مجله ایمنی زیستی
دوره ۱۰، شماره ۳، پاییز ۱۳۹۶

توسعه تکنولوژی، مصرف انرژی، انتشار گازهای گلخانه‌ای و آلودگی‌های محیط زیستی در صنایع آلومینیوم

فردیس نخعی*[۱]، مهدی ایران نژاد[۲]

۱ – دانشجوی دکتری فرآوری مواد معدنی، دانشگاه صنعتی امیرکبیر، دانشکده مهندسی معدن و متالورژی، تهران، ایران

۲ – دانشیار دانشگاه صنعتی امیرکبیر، دانشکده مهندسی معدن و متالورژی، تهران، ایران

fardis_nakhaei@aut.ac.ir

چکیده

آلومینیوم دومین فلز پرمصرف پس از فولاد در جهان است و بالاترین حجم تولید در بین فلزات غیرآهنی، را به خود اختصاص داده است. در این مقاله، مطالعه جریان مواد، مربوط به میزان تولید و مصرف (کاربرد) آلومینیوم و انرژی مصرفی در بین سال‌های ۱۹۸۰ تا ۲۰۱۳، همچنین وضعیت حاضر این صنعت، پیشرفت‌های صنعت تولید آلومینیوم، پیامدهای مصرف انرژی و همچنین شناسایی تکنولوژی‌های جایگزین مورد بحث قرار گرفته و در نهایت پیشنهادهایی برای کاهش انرژی مصرفی در مراحل مختلف تولید، داده شده است. نتایج تحلیل‌ها نشان می‌دهد که تولید آلومینیوم اولیه از ۱۹/۵۱ در سال ۱۹۹۰ به ٤٧/٧٨ میلیون تن متریک در سال ۲۰۱۲ افزایش یافته است. در این راستا، تولید جهانی آلومینا از ٤١/٤ به ۱۰۰ میلیون تن متریک در بین این سال‌ها افزایش یافته است. تولید آلومینیوم اولیه با مشکلات زیست‌محیطی بسیاری شامل مصرف انرژی بالا، انتشار گازهای گلخانه‌ای و تولید ذرات باطله همراه است. به دلیل استفاده از تکنولوژی‌های اخیر، میانگین مصرف الکتریسیته در تولید آلومینیوم از ١٦/٩ در سال ۱۹۹۰ به ١٤/٦ مگا وات ساعت بر تن در سال ۲۰۱۲ کاهش یافته است. همچنین میانگین مصرف انرژی برای تولید آلومینا در سال ۲۰۱۲ و ۲۰۰۰ به ترتیب در حدود ۱۳/۵۳ و ١٤/٥ گیگا ژول بر تن گزارش شده است.

کلمات کلیدی: آلومینیوم، بوکسیت، مصرف انرژی، گازهای گلخانه‌ای.

Introduction

Aluminium is the world's most abundant metal and is the third most common element, consisting of 8% of the earth's crust. The versatility of aluminium makes it the most widely used metal after steel.

Aluminium is a light-weight, durable, flexible, corrosion-resistant metal with high electrical and thermal conductivity, which is employed in in an ever-increasing number of applications. It is primarily utilized to produce pistons, engine and body parts for cars and airplanes, beverage cans, doors and windows, siding and foil. The main users of aluminium include the container and packaging industry, the transportation industry, and the building and construction industry.

In 2006, the world's primary aluminium production was almost 34 million tonnes, whereas aluminium recycling produced another 16 million tonnes. This total of about 50 million tonnes in aluminium greatly exceeds the 17 million tonnes of copper, 8 million tonnes of lead and 0.4 million tonnes of tin produced all around the world [1].

Aluminium metal is categorized as primary

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

aluminium if it is produced from ore and as secondary aluminium if it is produced mainly from recycled scrap material. Primary aluminium metal production consists of bauxite mining, refining bauxite to produce alumina, and finally, smelting alumina to produce aluminium. Secondary aluminium is produced by sorting, melting and treating scrap aluminium. Primary and secondary aluminium metal are further processed using traditional metal working technologies-rolling, extrusion, forging, shaping and casting into thousands of products.

Energy is one of the most important inputs in the process of economic growth and industrial development. The demand for various energy sources varies across different industries depending on technological progress, extent of economic activities and several other factors. In the close future, manufactured products will compete not only on price and performance, but also on their impact on society.

This report provides reliable and comprehensive statistical data over the period of 1990 to 2012 for the evaluation of energy trends and issues in the global aluminium industry. Also, this paper focuses on the most energy-intensive manufacturing operations for electrolysis (smelting) and process heating operations.

Primary aluminium production is associated with serious environmental problems including high energy demand, substantial GHG emissions and solid waste generation. In the twenty-first century, greenhouse gas (GHG) emission reduction is a pivotal environmental and sustainability issue. Energy-intensive manufactured materials (such as aluminium) could be significantly affected both in terms of price and use by GHG emission reduction policies. However, opposed to common belief, aluminium production could be positively influenced by GHG emission reduction policies. A combination of emission mitigation in production and significant GHG emission reduction further down the product chain enhance the attractiveness of aluminium for end-use applications.

Primary aluminium industry is one of the world's largest industrial consumers of energy. It consumes about 1% of the globally produced electric energy and about 7% of the total energy consumed by industry worldwide [2] and it is responsible for the 2.5% of the world's anthropogenetic CO2-equivalent emissions [3] as well as for the generation of 30 to 35 million tonnes per year of the red mud solid waste (on a dry basis) worldwide [4, 5].

Many researchers have studied either country or global level material cycles for specific substances such as copper, cadmium, mercury, steel and zinc have been carried out in the last decade [6, 7 and 8]. Their studies have advanced our understanding on various anthropogenic material cycles and thereby providing with solutions to optimise their production, use and recycling. Nevertheless, little research has been conducted on aluminium industry.

The main goal of this paper is to develop a global quantitative report of current Bauxite ore and aluminium mass flows and to quantify the GHG emissions resulting from aluminium production. This report is based on the historical statistical data extracted from various government organisation, industry association and individual industry annual.

