

KN03 - Net-zero Emissions from Primary Aluminium Production - Is it Technologically and Economically Possible by 2050?

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Abstract

Reducing greenhouse gas emissions and combating climate change have become a priority for nations and businesses, and that includes also the aluminium industry. 2050 has been chosen as the target year when the global primary aluminium industry will have reached net-zero greenhouse gas emissions. There is a clear path to decarbonization for the aluminium industry, and many aluminium producers have now developed their own low-carbon roadmaps. However, reaching the goal of net-zero emissions will require significant decarbonization of the electric energy mix, the alumina and anode production and supply chains, the aluminium electrolysis process, and also the downstream recycling. Is it technologically and economically possible for the global aluminium industry to reach net-zero emissions, and which new technologies are required to achieve this? The present paper gives an overview and discussion of the main processes that have been suggested in the open literature to reach net-zero emissions from the primary aluminium industry.

Keywords: Primary aluminium production, Greenhouse gas emissions, Decarbonisation, Net-zero emissions.

1. Introduction

The process of reducing carbon dioxide emissions from industrial processes through various strategies is called decarbonization, which implies removing carbon from the system. Leading companies in the aluminium sector have endorsed a new strategy for action to decarbonize the sector in this decade [1]. With the present extensive use of carbon-containing raw materials for electricity and other energy sources for the aluminium industry this is a formidable task.

2. What Do We Mean by Net-zero Emissions?

Natural ecosystems like wetlands and forests absorb carbon dioxide from the air and turn it into biomass, which is a part of earth's natural carbon cycle. Forestation means to plant, manage and grow forests and is a low-tech way to remove and store carbon in the biosphere, and this works also on a large scale.

The industry is now using the expression net-zero greenhouse gas (GHG) emissions. Net-zero does not necessarily mean that all greenhouse gas emissions are eliminated. At net-zero, emissions are still generated, but an equal amount of CO₂ is removed from the atmosphere as we release into it. Thus, net-zero means that emissions from human activity must be balanced by absorbing an equal amount of greenhouse gases, primarily CO₂, through climate projects.

CO₂ emissions cannot be avoided completely, so when are they "close enough to zero" to be called net-zero? The International Aluminium Institute (IAI) [2] has modelled a 1.5 Degree Scenario for global warming and the result is a low total emission of 0.5 tonne of CO₂ equivalent per tonne of aluminium (t CO₂e/t Al). So this may be low enough to be called net-zero. However, it means that the aluminium producers presently operating with a low total emission of

4.0 t CO₂e/t Al must reduce their emissions by 88 % and the total global emissions from primary aluminium production must be reduced by 97 %.

3. The Emission Target for 2050 - Net-Zero Emissions from Primary Aluminium Production

The time horizon for net-zero targets - 2050 - feels distant and the target sounds simple and plausible. The year 2050 is probably chosen because it is just a round number and halfway into the 21st century. For comparison, let us go 27 years back in time and take a look at the situation in 1996. Some global average data are compared in Table 1.

Table 1. Comparison of some global average data from 27 years ago with present data [3], and IAI data for business as usual (BAU) and net-zero target by 2050 [2]. The data for 2023 is from 2021 and 2022 [3].

Process/Year	1996	2023	2050 (business as usual)	2050 (net-zero target)
Global production of Al (Mt/year)	20.9	68.5	88	68
Energy consumption (kWh/kg Al)	14.5	13.2	12	~ 10 (?)
Percentage of electric power from coal and natural gas (%)	43	67	61	19
GHG emission (t CO ₂ e/t Al)	16.9	16.6	15.8	0.5

The annual global primary aluminium production has increased by almost 50 million tonnes since 1996, but the IAI modelling does not include any large increase up to 2050. The energy consumption has shown a nice reduction and this will surely continue. The amount of electric power from fossil sources has increased considerably, and the GHG emissions are the same now as in 1996. So it is obvious that the electric power mix must change and the emissions must be reduced dramatically in the next 27 years to reach the net-zero target.

To get to net-zero emission is a big and challenging task, and the way to achieve it is partly unknown at present. We know that this is not possible with the process technologies we have and use today. Genuinely new and yet-to-be-developed technologies are needed. If and when these new technologies are available, the commercial adoption will require a significant investment across the aluminium industry.

