

Aluminium Production

HIGHLIGHTS

■ **PROCESSES AND TECHNOLOGY STATUS** – Primary aluminium is produced from aluminium oxide (alumina, Al_2O_3) which is obtained from bauxite, a widespread mineral. The primary aluminium production from alumina is based on an energy-intensive electrolytic process at a temperature of approximately $960^\circ C$, where a high current (200 to 350 kA) is passed through the electrolytic bath to produce aluminium metal. There are basically two different technologies for primary aluminium production, i.e. Prebaked and Søderberg technology. The first one is more efficient and less polluting. The use of the Prebake technology has increased from about 63 % in 1990 to about 90 % in 2010. An aluminium plant consists of many electrolytic cells in series (pot-lines). Secondary aluminium is produced by melting scrap (recycled) metal in a furnace. Production of secondary aluminium consumes less than 5% of the energy needed to produce primary aluminium. It accounts for 33% of today's global supply and is expected to rise to 40% by 2025. In 2010, the global production of primary aluminium was 41.2 million tonnes (Mt), about twice as much as in 1990. China, Canada, Russia, and the United States accounted for 59% of the 2008 global production.

■ **PERFORMANCE AND COSTS** – Today's electricity consumption for primary aluminium production ranges from 13 to 17 kWh/kg, with best performance in advanced large-scale pilot plants of 12.5 kWh/kg. The target is to reduce it to 11 kWh/kg in next generation of production cells (theoretical minimum energy use for electrolysis is 6.3 kWh/kg). Aluminium production involves the emission of pollutants in all phases of the process including alumina production and electrolysis. The emissions from the electrolytic cells consist of greenhouse gases such as CO_2 and poly-fluorinated hydrocarbons (PFC), and other pollutants including fluorides, polycyclic aromatic hydrocarbons (PAH), SO_2 , dust, metals, NOx, CO. Apart from CO_2 , the actual emissions depend on the efficiency in flue-gases treating, which usually ranges from 95% to more than 99%. In 2006, the average direct GHG emissions from aluminium production were about 1.5 t CO_2 eq/t Al from alumina production, 2.5 t CO_2 eq/t Al from electrolysis (of which 0.7 due to PFCs) and 5.5 t CO_2 eq/t Al from electricity generation, thus totalling 9.5 t CO_2 eq/t Al. The secondary aluminium produces by far less emissions than primary aluminium, but salt slag (up to 500 t/t Al). A major waste from alumina production is the red mud (600-1500 kg/t Al_2O_3). As far as cost is concerned, the investment cost for new aluminium production facilities is between €4000 and €5000 per tonne of production capacity per year. Due to this high investment cost, an option to increase the capacity is to upgrade and modernise existing plants thus increasing capacity and energy efficiency, rather than building new facilities. The typical cost breakdown of aluminium production is dominated by the cost of electricity and alumina (about 60%), with the electricity share varying significantly among producers. Profitability of the aluminium production depends on market prices, operation costs and the cost of the raw materials. Market prices can vary significantly, e.g. high-grade primary aluminium ingots ranged from \$0.75 per pound in 2009 to \$1.17 per pound in 2008 (London Metal Exchange average).

■ **POTENTIAL AND BARRIERS** – The main areas of growth for the aluminium market are expected to be in non-OECD countries such as China, Brazil, Middle East and South Africa. New production plants are usually located where the production and electricity costs are expected to be lower. The associated emissions can be significantly reduced if aluminium production is based on electricity from hydro power and other renewable sources rather than from coal-fired power plants. Emerging technologies like inert anodes (carbon free) and new cathode materials (wettable cathode) might succeed in achieving highly efficient electrolysis processes, but still are at a pilot plant level. Increased aluminium recycling will reduce significantly the use of raw materials, energy and emissions for aluminium production.