Overview of Primary Aluminium Production

Bauxite Mining

Aluminium is the third most abundant element in the earth's crust and the most abundant metallic element. Aluminium, never found as a free metal, occurs naturally in the form of hydrated aluminium oxides or silicates. Since the silicates are mixed with other metals such as sodium, potassium, iron, calcium, and magnesium and it is chemically difficult and expensive to extract aluminium from them, the silicates are not a practical source of aluminium. Alumina, used for the production of aluminium, is obtained from bauxite deposits. Bauxite is not a true mineral but a rock that contains mostly boehmite and gibbsite along with diaspore, corundum and numerous impurities (mostly compounds of iron, silicon and titanium) [9]. The aluminium oxides commonly found as naturally occurring minerals include:

- Corundum (alumina, Al_2O_3)
- Boehmite (α-$Al_2O_3.H_2O$, a monohydrate containing 85 weight percent alumina)
- Diaspore (β-$Al_2O_3.H_2O$, chemically same as boehmite but with a different crystal structure)
- Gibbsite (γ-$Al_2O_3.3H_2O$, a trihydrate containing 65.4 weight percent alumina)

Approximately, all bauxite currently mined is produced by open-pit mining because underground mining tends to be costlier.

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

Bauxite is extracted from a mine by removing the overburden and loosening the bauxite deposit with explosives, contingent on its hardness and other local conditions. In some cases, the bauxite is crushed to shipment to the alumina refinery. Today, the main bauxite mining locations are in Guinea, Australia, Brazil, Vietnam, Jamaica and India.

Alumina Refining

Grinding is the first process unit of the overall Bayer process in which the bauxite ore is grounded in the presence of Bayer liquor to ensure the optimal particle size of the bauxite in the slurry. This step ensures the correct process parameters so as to achieve optimum alumina leaching efficiency in the downstream digestion. The hydrated aluminium oxides, especially gibbsite and boehmite dissolve well in a hot solution of sodium hydroxide, while the other components of bauxite do not dissolve. This is a standard process employing sodium hydroxide to extract alumina from bauxite at elevated temperatures and pressures in digesters. The solution is approximately 30% NaOH at a temperature between 150 and 230ºC [9].

The resulting liquor consists of a solution of sodium aluminate and undissolved bauxite residues containing iron, silicon and titanium. The slurry is flash cooled and an insoluble residue, known as red mud, is separated from the aluminate liquor. The green liquor is then passed through sand bed filters to be clarified.

The sodium aluminate solution is then pumped to the precipitation stage. The aluminate is further cooled to between 60-75ºC, and fine particles of alumina are added to seed the precipitation of pure alumina particles as the liquor cools. Seed hydrate crystals are added to the solution to increase the growth of alumina hydrate crystals. The precipitate sinks to the bottom of the tank, is settled and filtered off. Finally, the crystals are washed and then calcined in rotary kilns or fluid bed/fluid flash calciners (1050°C) before use or shipping. Although this process is standard across the industry, a variety of different equipment is applied, in particular by considering the digesters and calciners [10].

The production of alumina is highly demanding for raw-materials. Four tonnes of bauxite are required to produce two tonnes of alumina, from which one tonne of primary aluminium can be produced. Hence, two tonnes of waste (red mud) are produced per tonne of aluminium metal. Figure 1 displays that the production of alumina is a complex chemical process.

Aluminium Smelting

Commercial primary aluminium is produced by the electrochemical reduction of alumina. Charles Martin Hall in the United States and Paul Lewis Toussaint Héroult in France independently developed and patented a commercially successful process for alumina reduction in 1886. This process, commonly referred to as the Hall-Héroult process, is still the primary method in use for aluminium production which involves the electrolysis of alumina dissolved in a bath of molten cryolite (Na_3AlF_6) at a temperature of 960ºC [9, 11].

An electric current is passed through the electrolyte at low voltage, but very high current. The electric current between a carbon anode made of petroleum coke and pitch, and a cathode formed by the thick carbon or graphite lining of the pot. Molten aluminium is then deposited at the bottom of the pot.

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

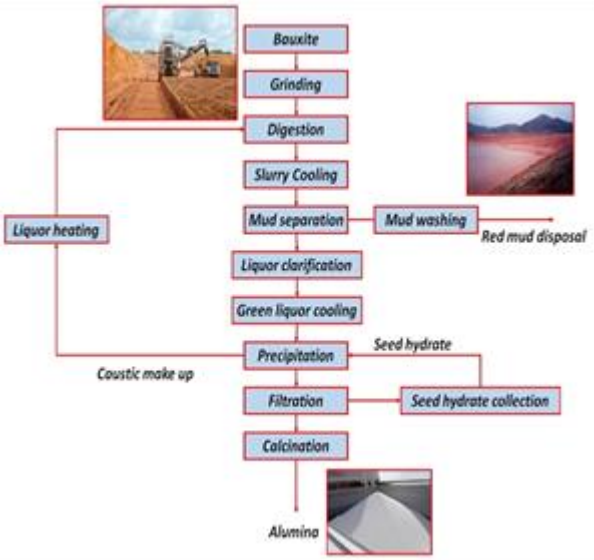


Fig 1- Schematic of the Bayer process

The electrolytic process occurs in steel cells lined with carbon. Carbon electrodes developed into the cell and serve as anodes whereas the carbon lining of the cell is the cathode. An electric current is passed through the bath, which reduces the alumina to form liquid aluminium and oxygen gas. The oxygen gas reacts with the carbon anode to form carbon dioxide. Molten aluminium collects at the cathode in the bottom of the cell and is removed by siphon. The net electrolytic reduction reaction can be written as:

$2\ Al2O3 + 3\ C \rightarrow 4\ Al + 3\ CO2$

The alumina is added to the cells, to keep an alumina content of 2–6 % in the molten bath. A modern plant uses computer controlled additions. To decrease the melting point, industrial cryolite-alumina mixtures also contain various amounts of other salts, such as aluminium fluoride (AlF_3) and calcium fluoride (CaF_2); sometimes lithium carbonate (Li_2CO_3) is present and, less frequently, magnesium fluoride (MgF_2) is introduced. These additions also improve current efficiency and reduce evaporation losses.

Aluminium fluoride (AlF_3) is also added to neutralise the sodium oxide present as an impurity in the alumina feed. The AlF_3 content of the bath is significantly in excess of the cryolite in modern plants. Consequently, fluoride emissions increase as the excess AlF_3 in the bath is increased [12, 13].

Theoretically, for producing each tonne of aluminium, 4 tonnes bauxite, 1390 kg alumina, 13500 KWh electrical energy, 0.5 tonnes of anode coke and small amounts of fluoride salts are generally consumed (Table 1).

