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Abstract

Aluminium resources are abundant and will cover the world demand for several hundred years. Production of primary aluminium is increasing worldwide, and the same holds for secondary aluminium, at an even higher rate. Aluminium stocks in products have been growing, and a shift towards more reliance on and better utilization of these is taking place as more of these resources are returned from products ending their lifetime. Bauxite, alumina and aluminium production and consumption are described, and future primary aluminium demand projected for the next decades, showing strong growth in most parts of the world. Environmental implications from processes involved in aluminium production are discussed, in particular emissions of CO_2 and PFC compunds, which are both reduced in terms of specific emissions.

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Chapter 1

Introduction

Aluminium compounds make up 7,3% of the earth's crust, making it the third most common crustal element and the most common crustal metal on earth. Aluminium was first produced in 1808. There are three main steps in the process of aluminium production. First is the mining of aluminium ore, most commonly bauxite, referred to as bauxite mining. Second is the refining of bauxite into aluminium oxide trihydrate (Al_2O_3), known as alumina, and third is the electrolytically reduction of alumina into metallic aluminium. The process requires approximately two to three tonnes of bauxite for the production of one tonne of alumina, and in turn, approximately two tonnes of alumina is required for making one tonne of aluminium.

Primary aluminium possesses a range of favorable material properties, making it attractive for a multitude of applications. These properties are not lost during recycling, and combined with low recycling costs and reduced environmental stress, secondary aluminium is also a very attractive material.

Development in the aluminium producing industry, consumption and environmental implications are discussed, as well as aspects of future trends. This also includes the preceding processes of bauxite mining and alumina refining. Each of these process steps are described consecutively.

Chapter 2

Bauxite mining

Aluminium is the third most abundant element in the earth's crust, but because of its chemical reactivity it is never found pure in nature, but always in oxidized form. There are three main variants of bauxite, each containing hydrated forms of aluminium oxide. The variants depend on the number of molecules of water of hydration and the crystalline structure, and are known as gibbsite, böhmite and diaspore. The former exists in trihydrate form, as opposed to monohydrate for the other, and is currently the most dominant form being mined. Trihydrate forms contain approximately 50% alumina by weight [13].

2.1 Bauxite production

Bauxite mining takes place in four main climate groups. According to 1998 figures, the distribution was; Tropical 48%, Mediterranean 39%, Subtropical 13% and Temperate 0.5%. In the U.S. Geological Survey of 2004, world bauxite reserves presently economically extractable are estimated to 23bn tonnes. The distribution of reserves and potential reserve base are shown in Table 2.1, along with bauxite production figures. World estimates of bauxite reserve base have roughly doubled every ten years for the last fifty years.

Table 2.1: Distribution of world bauxite production, reserves and reserve base (10e3 tonnes) [26].

	Mine production		*Reserves*	*Reserve base*
	2002	2003		
United States	NA	NA	20,000	40,000
Australia	54,000	55,000	4,400,000	8,700,000
Brazil	13,900	13,500	1,900,000	2,500,000
China	12,000	12,000	700,000	2,300,000
Guinea	15,700	16,000	7,400,000	8,600,000
Guyana	2,000	1,500	700,000	900,000
India	9,270	9,000	770,000	1,400,000
Jamaica	13,100	13,400	2,000,000	2,500,000
Russia	3,800	3,800	200,000	250,000

	Mine production 2002	2003	*Reserves*	*Reserve base*
Suriname	4,500	4,500	580,000	600,000
Venezuela	5,000	5,000	320,000	350,000
Other countries	11,200	10,700	4,300,000	5,000,000
World total	144,000	144,000	23,000,000	33,000,000

The bauxite reserves are substantial, and the known reserves of high quality bauxite from which most of the aluminium is produced, are sufficient to provide over 300 years supply. The major bauxite deposits are found in the Tropics and in the Caribbean and Mediterranean regions [16].

Bauxite is found in four different types of deposit; blanket, pocket, interlayered and detrital. Blanket deposits are flat layers lying near the surface. They can be very large and cover many kilometers, with a thickness ranging from less than a meter to forty meters. The average thickness is four to six meters. Pocket deposits are depressions in which the bauxite is found, with their depth ranging from less than one meter to more than thirty. The pockets may be isolated or overlapping each other to compose a large deposit. Interlayered deposits originally existed at the surface, and are more compact due to the additional weight of the overburden. Detrital deposits are formed by the erosion, transportation and redeposition of material from the other three types of deposits. Most mining locations are presently situated in the Caribbean area, South America, Australia and Africa [13]. Figure 2.1 illustrates this by showing different regions share of world bauxite production.