PROCESS OVERVIEW

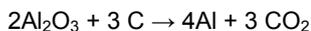
Aluminium is the third most common element on the earth. It is obtained from bauxite, a mineral largely available at commercial prices. In 2010, the global production of primary aluminium was 41.2 million tonnes, up from 37.3 million tonnes in 2009 and 39.6 million tonnes in 2008. Four countries (China, Canada, Russia, and the United States) accounted for 59% of the total production in 2008, see [Figure 1](#) [Figure 4](#) [1].

■ Production of Primary Aluminium

Primary aluminium is produced from aluminium oxide, Al_2O_3 , also called alumina. Alumina is produced from

bauxite. Most primary aluminium production plants do not have an alumina production process on site. The most common process for alumina production is the Bayer process, where bauxite ore is grinded, mixed with caustic soda and heated up to $280^\circ C$. The dissolved aluminium hydrate is then precipitated as a solid material at about $55-70^\circ C$. The aluminium hydrate crystals can be removed by either filters or thickeners and finally converted to alumina by calcination at a temperature of around $1000^\circ C$. The production of one tonne of aluminium requires two tonnes of alumina and about four tonnes of bauxite [2]. The energy use for bauxite mining, raw materials

preparation through the Bayer process is approximately 25 GJ/tonne aluminium [3]. Primary aluminium is produced from alumina by the Hall-Héroult electrolytic smelting process. The overall chemical reaction can be written as:



The chemical reaction enthalpy, i.e. the minimum amount of energy that is required for reduction of aluminium oxide to aluminium, is 29.2 GJ/t aluminium (8.1 kWh/kg) [3]. Aluminium oxide is dissolved in an electrolytic bath of mainly molten sodium-aluminium fluoride (cryolite) at a temperature of approximately 960 °C [2]. It is produced in electrolytic cells (pots) comprising of a steel container lined with carbon or graphite acting as the carbon cathode, and a carbon anode suspended from an electrically conductive anode beam. The cells are connected in series to form an electrical reduction line (pot line). A direct current is passed from a carbon anode through the bath to the cathode and then to the next cell. The voltage is low, but the current is very high, typically from 200 000 A to 350 000 A. Depending on the production process of the anodes, the electrolytic cells are divided in two main types, i.e. Søderberg and Prebaked cells (Figure 2). Prebake cells are used in about 90 % of global primary aluminium production in 2010 [5]. In a Søderberg cell, the anode is produced in situ, while in the Prebake cell, the production of anodes takes place in a separate anode plant, often integrated with the primary aluminium plant. In the Søderberg cell the current is fed into the anode through studs that have to be withdrawn and re-located higher up as the anode is consumed. In the Prebake cell the anodes are gradually lowered as well as they are consumed. Prebake cells can be side worked (SWPB) or centre worked (CWPB) depending on whether alumina is fed into the cells around the circumference or along the centreline. The centreline cells are further divided in centre-break and point feeder (see Figure 2). The best available technique is the centre worked Prebaked cells with automatic multiple point feeding of alumina. Oxygen is released at the anode forming carbon oxides while consuming the carbon anode. At the cathode (bottom of the cell), liquid aluminium is deposited and periodically withdrawn from the cells by vacuum siphons and passed into crucibles. Because of deterioration, the cathode is replaced after 5 to 8 years [2]. An aluminium plant consists of one or several potlines. Each potline typically counts around 300 pots with an annual capacity from 150,000 to 300,000 tonnes. The process is continuous and cannot easily be stopped and restarted.