Table 1- The major raw material (Kg per Ton of Aluminium) and energy (KWh/t Al) required for one tonne aluminium production.

Bauxite	Alumina	Carbon	Cryolite	Aliminim Fluoride	Energy
4000	1930	415	2	20	13460

Electrolysis plant needs large amounts of electrical energy. Accordingly, besides good bulk transport facilities, abundant inexpensive electric power is necessary. Because hydroelectric power is a relatively inexpensive and clean source of energy, aluminium smelters are mainly built in countries with readily available hydroelectric power, such as Canada,

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

Norway, Venezuela, and Brazil, or in countries with many deposits of low-grade coal such as Australia or the Republic of South Africa (RSA). Furthermore, the same regions lack other local industry to use this energy, and it is infeasible to transport electric power over very long distances to the industrialized regions that could use it. Considering their large energy consumption, aluminium smelters are leading customers that guarantee a stable base load and, thereby, assist to lower their power suppliers' unit costs. At present, hydroelectric and coal sources produce the power for about 90% of world aluminium production, although locating a smelter next to a nuclear power plant can also be economically attractive, as at Dunkerque in France [13]. Figure 2 illustrates an aluminium smelter with its long pot rooms and tall alumina silos.

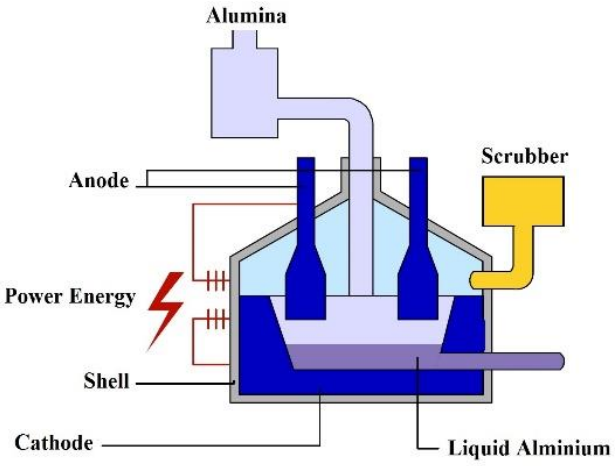


Fig 2- View of the cross-section of an electrolysis

There are two main types of aluminium smelting technologies, known as Prebake and Soderberg. The principal difference between them lies in the type of anode used. Soderberg technology uses a continuous anode delivered to the cell in the form of a paste, and which bakes in the pot itself. On the other hand, prebake technology uses multiple anodes in each cell. These anodes are pre-baked in a separate facility and then suspended in the cell [13].

The prebake technology has two variants referring to how alumina is added, namely, center-worked prebake (Bar broken centre feed (CWPB) and Point centre feed (PFPB)) and side-worked prebake (SWPB). Also, the Soderberg technology has two variants based on how the electricity is presented to the cell, namely, vertical stud Soderberg (VSS) and horizontal stud Soderberg (HSS). All plants built since approximately 1970 are of the prebake type. Soderberg is the oldest technology and is gradually stopped in favor of Prebake technology, which is a more enclosed process. Fugitive emissions are much lower, and are being collected inside the cell and transported to scrubbing systems to remove particulates and gases.

The newest primary aluminium production facilities use a variant on pre-bake technology called PFPB Technology. This technology provides for computer controlled precise alumina feeding through the use of multiple "point feeders" and other automated controls. A key feature of CWPB plants is the enclosed nature of the process. Fugitive emissions from these cells are very low, less than 2% of the generated emissions. The balance of the emissions is collected inside the cell itself and carried away to very efficient scrubbing systems (removing particulates and gases) that return the collected material to the cells. Computer technology controls the process down to the finest detail, which means that occurrence of the anode effect -the condition which causes small quantities of PFC's to be produced- can be minimised. All new plant and most expansion of existing plant are based on pre-bake technology [12].

Figure 3 shows the worldwide smelter technology distribution from 1990 to 2012.

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

Regarding aluminium world production, 37% was produced using Soderberg technology in 1990, 27% in 2001 and 8.5% in 2012. Also it can be seen, 59% and 87% of world primary aluminium production was provided by PFPB in 2001 and 2012, respectively [13].

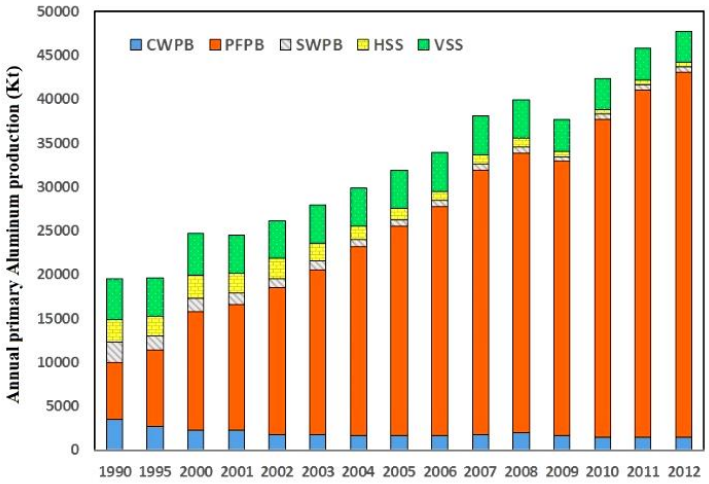


Fig 3- The worldwide primary aluminium smelter technology distribution from 1990 to 2012

After the electrolysis, the metal is refined to remove impurities such as sodium, calcium oxide particles and hydrogen. This refining stage is performed by the injection of a gas into the molten metal usually in an in-line reactor. The treatment gas used varies depending on the impurities.

Slabs, T-bars or billets are cast in vertical direct chill casting machines that use water-cooled metal moulds and a holding table at the bottom part of the moulds. The table is lowered as the ingot is formed. Other casting methods include the use of metal moulds (static or continuously moving), continuous casting of thin sheets and continuous casting of wire rod.

Under the ingot casting technique, molten aluminium metal is poured into separate moulds until the metal solidifies into ingots. This technique consists of uphill and downhill casting. Uphill casting leads to better surface quality due to the usage of casting powder. The quality of products in this process is higher with simultaneous casting of many ingots. Downhill casting, on the other hand, is cheaper but results in lower quality of products and casting rate.

