_2 equivalent; and
3) Indirect CO_2 emissions from electricity consumption [5].

2.1 Carbon Emission Mechanism of Anode Consumption

The cryolite-alumina molten salt electrolysis process is adopted for aluminium electrolysis production. Both the anode and cathode materials need to possess properties such as high-temperature resistance, immunity to molten salt corrosion, and high electrical conductivity, typically fulfilled by carbon materials. When direct current is applied, electrochemical reactions occur at both anode and cathode, with the process described as follows [6]:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \quad (1)$$

The above reaction Equation (1) indicates that the carbon anode not only serves as a conductive material but also participates in the electrochemical reaction, generating carbon dioxide with oxygen. According to the calculation of the reaction Equation (1), the theoretical carbon consumption per tonne of primary aluminium produced is 333.867 kg/t Al, corresponding to CO_2 emissions of 1223.331 kg CO_2/t Al. Currently, the actual net carbon anode consumption in domestic aluminium production in well operated cells is around 400 kg C/t Al, resulting in CO_2 emissions of approximately 1467 kg CO_2/t Al, assuming no influence from other impurities.

2.2 Formation Mechanism of PFC

The primary components of PFC are tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). The formation mechanism of PFC primarily occurs during aluminium electrolysis when the alumina (Al_2O_3) mass fraction in the electrolyte is below 1 %. At this point, the mass fraction of oxygen ions on the anode surface decreases rapidly, leading to an increase in anode overvoltage and cell voltage (typically reaching 25–35 V). This phenomenon is termed as "anode effect". The occurrence of anode effects causes carbon from the anode to react with fluoride ions in the cryolite bath, generating CF_4 and C_2F_6 through the following chemical reactions [7–8].

$$4Na_3AlF_6 + 3C = 3CF_4 + 12NaF + 4Al \quad (2)$$

$$2Na_3AlF_6 + 2C = C_2F_6 + 6NaF + 2Al \quad (3)$$

Meanwhile, according to the non-anode effect gas emission monitoring results (as shown in Figure 1), CF_4 generation is observed even under non-anode effect conditions. This may occur when localized current density becomes excessively high or alumina concentration drops too low in certain places of the electrolytic cell, causing the localized overvoltage to persistently exceed the formation potential of CF_4. C_2F_6 emissions in non-anode effect conditions are very small, below the instrument detection limit; this is why the values in Figure 1 are negative and should not be taken as true. Typically, the instrument C_2F_6 detection limit is 0.02–0.05 ppm (or 20–50 ppb) and it depends on the pathlength of the gas cell and the measurement time.

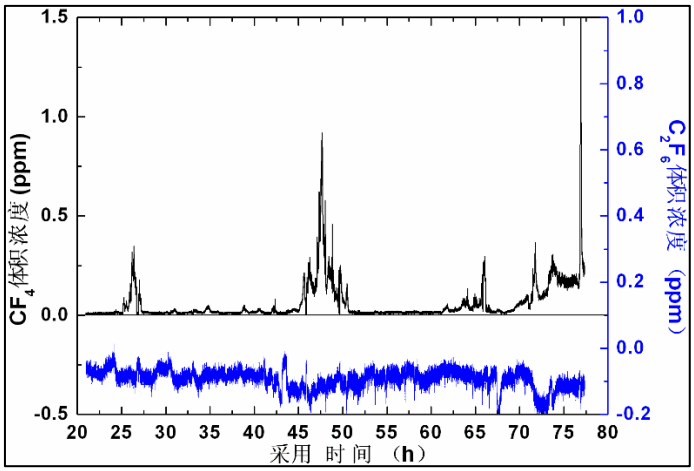

Figure 1. Volume concentration (ppm) of CF_4 and C_2F_6 emissions during non-anode effect period in electrolytic cell.