Production of carbon and graphite anodes and cathodes products starts with the production of green paste. The paste is produced from calcined petroleum coke and coal tar pitch in a heated mixer, and cleaned

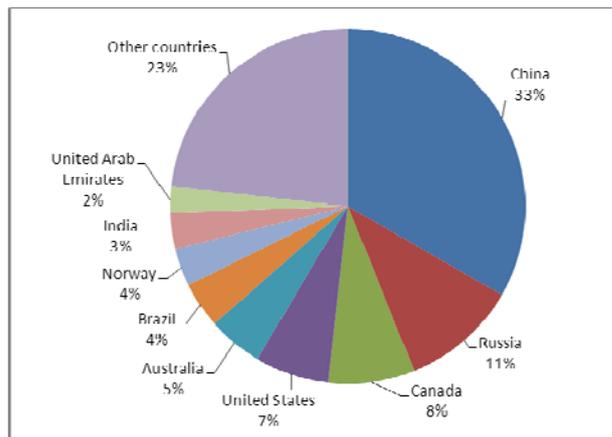


Figure 1 - Aluminium production share in 2008 [1]

anode butts (residues) might also be added. In a Søderberg cell, the paste is added to the cell. In a Prebake anode plant, green anodes are baked in ring furnaces with a large number of pits containing the anodes. Coke is used for separation and to prevent oxidation, and it is consumed at a rate of 12-18 kg per tonne of anodes. The normal baking time of prebaked anodes is approximately 18 to 21 days. During the process approximately 5% of the weight is lost. The energy use per tonne of anode is approximately 2.4 GJ. [2]. The theoretical minimum anode consumption is 0.334 tonne carbon per tonne of aluminium [3]. Carbon or graphite cathodes are made in special production plants, similar to the production of prebake anodes, with different composition and temperature.

■ Production of Secondary Aluminium

Secondary aluminium is produced from scrap metal, either "new scrap" from production and manufacturing and "old scrap" from recycled aluminium. A variety of furnaces are used such as rotary, reverberatory (hearth/closed well), induction and shaft furnaces. The reverberatory furnaces are used for batch melting, refining and holding. They are refractory lined, and fired by wall or roof mounted burners using different fuels. Oxy-fuel burners can also be used in order to increase the melting rate. An oxide layer known as skimmings or dross is produced when melting aluminium. This must be removed from the furnace and its aluminium content is recovered by several treatment processes. Molten aluminium is transported to holding furnaces in the casting plant. The furnaces are usually induction or reverberator furnaces. The metal is refined and filtered and might be blended before casted to slabs, T-bars, billets, thin sheets or wire-rod. The production and refining of secondary aluminium consumes less than 5% of the energy needed to produce primary aluminium [4]. Recycled aluminium constitutes 33 % of world supply and is forecast to rise to 40% by 2025 [6].

■ Emissions and Waste

Emissions to the atmosphere occur from alumina calcination and heating, anode baking, electrolytic cells, pot room ventilation and from degassing and casting. The emissions from the electrolytic cells can be fluorides, poly fluorinated hydrocarbons (PFC), polycyclic aromatic hydrocarbons (PAH), SO₂, dust, metals, NO_x, CO, COS and CO₂. Carbon dioxide (CO₂) and PFC are greenhouse gases and the global warming potential (GWP) value of PFCs are very high; 6200 for CF₄ and 9200 for C₂F₆. The other emissions mostly contribute to local pollution and particularly fluorides have caused severe local contamination. The emissions depend on the efficiency of capturing and treating the flue-gases. Normal efficiency values are from 95% to more than 99% for Prebake CWPB and about 85-95% for Prebake SWPB and Söderberg [2]. Captured gases are cleaned in scrubbers. Carbon from the anode reacts with oxygen formed by the electrolysis, thus giving 1.4 to 1.7 tonne CO₂ per tonne aluminium in an efficient Prebake plant [2]. Typical emission figures are presented in Table 1.

In 1990, the GHG emissions from production of aluminium was 1% of global emissions and 0.4% was direct emissions from the aluminium plants [7]. In 2006, the average direct GHG emissions were 1.5tCO₂eq/t Al from alumina production, 0.7 tCO₂eq/t Al from PFC generation (varying from 0.03 to 18.9), 1.8 tCO₂eq/t Al from anode carbon of the electrolysis process and 5.5 t CO₂eq/t Al from electricity generation (varying from 0 to 20.8), adding up to a total of 9.5 t CO₂eq/t Al [8]. In 2010, global average PFC emissions were calculated to be 0.59 t CO₂eq/t Al [5].