Mould casting can be chiefly subdivided into die and sand casting. Under die casting process, molten aluminium metal is poured into mould cavities under high pressure; the cavities are subsequently machined into dies. The die casting method is especially suited for applications where many small to medium sized parts are needed with a fine surface quality and dimensional consistency.

Sand casting allows smaller batches of products to be made at a reasonable cost. Through this technique, manufacturers benefit from the small size of operations and can create products at a low cost. Sand casting also allows most metals to be cast depending on the type of sand used for the moulds. In addition to this, sand can be recycled many times and requires little maintenance.

Secondary Aluminium Production

A secondary aluminium smelter is defined as any plant or factory in which aluminium-bearing scrap or aluminium-bearing materials, other than aluminium-bearing concentrates (ores) derived from a mining operation, is processed into aluminium alloys for industrial castings and ingots. Energy for secondary refining consumes only about 5 % of that required for primary aluminium production.

The furnace used for melting aluminium scrap depends on the type of scrap and there is a wide variety of scraps and furnaces used. In general for fabrication scrap and cleaner materials, reverbatory and induction furnaces are used. For more contaminated grades of scrap, rotary furnaces, tilting or horizontal furnaces are used.

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

The scrap may also be pre-treated, depending on type of scrap and contamination. Coated scrap, like used beverage cans, is de-coated as an integrated part of the pre-treatment and melting process. The metal is refined either in the holding furnace or in an inline reactor to remove gases and other metals generally in the same way as for primary aluminium. If magnesium needs to be removed, this is done by treatment with chlorine gas mixtures.

World Production of Bauxite and Alumina

According to USGS data, global world bauxite production was 259.42 million metric tons in 2011, with the top 5 bauxite producing countries being Australia (70.0 million metric tons), China (45.0 million metric tons), Brazil (31.0 million metric tons), Indonesia (37.0 million metric tons) and India (19.0 million metric tons) [14]. As Shown in Table 2, the amounts current bauxite reserve is 27800 Mt in 2011. The proportion of the bauxite production and reserve by countries are also presented in this Figures 4 and 5.

World alumina production have increased by 59Mt from 1990 to 2012 (Figure 6). Only three countries produced more than 10 million metric tons of alumina in 2011, with China topping the chart at 35.1 million metric tons, followed by Australia at 19.6 million metric tons and Brazil at 10.3 million metric tons; together, they produced approximately 70% of the world production (98.1 million metric tons).

Table 2- Distribution of world bauxite production, reserves

Country	Bauxite production Mt	Bauxite reserve Mt
Australia	70	6000
China	45	830
Indonesia	37.1	1000
Brazil	31.8	2600
India	19	900
Guinea	17.6	7400
Jamaica	10.2	2000
Russia	5.89	200
Kazakhstan	5.5	160
Venezuela	4.5	320
Suriname	4	580
Greece	2.1	600
Guyana	1.82	850
Sierra Leone	1.46	180
Vietnam	0.6	2100
Others	2.85	2100
Total	259.42	27820

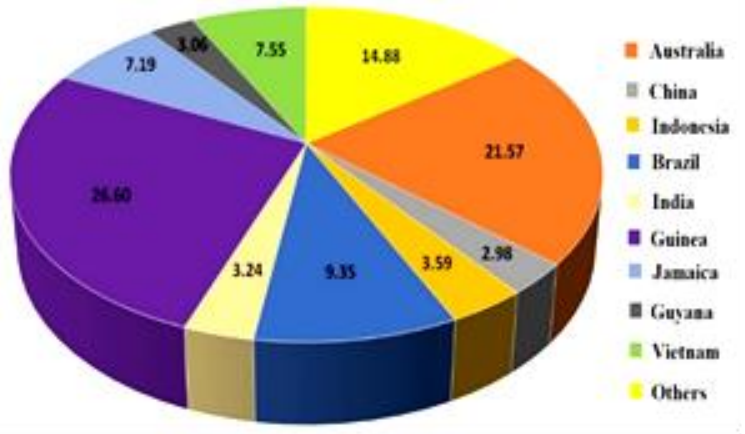


Fig 4- Distribution of bauxite production by country

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

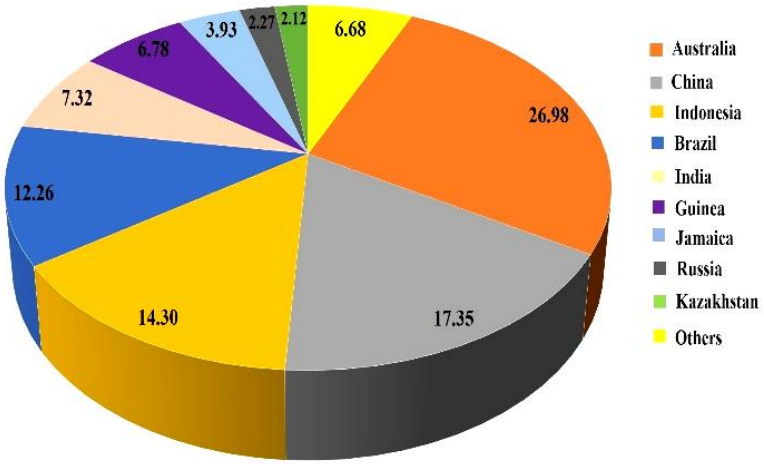


Fig 5- Distribution of bauxite reserves by country

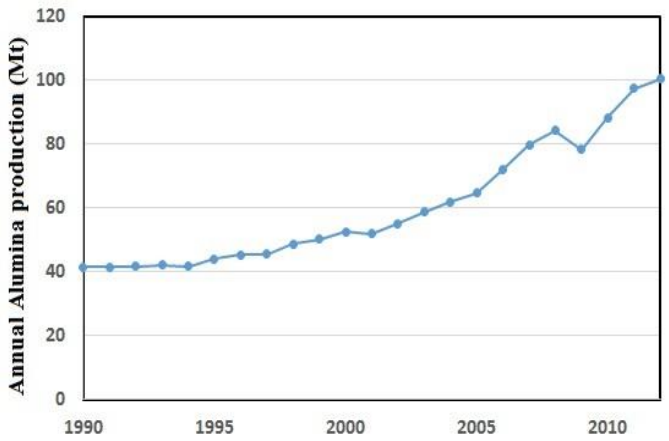


Fig 6- Annual alumina production from 1990 to 2012

Aluminium Production

World primary aluminium production volumes have increased by 50% from 2005 to 2012. New capacities in India, China and Qatar, as well as restarting smelters, let to the increased production. This growth was partially offset by shutdowns primarily in the second half of the year when aluminium prices decreased. Other factors behind these shutdowns were labour disputes, currency fluctuations, electricity price increases, power shortages. The main world producers of aluminium in 2012 were China (45% of the total), CIS (10%), Europe (9%) and North America (10%) traditionally remain important production areas, but regions such as the Middle East and India are emerging as important producers of primary aluminium (Figure 7).