The quantification of PFC emissions in aluminium electrolysis is complex, typically requiring the Intergovernmental Panel for Climate Change (IPCC) Tier 3 methodology with continuous emission monitoring systems. The GasmetDX4000 FTIR analyser is used for measurement, and then the final result is calculated through the CO_2 equivalent emissions of PFC. This is primarily due to the extreme stability of the carbon-fluorine structure in CF_4 and C_2F_6, which enables them to persist in the atmosphere for a long time. CF_4 and C_2F_6 have atmospheric lifetimes exceeding and Global Warming Potential (GWP) equal to 7 380 and 12 400 times that of CO_2 respectively. Both gases are included among the six greenhouse gases regulated under the *Kyoto Protocol* [9-10].

Table 1. Lifetime and CO_2 equivalent values of greenhouse gas PFCs.

Gas	No.	Atmospheric lifetime (Years) [11]	PFC GWP (100 years) IPCC 6th Assessment Report [12]
CF_4	PFC-14	50 000	7380
C_2F_6	PFC-116	10 000	12400
C_3F_8	PFC-218	2600	9290

2.3 Carbon Emission Mechanism of Electricity Consumption

Thermal power generation primarily relies on the combustion of fossil fuels (such as coal, natural gas and petroleum) to produce electricity. During combustion, carbon in the fuel reacts with oxygen to generate carbon dioxide (CO_2), which is the main source of carbon emissions from

power plants. The cryolite-alumina molten salt aluminium electrolysis process requires a stable and continuous electricity supply to sustain its electrochemical reactions. However, China's electricity mix remains predominantly thermal power, and large-scale consumption of thermal power indirectly leads to significant CO_2 emissions.

On August 27, 2021, the National Development and Reform Commission issued the *Notice on Improving the Tiered Electricity Price Policy for the Aluminium Electrolysis Industry*, mandating that the comprehensive AC power consumption for molten aluminium production must achieve 13 450 kWh/t Al by 2023 and 13 300 kWh/t Al by 2025. For every 20 kWh exceeding the tiered threshold, the electricity price will be increased by 0.01 RMB/kWh (1.38 USD/MWh approx.). Consequently, aluminium smelters across China actively pursued technological innovations in energy conservation and emission reduction, successfully meeting the 2023 target in the national electrolytic aluminium industry. In October 2023, the Chinese Academy of Environmental Planning released the *Research on CO_2 Emission Factors for China's Regional Grids (2023)*. The CO_2 emission factors of provincial power grids in China are relatively scattered, ranging from 0.095 to 1.092 kg CO_2/kWh, with an average of approximately 0.608 kg CO_2/kWh. Based on these data, the indirect CO_2 emissions per tonne of aluminium produced are calculated to be 8177.6 kg CO_2/t Al. This result is slightly lower than previously reported values, primarily due to the continuous reduction in coal consumption for power supply and the overall AC power consumption per tonne of molten aluminium in recent years, as well as the increased proportion of green electricity and thermal power allocated to aluminium smelters across provinces.

3. Carbon Reduction Technologies and Pathways for Aluminium Electrolysis

In 2021, the International Aluminium Institute (IAI) released its *Aluminium Sector Greenhouse Gas Pathways to 2050* [13], outlining three key decarbonization approaches for the industry: power decarbonization, direct emission reduction, as well as recycling and resource efficiency [14]. China's aluminium industry has made significant efforts in these three directions in recent years, achieving notable progress.

3.1 Power Decarbonization

3.1.1 Reducing Electricity Consumption

Both from smelter cost pressures and national policy requirements, reducing electricity consumption in aluminium electrolysis has always been a key goal for aluminium industry practitioners. Since the beginning of the 21st century, Chinese electrolytic aluminium experts have continuously developed new energy-saving and emission reduction technologies, including zero-anode-effect low-voltage operation, three-dimensional process optimization, current-blocking baffles, profiled cathode technology, and high-conductivity cathode bar technology, which have significantly reduced cell voltage from above 4.0 V to around 3.9 V [15]. Figure 2 shows the trend of China's comprehensive AC power consumption per tonne of aluminium ingot from 2000 to 2023. As illustrated, the energy consumption of electrolytic aluminium has consistently decreased, with a cumulative reduction of over 2000 kWh/t Al. Over the past three years, aluminium smelters in China have been actively promoting the application of fully graphitized cathodes combined with phosphorous-containing cast iron cathode rod technology, which reduces cathode voltage drop to below 200 mV, decreases horizontal current by over 25 %, and achieves a DC power consumption of molten aluminium below 12 300 kWh/t Al. Consequently, the AC power consumption of molten aluminium falls under 13 000 kWh/t Al, meeting the benchmark for energy efficiency performance. Based on this projection, China's electrolytic aluminium industry can achieve an annual energy efficiency improvement of over 10 % in production capacity meeting the benchmark level, reaching the 30 % target by 2025, required by the 2024-2025 *Action Plan for Energy Conservation and Carbon Reduction* [16].