4. What will the Aluminium Industry Need to Reach Net-zero Emissions with the Present Electrolysis Cell Technology?

With the main raw materials (electricity, alumina, and carbon anodes) and the electrolysis cell technology we have in 2023, the industry will need the following improvements before 2050:

4.1 Electric Energy Mix Decarbonization

In 2021, 67 % of the electric power used to produce aluminium originated from fossil fuel sources; mainly coal (57 %) but also natural gas (10 %) [3]. Globally there has been an increase in the specific CO₂ emissions from the energy used for aluminium electrolysis from 6 to 10 t CO₂e/t Al since 1990, and there has been only a small reduction since 2015, as shown in Figure 1. It is obvious that this trend must change, and change rapidly now.

Switching to decarbonized power generation offers the most significant opportunity of emissions reduction and is critical to the transition. It means using “clean” energy from renewable sources

(water, solar, wind, geothermal, nuclear) instead of fossil fuels (coal, gas, oil). This is the biggest step that the global aluminium industry can take for emissions reduction and it is therefore the number one technological pathway (“green” energy is the key).

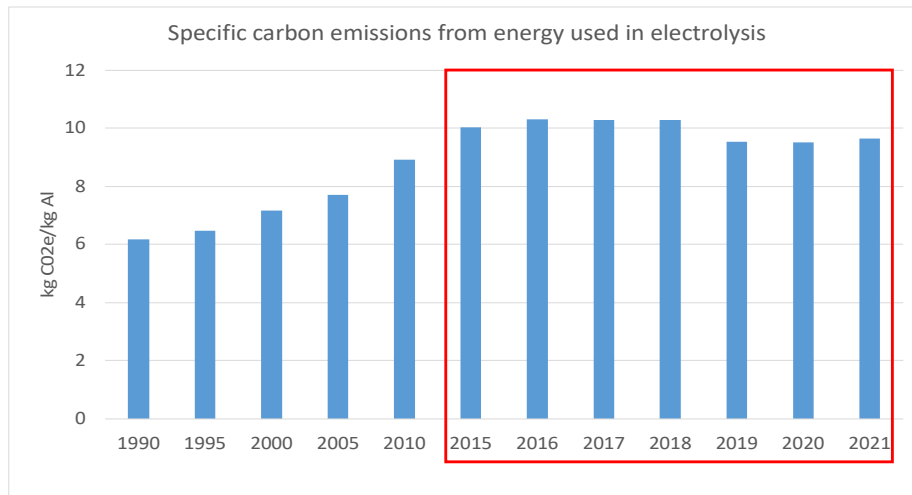


Figure 1. The specific CO₂ emissions from the electric energy used in aluminium electrolysis [4].

4.2 Emission-free Production of Alumina

CO₂ is not produced directly in the Bayer process. Most of the emissions from alumina production come from fossil fuel combustion, supplying thermal energy to the process. The main sources of CO₂ from the Bayer process are steam generation for digestion to dissolve the aluminium-bearing minerals in bauxite (coal boilers are the standard solution) and high-temperature calcination for dewatering. To decarbonize the emissions from alumina refineries new low-carbon digestion and calcination technology will be required. And in addition the transportation of alumina from the refinery to the potrooms should be done by electric ships and vehicles to avoid fossil fuel consumption and CO₂ emissions.

4.2.1 Alumina Digestion

The requirements are:

- Fuel switching by converting coal boilers to use liquid natural gas (LNG).
- Electric and hydrogen boilers have the potential to abate 100 % of the direct emissions.
- Mechanical vapor recompression (MVR) is an energy recovery process, which can be used to recycle waste heat to improve efficiency. Electricity from renewable sources will power compressors to turn waste vapor into steam, which will then be used to provide heat for the refinery process.

4.2.2 Alumina Calcination

Calcination is a direct-firing process with temperature requirements of 1000 °C - 1300 °C to drive off volatiles (water). This is currently done by natural gas or heavy fuel oil combustion. Fuel switching, either to electricity or to green hydrogen, is the only option to decarbonize the alumina calcination. The calcination stage of alumina refining has been claimed to be potentially well suited to the application of concentrated solar thermal energy (CST) [5].