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

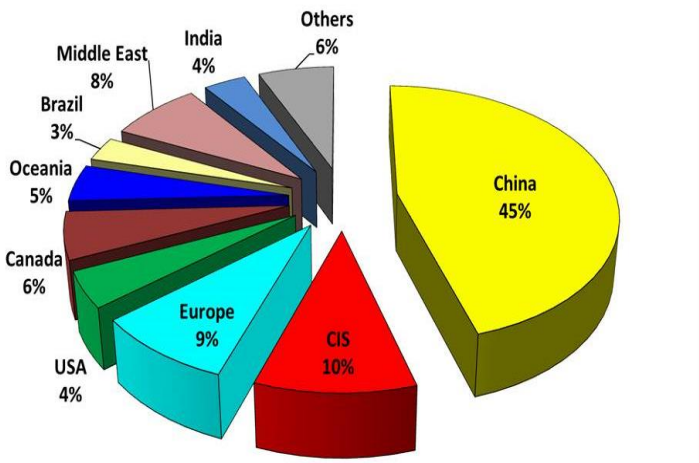


Fig 7- The main world producers of aluminium in 2012

China dominated primary aluminium production with 19.0 million metric tons of aluminium produced in 2012; more than 4.5 times the level of the second largest producing country, Russia (4.2 million metric tons). Global production of primary aluminium was 47.87 million metric tons in 2012.

The principal production countries can be characterised as strong growth in China at a yearly average of 24%, decline in the USA (at -2% per year) since 2000 and the rest little change or slight incline as shown in Figure 8.

The share of primary production in China increased from 12% in 2000 to 23% by 2004 and 45 % by 2012.

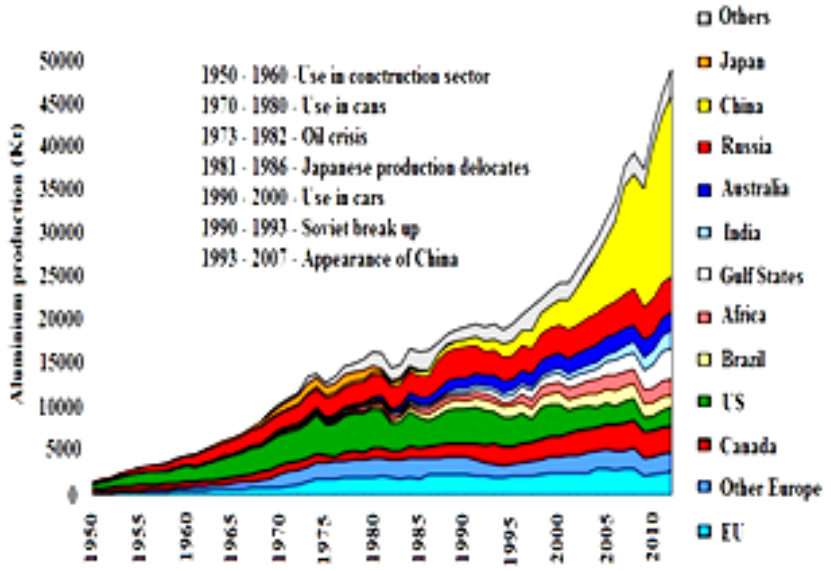


Fig 8- The history of primary aluminium world production, since the 50s.

Aluminium Consumption

Aluminium is a material with a wide range of applications, e.g. transport vehicles, construction, packaging industry, electronic production, household appliances, etc., and consequently the economic activities of these industrial sectors determine the overall demand for aluminium.

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

Consumption of primary aluminium was approximately 32 Mt in 2005, with China taking the largest share of 22% (four times more than the year 1994) followed by the USA and Japan with 20% and 8%, respectively, as details shown in Table 3. Although the share has kept relatively unchanged for most of the principal countries, the relative share of the USA and Japanese markets has decreased sharply by 8 and 4% respectively. Consumption of primary aluminium in the EU- 27 countries has been increasing, annually at around 2%, lower than the growth rate of total aluminium (3%), which implies that the availability of scrap for secondary aluminium is increasing [10].

Table 3- Consumption of primary aluminium and share of countries

Country	1994(kt)	2005(kt)	1994(%)	2005(%)
USA	5557	6360	28	21.3
China	1500	7105	8	22
Japan	2346	2405	12	8
Germany	1370	1846	7	6
Russia	470	940	2	3
South Korea	604	1140	3	4
Canada	559	805	3	3
France	736	810	4	3
India	474	930	2	3
Brazil	414	683	2	2
Oceania	393	415	2	1
Others	5445	8362	27	23.7
Total	19868	31801	100	100

The growth in demand for aluminium is underpinned largely by the rapid development and urbanization of China, which in 2010 accounts for over 40% of global aluminium consumption (that was 39.66 Mt). The other major consumers of aluminium are Japan (5%), US (11%) Germany (5%) India (4%).
Due to considerable growth in demand for aluminium in China, as well as growth recovery in the US, Europe and Japan, global aluminium consumption increased by 6% than the previous year and reached 47.7 million tonnes in 2012. China is the main user of primary aluminium worldwide, with 20.9 Mt (45%) in 2012. Figure 9 presents use of primary aluminium by region in 2012.



Fig 9- The proportion rate of primary aluminium utilization by region in 2012

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

Wide range of aluminium applications in developed and developing countries were shown in Figure 10. In developed countries the demand for aluminium comes mainly from the rapidly growing transport industry, which is driven by an expanding auto market. Mature countries traditionally use more aluminium in the light vehicles production. Because of its lightness, aluminium makes cars more energy efficient, which is in line with the environmental targets, set and adopted by the US, Japan and the EU member countries.

Developing countries are expanding their infrastructure to satisfy the needs of a growing population, migrating to large cities. Therefore, the construction sector represents the biggest consumer of aluminium across developing economies.