Currently, domestic research institutions and design institutes are developing technologies such as copper-embedded cathode steel bars and full-copper cathode collector bars, aiming to reduce the cathode voltage drop to below 150 mV and further lower DC power consumption by 300 kWh/t Al, achieving a target of less than 12 000 kWh/t Al. Based on China's current production capacity, this would result in an annual reduction of CO_2 emissions by over 20 million tonnes.

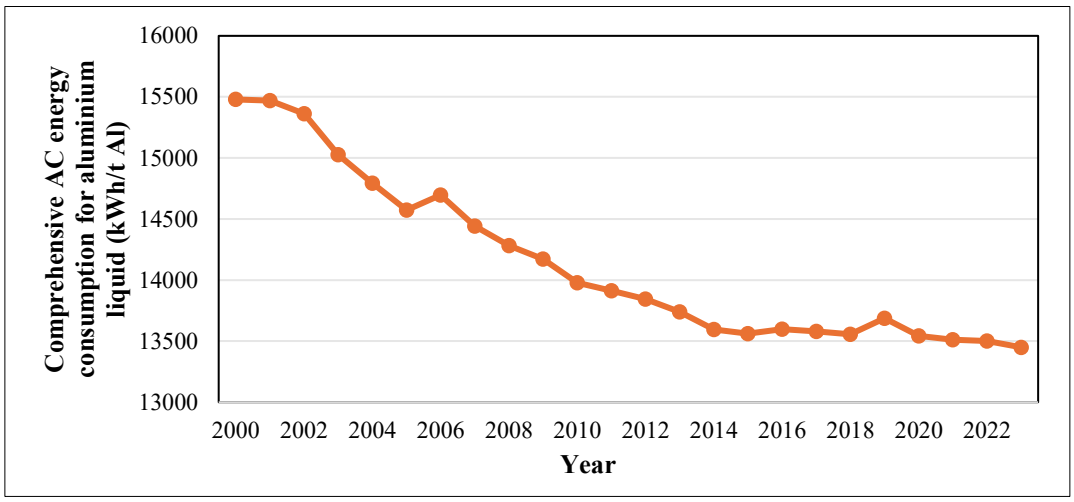

Figure 2. Changes in comprehensive AC electricity energy consumption of aluminium ingots in China from 2000 to 2023.

3.1.2 Adjusting Electricity Consumption Structure

In recent years, China has been relocating its electrolytic aluminium production capacity to hydropower-rich regions in the southwest, such as Yunnan and Sichuan, including existing hydropower-based production in Qinghai, which has gradually increased the proportion of hydropower used in China's electrolytic aluminium industry. Meanwhile, renewable energy sources, particularly photovoltaic (PV) power generation, are providing reliable and low-cost green electricity for the electrolytic aluminium industry. Aluminium smelters have begun installing on-site PV systems to capture solar energy and convert it into electricity, reducing energy losses during traditional power transmission and improving overall energy efficiency. In 2022, China's first distributed PV project for a smelter, the Qingtongxia 23 MW Distributed PV Project, was fully connected to the grid, with all generated electricity supplied to Qingtongxia's 430 kt/a electrolytic aluminium smelter. In 2023, China's first pilot project integrating PV DC power directly into aluminium smelting production was commissioned at the Yangzonghai Green Aluminium Industrial Park in Kunming, marking a significant breakthrough in directly supplying electrolytic aluminium production with photovoltaic-generated DC electricity.