The 2021 global average emissions from production of alumina were as high as 2.7 t CO₂e/t Al, while the lowest value at present is probably 0.97 t CO₂e/t Al [6]. The minimum obtainable value has been estimated to 0.2 t CO₂e/t Al [7].

4.3 Emission-free Production of Prebaked Carbon Anodes

CO₂ is formed directly during production of carbon anodes. Most of the emissions from prebaked carbon anode production now come from the production of the main raw material calcined petroleum coke (CPC). During the anode baking process three main sources of CO₂ emission occur: baking furnace fuel consumption, pyrolysis of coal-tar pitch, and inadvertent combustion of packing coke used to support the anodes in the pits of the baking furnace. Further improvement is possible by a switch from fuel oil to natural gas in the anode baking furnaces.

The global average emissions from production of prebaked carbon anodes are 1.0 - 1.5 t CO₂e/t Al, while the lowest reported value at present is 0.8 t CO₂e/t Al [8]. The minimum emission value for carbon anodes is considered to be 0.5 t CO₂e/t Al [7], and it is difficult to reduce these emissions much further. Developing a new calcination technology to capture carbon emissions from the production of the raw material CPC seems to be the only way to reduce these emissions significantly.

4.4 Emission-free Electrolysis of Alumina to Aluminium

There are two major ways of reducing the direct emissions from the existing electrolysis cells, lowering the net anode carbon consumption and lowering the anode effect frequency and duration, causing perfluorocarbon (PFC) greenhouse gas emissions. However, at present there is no demonstration of capture of perfluorocarbon emissions from anode effects and the only way to reduce them is to avoid that they are formed. Using prebaked carbon anodes the average CO₂e emissions are now between 1.5 and 1.6 t CO₂e/t Al, while the theoretical minimum value is 1.22 t CO₂e/t Al [7]. Thus, as long as carbon anodes are used there will be emissions of CO₂ from the electrolysis cells, and the possibility of further reduction is limited.

4.5 Carbon Capture, Utilization and Storage (CCUS)

Carbon capture, utilization and storage (CCUS) offers a potential solution to eliminate the GHG emissions from the conventional electrolysis cells with carbon anodes. The CCUS technology comprises three different processes: separating process-related CO₂ from emission sources, CO₂ conversion, and utilization or storage, by injecting it deep underground where it cannot escape into the atmosphere. Once captured and isolated, the CO₂ is pressurized into a liquid state, so that it can be transported by a pipeline to a place where it can be used or stored.

In addition to the development of a good technological method, CCUS has challenges in terms of economic feasibility, both in terms of initial Capex investments and increased auxiliary power consumption, which increases Opex. Energy is required for separating CO₂ from the other substances in the anode gas mixture and also for compressing CO₂. It depends on the availability of the CO₂ transport and storage infrastructure, and captured CO₂ needs to be sold or storage be paid for.

There is a new method for carbon up-concentration based on electrochemical methods, which indicates that it may be possible to capture CO₂ from streams with concentrations as low as 0.6 % and with energy use of around 0.85 kWh/kg Al [9]. It has been commonly assumed that a lower suction off-gas system is needed to increase the CO₂ concentration, and also cell hooding redesign with less gas leakage to the potrooms will be required. This new method may possibly reduce the necessity of changing the cell design.

5. Comments to the Present Technologies to Maintain the Existing Cells in Operation

The possibilities for reaching net-zero emissions with the present electrolysis cell technology have been discussed above. With the present best available technologies (BAT) and renewable electric energy the production of alumina and carbon anodes will give about 1.0 and 0.8 t CO₂e/t Al and combined with 1.4 t CO₂e/t Al from the electrolysis cells this amounts to 3.2 t CO₂e/t Al [7]. However, this is far from net-zero emission.

The CCUS technology is expected to be capable of reducing CO₂ emissions in smelter flue gases by 90 %, but not reducing the PFC emissions [10]. This means that with CCUS about 0.15 t CO₂e/t Al will still remain from the carbon anodes, plus about 0.1 t CO₂e/t Al from the PFC emissions, which are not captured by CCUS, giving a total cell emission of about 0.25 t CO₂e/t Al. So even with CCUS the electrolysis process is not completely carbon emission-free, but it may be small enough to be called net-zero. But this requires that the alumina and carbon anodes arrive emission-free at the smelter!