Besides emissions, the secondary aluminium production produces up to 500 tonnes of salt slag per tonne of aluminium. Salt can be recovered for further use by separation and crystallisation processes and the aluminium oxide portion might be sold to the mineral industry. Red mud is a major waste from alumina production with the Bayer process. It is the remaining solid material after the extraction of the bauxite and the quantity varies between 600 to 1500 kg /t Al₂O₃ [2].

■ Improving Efficiency in Al Production

Plants using the conventional Söderberg technology are more likely to be closed down or replaced by the more efficient Prebake technology. Modernised Söderberg technology including cells with point feeders, improved burners, dry anode paste and better anode casing/cover (see costs in Table 1) can improve the current efficiency by 15% [2] and the environmental performance. The smelting energy use has decreased by 5% from 1990 to 2004 [7]. The best available technique is the use of centre worked Prebaked cells with automatic multiple point feeding of alumina. In

2010 85% of all aluminium was produced with this technology, compared to 33% in 1990 [5]. The electrolysis process should be computer controlled based on active cell databases and with monitoring of cell operating parameters to minimise the energy consumption and reduce the number and duration of anode effects. Enhancing the production by increasing the current is a major measure that initially decreases the specific consumption of electricity, but beyond a certain level may involve increased consumption.

The best specific electricity consumption of today is 12.5 kWh/kg Al in large scale pilot plants [9]. The vision is to reduce it to 11 kWh/kg Al in the next generation of production cells [10]. Technologies for reduced energy consumption may be millivolt chasing, reducing variability, improved materials, off-gas heat recovery, cathode heat recovery, drained cathode cell and innovative cell concepts [10].

Important emerging technologies are the development of inert anodes (carbon free) and the development of new cathode materials (wettable cathode) to achieve better energy efficiency for the electrolysis process, but they are still at a pilot plant stage. In the secondary aluminium production, the energy use can be reduced by enclosures or hoods for the feeding and tapping areas. Heat recovery might also be a possible measure. In addition, several measures are adopted to reduce the emissions [2].

INVESTMENT AND PRODUCTION COSTS

In general, aluminium production involves high investment costs and an option to increase the production capacity is upgrading existing plants by increasing capacity and improving efficiency, rather than building new facilities. The size of individual production cells has also increased substantially. Typical investment costs are presented in Table 1. New point feeder Prebaked plants (green site) may cost between € 4000 and €5000 per tonne of capacity while upgrading existing plants involves significantly lower investment costs (see Table 1), with the sole exception of the conversion of a Vertical Stud Söderberg (VSS) plant to a Point Feeder Prebaked plant which requires major technical changes.

Typical share of production costs is presented in Figure 3 [11]. Power dominates the cost and varies the most among producers. Profitability of the aluminium production depends on the price of the product, the cost of the raw material and the operating costs. Product market prices vary significantly depending on demand and the economic course: for example, in 2009 the annual average LME (London Metal Exchange) cash price for high grade primary aluminium ingot decreased to \$0.755 per pound from \$1.167 per pound in 2008.

POTENTIAL AND BARRIERS

The main areas of growth for the aluminium market are expected to be in non-OECD countries such as China, Gulf States, Southern Africa and Brazil [7]. The location of new production plants depends on where production and electricity costs are expected to be lower. Since energy costs is a major part of the total production costs and the differences in energy costs is high, access to energy at the lowest cost will be of vital interest. The associated emissions can be significantly reduced if aluminium production is based on electricity from hydro power and other renewable sources rather than from coal-fired power plants. Emerging technologies like inert anodes (carbon free) and new cathode materials (wetable cathode) might succeed in achieving highly efficient electrolysis processes, but still are available as a pilot plants. Increased recycling will reduce significantly the use of raw materials, energy and emissions for aluminium production.