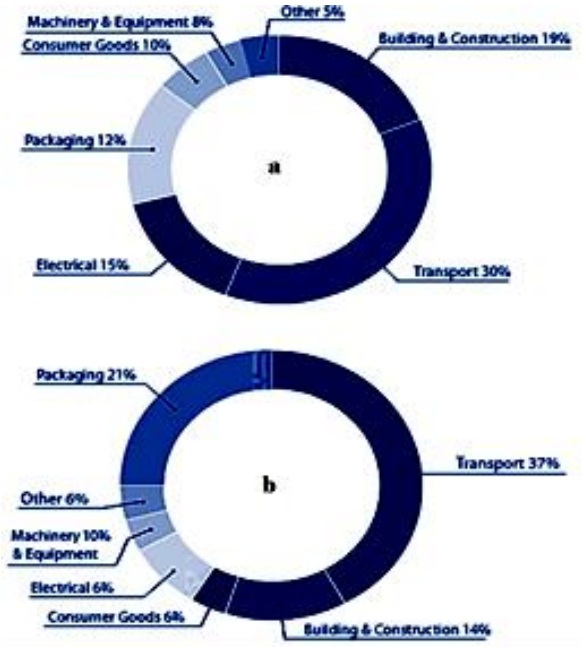


Fig 10- wide range of aluminium applications in developed (a) and developing (b) countries

Energy Consumption

Energy is one of the most important inputs in the process of economic growth and industrial development. The demand for various energy-sources varies across different industries depending on technological progress, extent of economic activities and several other factors.

According to IEA Data Services, World Energy Balances (2007) energy consumption industry share in total industrial sector energy consumption for 2006 was chemicals (29 percent), steel (20 percent), nonmetallic minerals (primarily cement) (10 percent), pulp and paper (6 percent), nonferrous metals (primarily aluminium) (3 percent) and others (32 percent). So 68 percent of the total energy consumed is accounted for by these five industries itself [15].

These industries are heavily energy-intensive and they together account for the largest share in the total industrial demand for energy. The demand for energy in these industries varies according to the techniques used in the production process.

Alumina refining mainly requires thermal energy for bauxite digestion and calcinations, which is reported to be less than 10% of the total energy needed for the entire primary aluminium production route. The process of alumina reduction to aluminium is very electricity intensive. The pot efficiency of majority of the smelters currently ranges between 13 and 16 MWh per tonne of aluminium and this has improved by nearly 100% since 1945 (20-25MWh/t). Secondary aluminium production requires much less energy input, equalling about 5% of that of the

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

whole primary production process (incl. alumina refining) [11].
Figure 11 illustrates the trends in energy use per tonne alumina and aluminium from 1980 to 2012. There has been continuous improvement in energy efficiency of smelting. In the 1980, the world average electricity consumption for primary aluminium production was about 16.95 MWh/tonne, and 2012 improvement 14.63. From 1985 to 1998, energy use in the alumina refining grew by 2000 MJ. Although energy use declined from 1998 to 2004, it increased by 2000 MJ in 2007, finally it decreased by 2500 MJ in 2012.

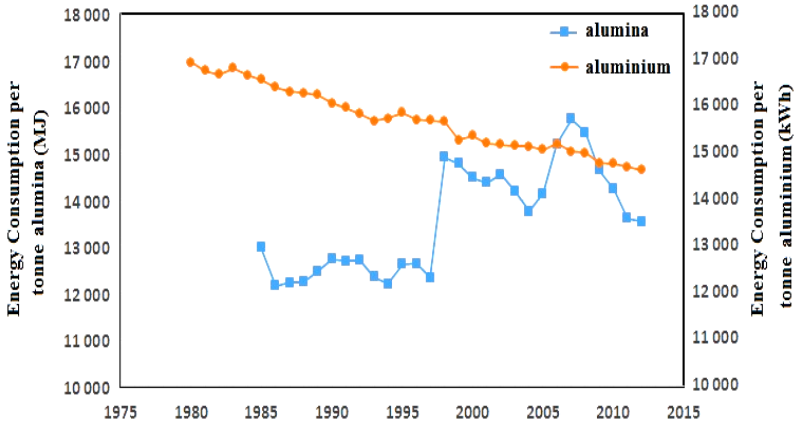


Fig 11- Energy improvement in world primary aluminium and alumina production

Energy consumption per tonne alumina and aluminium production differs somewhat in different regions, due to different technology mixes (Figure 12). The results for some developing countries (such as china) seem energy consumption per tonne aluminium surprisingly low, which is explained by a younger industry and the use of more recent technology for expansion and new capacity.

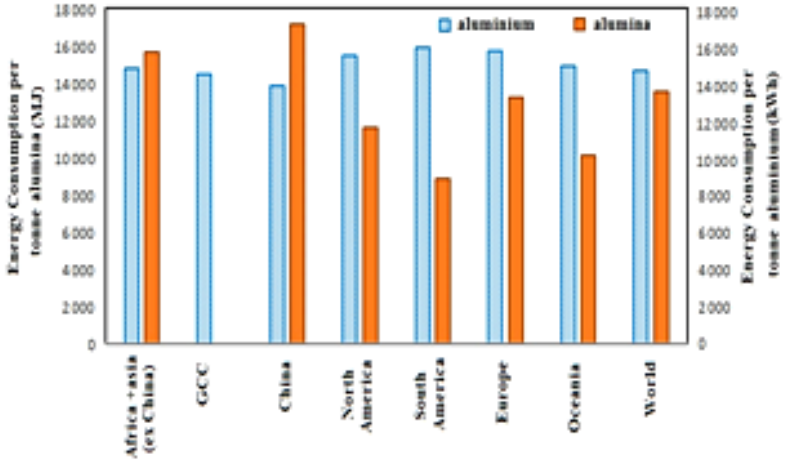


Fig 12- Energy consumption per tonne alumina and aluminium production differs somewhat in different regions

The International Aluminium Institute publishes annual statistics for, among others, consumption of electrical power for primary aluminium production [16]. In statistics for 2012, hydropower is the energy source for 37% and coal 53% of world electrical power in the aluminium industry. Figure 13 shows the energy sources of electrical power used in primary

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

aluminium production in different regions of the world in 2012. Aluminium production is located in areas with access to abundant power sources, like hydropower, coal and natural gas.