With our present knowledge and if net-zero CO₂ emissions shall be achieved, introduction of CCUS seems to be the only way to keep the cell technology with prebaked carbon anodes in operation in 2050. There are now about 200 aluminium smelters in the world, and with a rough estimate of about 300 cells in average per smelter, then about 60 000 cells are presently in operation. It would be a more beneficial and cheaper solution to be able to continue to use this anode carbon cell technology also in 2050. However, it is possible that there may exist some other and yet unpublished projects to achieve this target for the present aluminium industry.

6. A New Cell Technology with Inert Anodes

For many years several companies have been working actively with inert anode cell development, and here is a short summary of the present status for the inert anode development.

Elysis produced its first commercial batch of aluminium using inert anodes in late 2019. It is expected to increase production by 15 % and also to reduce operating cost by 15 %, when compared to the traditional smelting process. Elysis plans to complete its commercial-scale demonstration project in 2023 and in 2024 the technology will be able for installation [11]. A press announcement from February 2023 expresses some doubt about the economic viability of transforming Rio Tinto's aluminum smelters with Elysis cells [12].

Rusal states that Capex is the same as for the prebaked carbon anode cells, while Opex is 5 % lower. The GHG emissions are zero and the electric energy consumption has been reported to be 14.8 kWh/kg Al. It is expected that the Rusal technology will be ready for industrial scale implementation by 2030. Full scale industrial implementation will then follow, and from 2040-2050 Rusal plans to convert all their prebake cells to inert anode technology [6].

Arctus Aluminium Ltd. in Iceland is working on inert anode cells in cooperation with Trimet Aluminium in Germany. They claim to develop a cost competitive 170 kA cell technology with 20 % less energy consumption, 40 % less capital investment and 30 % overall reduction in annual production costs. The development milestones for Arctus are to have a demonstration plant in 2027 and to start industrial commercialization in 2030 [13].

Chinese inert anode cell technology: Inert anodes are expected to become commercially available in China around 2035 and achieving commercial competitiveness with carbon anodes after 2050. A photograph of a Chinese 240 kA inert anode cell has been published [14], together with a schematic drawing of the cell with horizontal electrodes. It is not known if this cell has been started yet.

6.1 Comments to Inert Anodes

With inert anodes there are no CO₂ emissions from the cells, and perhaps less than 0.10 t CO₂e/t Al is emitted from the thermal energy required to produce the inert anodes and cathodes. No perfluorocarbon gases are evolved, simply because there are no carbon anodes. The main emission contribution will then be from the production of the alumina. This means that inert anodes can give total emissions of about 0.2 to 0.3 t CO₂e/t Al. This is low enough to be called net-zero emission!

However, because the processes are different, the entire superstructure and cathode lining of the present cells will have to be removed and replaced with a new inert anode cell. Existing buildings, concrete, infrastructure, and so forth, can be used, which saves cost over a Greenfield expansion.

Most people want an inert anode cell and hope that the major players will succeed. The references in the present papers are from 2022 and very little technical information has appeared so far in 2023.

7. Data for the Present and Future Best Available Technology (BAT)

Data for the present global average emissions and for the present and future best available technologies (BAT) are summarized in Table 2, assuming that the electric power comes from renewable sources with zero CO₂ emissions. If we look towards 2050 for the future best available technology (BAT), it is reasonable to assume that the emissions from the alumina refining and the carbon anode processes will be reduced considerably. In Table 2 the estimated global average BAT emissions of 0.2 t CO₂e/t Al from alumina refineries in 2050 has been used, while the value 0.5 t CO₂e/t Al has been chosen for the future BAT value for carbon anode production [7].

Table 2. Data for the present global average emissions from aluminium production and the present and future best available technologies (BAT) for the processes for raw materials production and smelting with CCUS and inert anode cells, with power from renewable sources [7].