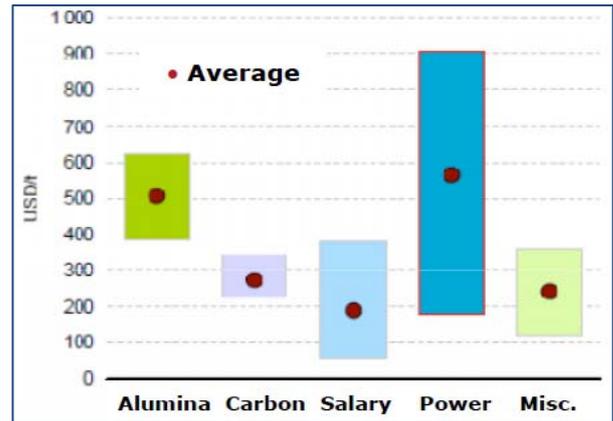


Figure 3 - Typical share of costs of aluminium production (USD/t Al) [11]

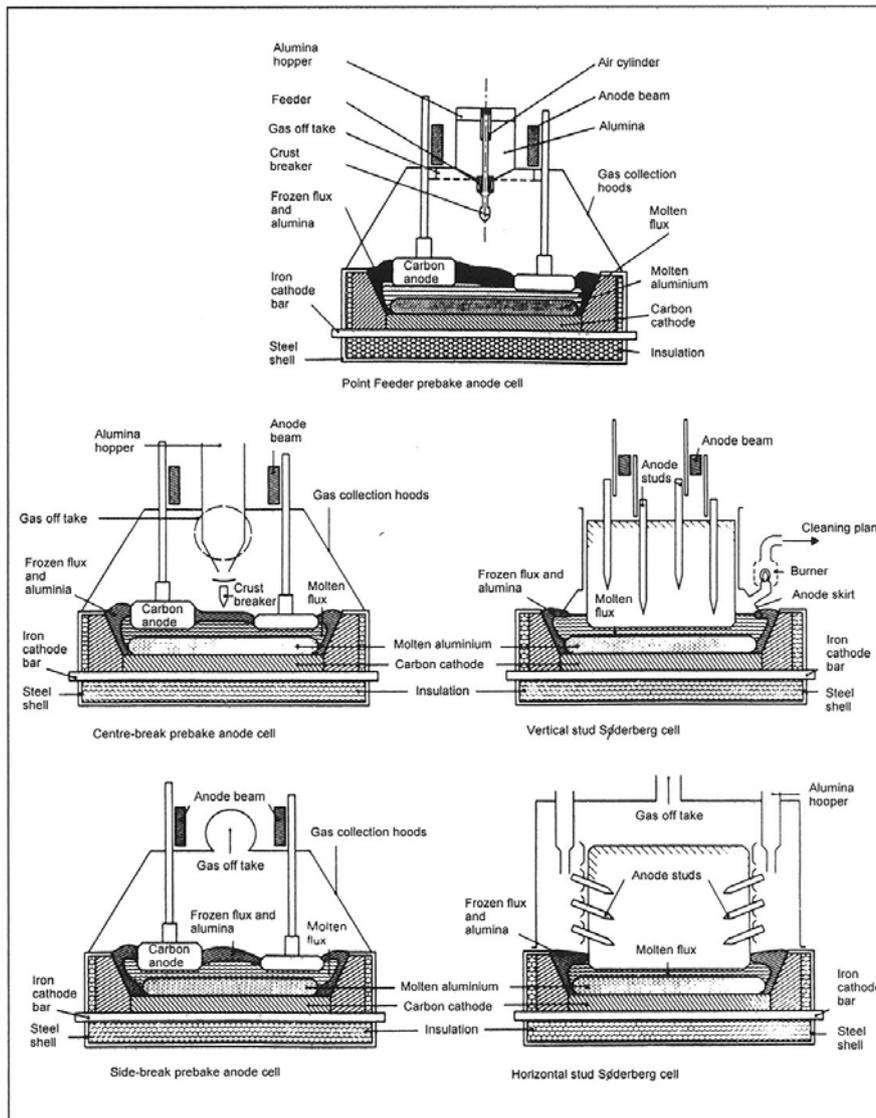


Figure 2 - Electrolytic cells for primary aluminium production [4]