Hydropower is the main energy source for aluminium production on the American continent, in Europe, while coal is dominating in Africa, Australia, China and for the world total. Hydropower is far above the world average in certain countries like Brazil, Canada, Norway and Russia (Russia 80% and Norway 100%). It should be noted that the most important energy source of electrical power used in primary aluminium production in the USA, Canada and Europe is hydro and in China and GCC are coal and gas, respectively.

Figure 14 shows the energy sources for alumina refining in different regions of the world in 2012. The alumina refining process requires significantly higher energy, primarily in the form of heat and steam; natural gas, coal and oil are the main fuel sources and are combusted on site. While the energy resources significantly from region to region, overall, coal plays a greatest role as a source of energy in the alumina production, accounting for nearly 49% of the total energy consumed.

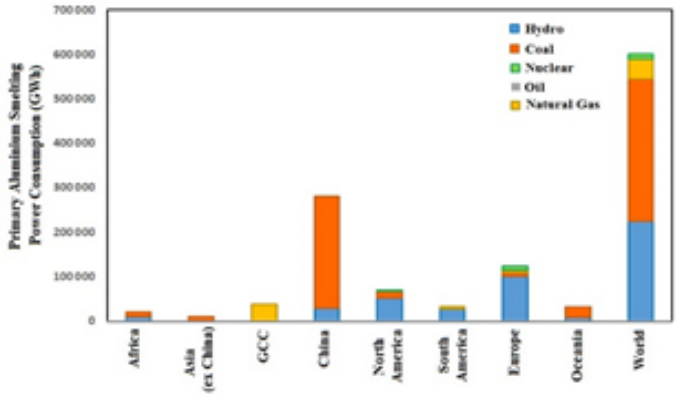


Fig 13- Energy sources for electrical power in primary aluminium production, 2012.

In addition to lower direct emissions from the smelting process, Prebake technology also has lower electricity consumption. The average consumption is approximately 16.6 MWh/tonne for Soderberg technology, while most modern Prebake facilities are as low as 13.3 MWh/tonne, using PFPB technology. Other Prebake technologies have slightly higher electricity consumption, like CWPB and SWPB.

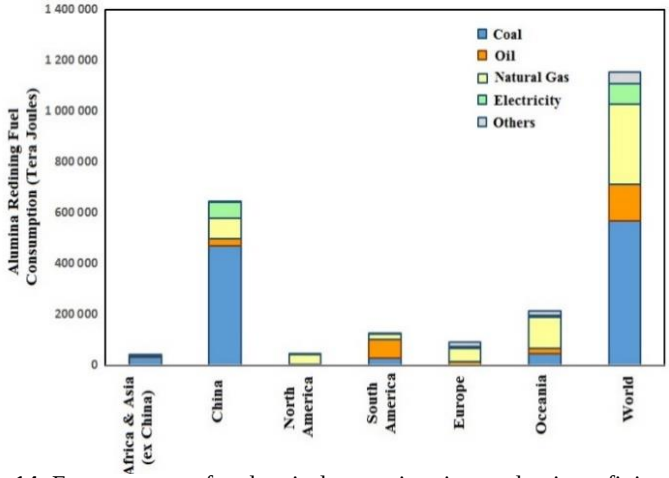


Fig 14- Energy sources for electrical power in primary alumina refining, 2012.

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

Greenhouse Gases (GHG) Emission

In 1995, about 1% of worldwide energy related CO_2 emissions were caused by the production of primary aluminium [17]. Emissions of greenhouse gases are mainly related to the smelting process. Primary aluminium production has been identified as a major anthropogenic source of two per fluorocarbon compounds (PFCs), tetra fluoromethane (CF_4) and hexa fluoroethane (C_2F_6). These compounds are very potent global warm- ing gases with long atmospheric lifetimes.

Emission intensity of (CF_4) is approximately ten times that of (C_2F_6). No measurable amounts of these compounds are generated during normal operating conditions, but forms during brief upsets conditions when the level of aluminium oxide in the electrolytic cell drops too low and the electrolytic bath itself begins to undergo electrolysis. These effects are known as "anode effects", and PFC emissions are directly proportional to anode effect intensity.

The International Aluminium Institute carries out annual surveys of PFC emissions for the purpose of tracking and inducing improvements, as well as for benchmarking between individual plants. Table 4 shows the worldwide improvement in PFC emissions from aluminium smelting in the period 1990 to 2012.

Table 4- Worldwide emissions of GHG from aluminium smelting

Year	CF_4 (Gg)	C_2F_6 (Gg)	PFC (kt CO_2e)	Mean PFC intensity (t CO_2e/t Al)
1990	11	1.52	87387	4.48
2000	6.273	0.875	48781	1.98
2012	3.78	0.275	27092	0.57

PFC emission intensities vary considerably for different technologies as well as for individual plants, with Prebake technology performing significantly better than Soderberg type plants. Table 5 presents improvements in specific PFC emissions for different smelting technologies in the period 2000 to 2012.

Table 5- Technology specific emissions of PFC compounds (kg/tonne) and total emissions (tonnes) [11].

Year	CWPB	PFPB*	PFPB**	SWPB	HSS	VSS
CF_4 emissions (Gg CF_4)						
2000	0.418	1.043	0.11	2.087	0.746	1.878
2012	0.036	0.625	2.215	0.264	0.131	0.58
C_2F_6 emissions (Gg C_2F_6)						
2000	0.051	0.131	0.004	0.526	0.063	0.1
2012	0.005	0.067	0.095	0.064	0.013	0.031
PFC emissions (kt CO_2e)						
2000	3180	7944	696	18405	5431	13126
2012	285	4663	15285	2301	975	3582
Mean PFC emissions intensity (t CO_2e/t Al)						
2000	1.44	0.64	0.69	12	2.01	2.8
2012	0.19	0.24	0.69	3.8	1.8	1

*(Non China)
** (China)

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

Prebake technologies have the largest improvements in PFC emission intensity, especially the PFPB technology which is the present state of the art technology.
Soderberg technology is being phased out, and emissions reductions are not very considerable.
Emissions of PFCs could eventually be eliminated in the future, by the introduction of inert anodes and replacement of carbon anodes.
Specific emissions from aluminium production are expected to decrease in the future, and there are three main reasons for this [17]:

- Lower CO_2 and PFC emission rates for electricity generated from fossil fuels,
- Replacement of old Soderberg plants with more energy efficient PFPB technology,
- The production of primary aluminium is being shifted to regions with larger share of electricity production relying on hydropower.