Processes	Present global average emissions (t CO ₂ e/t Al)	Present BAT emissions (t CO ₂ e/t Al)	Future BAT emissions with CCUS (t CO ₂ e/t Al)	Future BAT emissions with inert anode cells (t CO ₂ e/t Al)
Alumina refining	2.7	1.0	~ 0.2	~ 0.2
Anode production	0.9	0.8	~ 0.5	~ 0.01
Electrolysis	2.0	1.4	~ 0.25	0
Total	5.6	3.2	~ 1.0	~ 0.2

The data in Table 2 shows that the electrolysis emissions are reduced considerably with CCUS, but the total emissions are still about 1.0 t CO₂e/t Al. This is not close enough to the net-zero definition of 0.5 t CO₂e/t Al, but with an increased efficiency of the carbon capture and lower emissions from the carbon anode production the target can be reached.

Inert anode cells can bring the total emissions down to about 0.2 t CO₂e/t Al and the main emissions then comes from the production of alumina. Inert anode cells then represent the greatest carbon-reducing solution.

8. New Alternative Processes for Aluminium Production

In the open literature many alternative processes have been suggested for aluminium production, but so far without being able to compete with the Bayer and Hall - Héroult processes from the late 1880s. Here is a short description of two on-going processes where net-zero emissions are the target.

Aluminum Technologies: The CCR Process. This carbo-chloride reduction technology centers on the carbochlorination of clay, followed by reduction of the aluminium chloride to aluminium, and the process captures all of the CO₂ produced in the conversion of aluminium oxide to aluminium chloride [15]. The process produces high purity aluminium with no direct GHG emissions, while using one-third less electricity (which means an energy consumption of about 9 kWh/kg Al). The process is claimed to have lower capital and operating costs than the Hall-Héroult process - half Capex and lower Opex.

After 18 years of R&D work, Aluminum Technologies has designed and built their own smelter and reactors “to create a clean, simplified and energy-efficient process capable of rapid global adoption to produce low-cost, high purity aluminium metal” [15].

Norsk Hydro: The HalZero Process. The concept is to convert alumina to aluminium chloride by carbochlorination and then to do electrolysis in a sodium chloride - lithium chloride melt at about 700 °C. It builds on the aluminium chloride electrolysis process used by Alcoa in the 1980s [16], but with a change in the aluminium chloride production to overcome the problems experienced by Alcoa. The two new ideas in the HalZero process are to use CO (g) instead of carbon as the reducing agent in the carbochlorination process, and to collect and electrolyze CO₂ to form CO, which is recycled and fed into the carbochlorination reactor as the reducing agent for alumina.

Capex and Opex of the HalZero process are claimed to be comparable with those of the Hall-Héroult process, and the estimated energy consumption for the aluminium chloride electrolysis is less than 9.5 kWh/kg Al. In addition there is the electrical energy consumption for the CO₂ electrolysis, which is estimated to 5 kWh/kg Al [17].

The status of the process in March 2023 was that the company will invest in a test facility supported by the Norwegian government, and the total investment cost is expected to be approximately USD 37.5 million. With this step, Hydro claims to be on track to deliver pilot production of zero-carbon primary aluminium by 2030. However, it is also stated that “the plan is ambitious and there is considerable risk” [18].

The electrolysis of CO₂ is an important part of the HalZero process. CO₂ electrolysis is not yet a proven technology and much work remains to bring this to an industrial level. Figure 2 shows a schematic illustration of an electrolysis cell design used for electrochemical CO production from CO₂ in a solid oxide electrolysis cell (SOEC) [19]. Typical oxygen electrode materials for SOECs include doped perovskites of lanthanides and transition metals, where one example is strontium-doped LaMnO₃. It is seen in Figure 2 that O₂ is produced at the anode, while the cathode gas is not pure CO, but a mixture of CO₂ and CO.