Table 1 – Summary Table – Key Data and Figures for Aluminium Production

| Technical performance | | | | |
|--|------------------------|---------------------|-----------------------|-------------------------|
| Technology Variants for Primary Production | PreBake | | Söderberg | |
| Bauxite input per tonne primary aluminium [2] | ca 4t/tAl | | | |
| Alumina input per tonne primary aluminium [2] | 1.90-1.93t/tAl | | | |
| Energy use in bauxite and alumina production [2] | 15-26 GJ/tAl | | | |
| Carbon anode material [2] | 0.4-0.45 t/tAl | | | |
| Electricity for electrolysis [2] | 12.9-15.5 MWh/tAl | 14.5-17.0 MWh/tAl | | |
| Electricity, total (incl. anode prod.) [2] | 13.6-15.7 MWh/tAl | 15.1-17.5 MWh/tAl | | |
| Energy use anode production [2] | 5.5 GJ/tAl | | | |
| Cast house energy [2] | 0.3-2.5 GJ/t melted Al | | | |
| Lifetime cathode | 5-8 years | 4-6 years | | |
| Secondary Production (energy Input per tonne [2]) | 2-4.7 GJ/tAl | | | |
| Costs | | | | |
| Capital cost per tonne of annual capacity) [2, 4] | PreBaked | | Modified Söderberg | |
| Side Worked Prebaked (SWPB) upgrading to Point Feeder Prebaked (CWPB-PF) | €400-1000/t | | | |
| Centre Worked Prebaked upgrading to Point Feeder Prebaked | €100-200 /t | | | |
| Vertical Stud Söderberg (VSS) upgrading to Point Feeder Prebaked | | | €2500-4000/t | |
| Conventional VSS upgrading to modernised VSS | | | €100-250/t | |
| New Point Feeder Prebaked (green site) | €4000-5000/t | | | |
| Upgrading to modernised Söderberg technology | | | 15 % eff. improvement | |
| - dry paste, increased casing height | | | USD 200/t | |
| - point feeding system | | | USD 300/t | |
| - anode top hoods, gas cleaning | | | USD 300/t | |
| Operating cost, excluding fuel and capital costs | €950-1500/t | | | |
| Environmental impact | | | | |
| Primary aluminium smelters [2] | PreBake | Modified Söderberg | | Söderberg Vertical stud |
| | Scrubber | No Scrubber | Scrubber | Scrubber |
| | kg/t Al | kg/t Al | kg/t Al | kg/t Al |
| CO ₂ from consumption of anodes | 1600-1700 | 1600-1900 | | 1600-1900 |
| PFC; CF ₄ / C ₂ F ₆ | 0.01-0.38 | <0.05 calculated | | 0.05-0.5 |
| HF | 0.15-1.0 | 0.4-1.6 | 0.15-0.25 | |
| Total fluoride | 0.25-1.5 | 0.5-1.5 | 0.3-0.5 | 0.5-3.0 |
| Dust | 0.5-3.0 | 0.9-4.0 | 0.8-1.2 | 1.0-8.0 |
| SO ₂ | 0.88-3.5 | 10-30 | 0.8-1.5 | 1.0-3.5 |
| PAH; B(a)P (benzo-a-pyrene) | | 0.005-0.015 | 0.005-0.008 | 0.005-0.025 |

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