Conclusion

Primary aluminum is produced by means of electrolytic reduction of alumina. This paper describes the complete process of primary and secondary aluminum production consecutively. Also, covers the history of bauxite, alumina, aluminum production and consumption of aluminum at global and regional from 1980 to 2012.
Both primary and secondary aluminum productions are growing, with the strongest growth taking place in China, due to its recent strong economic improvements. Due to considerable growth in demand for aluminum in China, as well as growth recovery in the US, Europe and Japan, global aluminum consumption increased by 6% relative to the previous year and reached 47.7 million tonnes in 2012.
The history and explanation of current state of the art technologies and practices are presented so the reader can appreciate the values and benefits that new technologies or practices might bring to the aluminum industry.
Energy consumption and environmental implications development (in particular emissions of CO_2 and PFC compounds) in aluminum producing industry are discussed, as well as aspects of future trends.
Environmental implications from aluminum production are mainly related to the smelting process. Results show that considerate reductions in PFC emissions are recorded for the past decade, due to phase out of old technology and improvements in existing ones. CO_2 emissions have also decreased, these emissions being strongly dependent on electricity consumption and the energy carrier mix present in the different regions.

References

1- **C. Nappi**, "The Global Aluminium Industry 40 years from 1972", world-aluminium (www.thealuminiumstory.c om), February 2013.
2- **G. Switkes**, "Foiling the Aluminium Industry", International Rivers Network, 2005.
3- **A. Steinfeld**, "High-temperature Solar Thermochemistry for CO_2 Mitigation in the Extractive Metallurgical Industry", *Energy* 22 (1997), 311–6.
4- **L. G. Mason**, Focus on Hazardous Materials Research, Chapter 3: Red Mud and Paper Mill Sludge Treatment and Reuse for the Recovery of Contaminated Soils, Sediments and Waters: A focus on latest trends, Nova Science Publishers, 2007, 77-142
5- **D. Dimas, I. P. Gianopoulou, D. Panias,** "Utilization of Alumina Red Mud for Synthesis of Inorganic Polymeric Materials", *Mineral Processing and Extractive Metallurgy Review* 30 (2009), 1-29.
6- **G, Xueyi, S. Yu,** "Substance Flow Analysis of Copper in China", *Resour Conserv Recycl* 52 (2008), 874–82.
7- **T. Wang, D. B. Muller, T. E.** Graedel, "Forging the Anthropogenic Iron Cycle", *Environ Sci Technol* 41 (2007), 5120-9.
8- **K. Reclade, J. Wang, T. E. Graedel,** "Aluminium in Use Stocks in the State of Connecticut", *Resour Conserv Recycl* 52 (2008), 1271–82.
9- Industrial Technologies Program Energy Efficiency and Renewable Energy U.S. Department of Energy "U.S. Energy Requirements for Aluminium Production Historical Perspective, Theoretical Limits and Current Practices". February 2007.
10- A. R. Burkin, Production of Aluminium and Alumina, John Wiley & Sons, 1987.

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]

11- European Commission Joint Research Centre Institute for Prospective Technological Studies "Prospective Study of the World Aluminium Industry", *Printed in Spain*, 2008.
12- **H. S. Ray, B. P.** Singh, Energy in Minerals and Metallurgical Industries Allied Publishers, 2005.
13- European Aluminium Association. Production process. Available from: ⟨http://www.world aluminium.org/statistics)
14- U.S. Department of the Interior. U.S. Geological survey. Technical report, U.S. Department of the Interior, http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/index.html, 2011.
15- **M. Dutta, S. Mukherjee**, "An Outlook into Energy Consumption in Large Scale Industries in India: The Cases of Steel, Aluminium and Cement" *Energy Policy* 38 (2010) 7286–7298.
16- International Aluminium Institute. "Electrical Power Used in Primary Aluminium Production. Technical Report, International Aluminium Institute", London, 2003
17- **H. G. Schwarz, S. Briem, and P. Zapp.** "Future Carbon Dioxide Emissions in the Global Material Flow of Primary Aluminium", *Energy*, 2000.

Technology Development, Energy Consumption, Greenhouse Gases Emission and Environmental Pollution in Aluminium Industries

Fardis Nakhaei*[1], Mehdi Iranajad[2]

[1]Ph.D student, Department of Mining & Metallurgical Engineering, Amirkabir University of Technology Tehran, Iran.
[2]Associated professor, Department of Mining & Metallurgical Engineering, Amirkabir University of Technology Tehran, Iran.

iranajad@aut.ac.ir

Abstract

Aluminium is the world's second most-used metal after steel and the aluminium production industry is the largest, in volume of metal produced, in non-ferrous metal industry. In this study, results of the material flows (country and global scales) related to the production and use of aluminium and energy consumption in 1980 to 2012 were separately analysed. Also, overview of the current status of the aluminium industry, including the processes of bauxite mining, alumina refining and smelting, and the key economic and environmental issues were explained. Development in the aluminium producing industry, consumption and environmental implications, as well as identifying the alternative and future technologies that will impact the industry were discussed. Finally, some suggestions for the reduction of energy consumption in different stages were made. These analyses implied that world's primary aluminium (made from bauxite) production has increased from 19.51 million tonnes metric in 1990 to 47.78 million tonnes metric in the year 2012. The production of world alumina also raised from 41.4 to 100.5 million tonnes metric at the same time, whereas secondary aluminium (made from fabrication and post-consumer scrap) produced another 16 million tonnes in 2012. Primary aluminium production is associated with serious environmental problems including high energy demand, substantial GHG emissions and solid waste generation. So that, it consumes about 1% of the globally produced electric energy and about 7% of the total energy consumed by industry worldwide and it is responsible for the 2.5% of the world's CO_2-equivalent emissions. The findings of the study revealed that due to the use of recent technologies, the average of electrical power consumption in the primary aluminium production declined per tonne from 16.9 MWh in 1990 to 14.6 MWh in 2012. The average of specific energy consumption for alumina refining was around 13.534 and 14.5 GJ per tonne in 2012 and 2000 respectively.

Keywords: Aluminium, Bauxite, Energy Consumption, GHG Emissions

[Downloaded from journalofbiosafety.ir on 2026-11-12]

[DOR: 20.1001.1.27170632.1396.10.3.2.5]