According to data from the China Nonferrous Metals Industry Association, the proportion of green electricity used in China's electrolytic aluminium industry increased from 13.4 % in 2015 to 24.4 % in 2023. When green electricity is employed in electrolytic aluminium production, the CO_2 emission per tonne of aluminium eliminate those from thermal power generation, retaining only the electrolysis process emissions, achieving a reduction rate of over 85 %.

3.2 Reduction of Direct Carbon Emissions

3.2.1 Reduction of Net Anode Consumption

The reduction of anode net consumption is primarily related to improving current efficiency and preventing anode oxidation [17]. In recent years, Chinese researchers have been dedicated to improving current efficiency. However, due to factors such as alumina quality, carbon anode quality, complex electrolyte composition, and the pursuit of low-voltage operation, the overall current efficiency improvement has been limited, averaging 90–93 %, with significant variations among smelters. According to relevant reports, domestic electrolytic aluminium researchers are actively developing technologies such as continuous alumina feeding, alumina preheating, and anode preheating, all of which contribute significantly to enhancing current efficiency. With continued improvements in aluminium industry technology, a current efficiency of 94 % is achievable in the future, which would further reduce emissions by 30 kg CO_2/t Al.

The main technologies for preventing anode oxidation include low carbon consumption, anode anti-oxidation coating technology, etc. The low carbon consumption technology primarily optimizes from raw material preparation, forming process improvement, and calcination process operations to continuously enhance the CO_2 and air reactivity of carbon anodes, reducing carbon residue in electrolytic cells to less than 5 kg/t Al [18]. The anode anti-oxidation coating technology involves spraying a protective layer on the surface of anode blocks to reduce the corrosion of the electrolyte to the anode carbon block, thereby reducing oxidation and residue shedding [19]. The multifunctional anti-oxidation coating for aluminium electrolysis (see Figure 3), developed by the author's institution, can achieve this effect. This coating exhibits excellent wettability with the anode surface, fast drying, and high bonding strength. Industrial trials at an aluminium smelter demonstrated more regular butt dimensions, significantly increased butt thickness, and an extended anode change cycle by one day [20]. Through the application of the two technologies, the net anode consumption can be further reduced by over 30 kg C/t Al, and emissions can be decreased by more than 100 kg CO_2/t Al.

Figure 3. Anode with antioxidant coating.

3.2.2 Research on Carbon-Free Aluminium Technology

The carbon-free aluminium technology refers to an electrolytic process where carbon anodes are replaced by non-carbon anodes, or an electrolysis technology that eliminates CO_2 greenhouse gas emissions during the aluminium electrolysis process. Currently, this primarily includes inert anode technology and aluminium chloride electrolysis technology.

The inert anode electrolysis technology replaces prebaked carbon anodes with inert anodes, releasing O_2 during the electrolysis process, which can eliminate CO_2 and PFC emissions while

avoiding frequent anode replacement, resulting in more stable electrolytic cell operation [21]. Based on the material composition, inert anodes are classified into three types: alloy anodes, oxide ceramic anodes, and metal ceramic anodes [22]. Currently, global leading aluminium companies such as RUSAL, and Alcoa-Rio Tinto with ELYSIS are heavily investing in the research of inert anode aluminium electrolysis technology. In 2021, RUSAL achieved a major technological breakthrough with its inert anode electrolytic cells, producing the world's lowest-carbon aluminium at the Krasnoyarsk Aluminium Smelter. Compared to the industry average, this technology can reduce carbon emissions by approximately 85 %, emitting less than 0.01 t CO_2/t Al, with a daily output of around 1 t aluminium [23]. Since 2001, the authors' institution in China has continuously developed inert anode aluminium electrolysis technology under national funding programs such as the "973 Program" and "863 Program." In 40-kA cell tests, the inert anode achieved a cumulative operation of 178 days with an average corrosion rate of 20 mm/year.