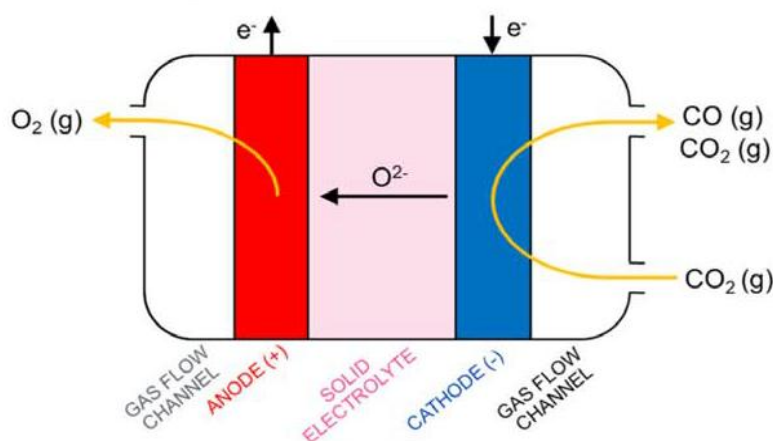


Figure 2. Schematic illustration of an electrolysis cell design used for electrochemical CO production in a solid oxide electrolysis cell [19].

8.1 Comments to the New Processes for Aluminium Production

The driving forces for developing new processes for aluminium smelting usually have consisted of two major factors: capital-cost reduction per tonne of aluminium produced and reduction of the electrical energy consumption. In recent years a third factor has become very important: greenhouse gas emissions reduction. To find an alternative to the Hall-Héroult process has been a dream for many years, but nobody has succeeded so far. And in addition the production of the raw material alumina also will cause some emissions, which have to be included. The comments in the present paper are based on information in the open literature, mainly press announcements and PowerPoint presentations. It is understandable that companies working on a new aluminium production process would like to keep detailed technological information and results confidential.

9. The Cumulative Investment Cost Needed to Obtain Net-zero Emissions by 2050

The aluminium industry has a strong focus on cost control, and to reach net-zero will cost a huge amount of money. According to Mission Possible Partnership (MPP) [20] the approximate investments estimations in four main categories across the primary aluminium production value chain will be:

- 1) Low-carbon electric power: US\$ 500 billion
- 2) Inert anodes retrofits in smelters: US\$ 200 billion (highly uncertain, however)
- 3) Alumina refineries: US\$ 36 billion
- 4) CO₂ transport and storage infrastructure: US\$ 26 billion

Recently MPP [21] published a report called “Aluminum Decarbonization at a Cost that makes Sense”. It was concluded that retrofitting existing smelters with CCUS technology could potentially add about 5 % of the initial capital cost of the project. The implementation of inert anode technology could require a similar capital cost to conventional smelter technology. The operating cost of implementation of CCUS in existing smelter facilities could potentially be increased by 6 %, with most of the share associated with the CCUS operating costs. Inert anode technology, on the other hand, was found to show a reduction in operating cost of 3 to 10 % [21].

10. Secondary Aluminium from Post-Consumer Scrap

The production of recycled aluminium will be more important in the coming years. This development will continue in parallel with the necessary improvements of the primary aluminium industry. Aluminium recycling is the process by which post-consumer aluminum scrap can be reused in products after its initial (primary) production. According to IAI statistics [3] the average process emissions from recycling of post-consumer scrap is 0.6 t CO₂e/t Al. Norsk Hydro [22] reports that their post-consumer scrap has a carbon footprint of about 0.5 t CO₂e/t Al. This results from post-consumer scrap collection, transport, sorting, and remelting. In June 2023 Norsk Hydro reported that the company had been melting aluminium scrap using green hydrogen instead of natural gas as fuel for the burners powering the remelt furnace [23]. This shows that zero emissions are possible from secondary aluminium production from post-consumer scrap.

11. Summary

To reach net-zero GHG emissions when using the existing electrolysis cell technology the main ways are a combination of the following requirements:

- Renewable electric power
- Emission-free alumina and anode production
- All material transportation, including alumina, by electric ships, railways and vehicles
- Carbon capture, utilization and storage (CCUS)
- Recycling of post-consumer scrap

However, one can also use new cells with inert anodes, or alternatively a new process for production of aluminium. Examples here are:

- A new and different process for aluminium production (CCR and HalZero), where the processes are based on carbochlorination of alumina to produce aluminium chloride, which is then electrolyzed to aluminium.

With the target of net-zero GHG emissions by 2050 it is possible that a new and emission-free process may be the main solution for the aluminium industry.

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