The aluminium chloride electrolysis technology is a method for producing aluminium by electrolyzing anhydrous $AlCl_3$ molten salt mixtures. During the electrolysis process, Al^{3+} ions are reduced to pure metallic aluminium, while Cl^- ions generate chlorine gas at the anode. The electrolysis process produces no CO_2 emissions and offers advantages such as a smaller occupied area, higher single-cell production capacity, and avoidance of strong magnetic fields. However, due to issues like chlorine gas corrosion and environmental pollution, this method has seen limited research in recent decades, with few publications in academic journals. Yet, as global carbon emission reduction requirements intensify, this carbon-free aluminium electrolysis method has regained attention from national authorities in recent years and is expected to achieve breakthroughs in industrial applications in the future.

3.3 Reduction of PFC Emissions

The latest fourth edition of the *Global Aluminium Life Cycle Inventory Report (LCI)* released by the International Aluminium Institute (IAI) [24] indicates that the PFC produced by the global aluminium industry is declining year by year, but the total PFC emissions from the global aluminium industry are still large due to the continuous growth of primary aluminium production.

Based on the preceding analysis of PFC generation mechanism, it can be concluded that the direct approach to reducing PFC emissions in aluminium electrolysis production is to decrease anode effect frequency and shorten anode effect duration [25]. Additionally, maintaining stable cell operation and preventing uneven anode current distribution are fundamental to reducing PFC emissions during the aluminium electrolysis production process. To achieve the above objectives, the following approaches can be implemented:

1) Optimize the cell control system by developing more precise alumina concentration control tactics to make the alumina concentration distribution in the cell more uniform;
2) Improve process conditions, including adjusting electrolyte composition, maintaining appropriate superheat, ensuring adequate electrolyte level, and enhancing alumina dissolution capacity;
3) Enhance magnetic field design for large-scale cells to improve magnetohydrodynamic stability and reduce localized overcurrent phenomena;
4) Strictly control raw material quality, particularly for alumina and anode carbon blocks, to prevent substandard products from entering the production system [26–27].

Several specialized technologies in China have demonstrated direct effectiveness in controlling anode effects and reducing PFC emissions.

1) Anode slotting technology. This technology facilitates the release of anode gases at the anode bottom surface by allowing gases to smoothly escape through slots toward the central channel. It reduces the accumulation of anode bubbles on the extra-large anode surface, increases the contact

area between the anode and electrolyte, lowers the actual current density of anode, and decreases the frequency of anode effects or localized effects, thereby reducing perfluorocarbon (PFC) emissions during production.
2) Aluminium electrolysis intelligent crust breaking and feeding control system. This system can detect and preprocess material blockages during feeding, prevent hammerhead clogging, and ensure a crust hole opening rate of over 90 %, thereby reducing anode effect occurrence [28].
3) Anode current online monitoring technology. This technology enables real-time online monitoring of anode current in aluminium cells, effectively eliminating the data delay inherent in manual measurements. It allows prompt adjustment upon detecting current imbalance, thereby mitigating various issues caused by anode current deviation and ensuring stable and efficient aluminium cell operation [29].

4. Conclusions

By analysing the carbon reduction potential and technology path of aluminium industry, the author believes that the development and industrialization of carbon-free aluminium technology (inert anode electrolysis and aluminium chloride electrolysis) should be the important direction of carbon reduction in aluminium industry in the future, and complete replacement with non-carbon anode will avoid direct emission of carbon dioxide; Focusing on developing more energy-efficient process technologies (copper-embedded cathode steel bars, full-copper cathode bars, and alumina preheating technology) as key carbon reduction measures, to further reduce electricity consumption by 300 kWh/t Al, achieving carbon emission reductions per tonne of aluminium of over 180 kg CO_2/t Al.

The dedicated PFC emission reduction technology should be based on further optimization of the alumina feeding control system to ensure the stability and uniformity of alumina concentration in the electrolytic cells, thereby reducing the occurrence of anode effects. Simultaneously, it is essential to develop and enhance PFC process monitoring technologies and further investigate their generation mechanisms and patterns to provide improved methods and measures for comprehensive PFC emission reduction.

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