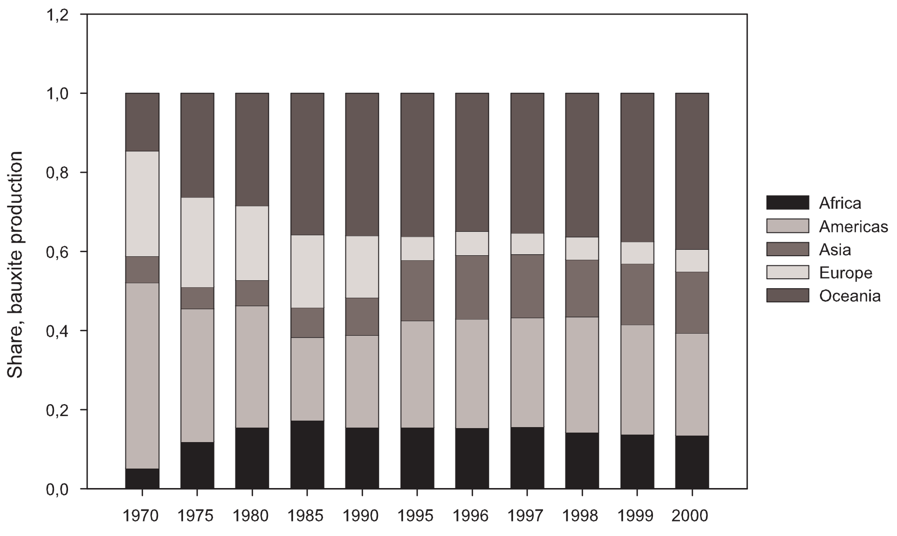


Figure 2.1: Different regions share of world bauxite production[25].

The world mine production of bauxite was 145,672 million tonnes in 2001, with Australia, Guinea, Brazil, Jamaica and China as the top five producers in ranked order [28]. Surface mining accounts for approximately 90% of world bauxite production, the remaining is extracted from deposits located on depths ten meters and more below the surface. Annual mine production capacity ranges from 50,000 tonnes to more than 1 million tonnes. Small scale operations are found mainly in India and Brazil, while 80% of western world's mines have capacities greater than 500,000 tonnes per year [19].

A survey performed by the International Aluminium Institute in 1998 showed that exporting bauxite mines generated about US$1.4m in revenue per hectare mined, and that a typical mine employed about 200 people for each million tonnes per year, or 11 employees per hectare mined [9]. World average costs of mining were estimated to US$^{1995}15/$t_{Output}$, distributed on 43% labor costs, 46% operating costs and 11% energy costs [24].

2.2 Bauxite mining - Environmental impacts

Bauxite reserves are substantial, as seen from Table 2.1. Still it contributes to resource depletion, although at a rate which should decrease with time as more aluminium is released from product stocks and recycled into new products. A more immediate impact is land use and habitat disturbance. Approximately 90% of bauxite mining is related to surface mining, requiring removal of topsoil. Today, this topsoil is usually removed and stored for later mine rehabilitation. The area disturbed by bauxite mining increased by 14% to 1,591 hectares from 1991 to 1998, with 80% being wildlife habitat. Currently, the annual mine rehabilitation rate is 1,256 hectares, which corresponds to 79% of annual disturbance. In the same period, efficiency increased from producing an annual output of 52 thousand tonnes to 56.5 thousand tonnes. Table 2.2 shows rehabilitation land use, based on the International Aluminium Institute's study on bauxite mine rehabilitation from 1998 [9].

Table 2.2: Rehabilitated mine use (1998) [9].

Land Use	*Share*
Native forest	70%
Pasture and agriculture	17%
Urban development	7%
Commercial forest	3%
Other	3%

The results are based on mining locations covering 72% of total bauxite production, and show that 70% is rehabilitated to native forest and 7% to urban and industrial development, housing and recreational purposes.

Chapter 3

Alumina refining

Producing alumina (Al_2O_3) from bauxite uses a process called the Bayer process for the refining into alumina. A flow chart for this process is displayed in Figure 3.1 [17].

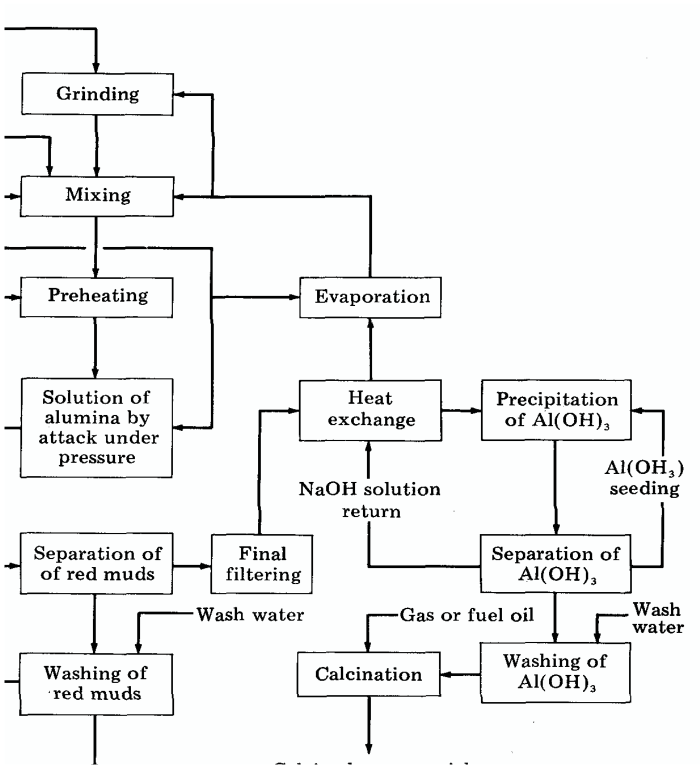


Figure 3.1: Flow chart for the Bayer process [17].

Bauxite is first washed, ground and dissolved in caustic soda (sodium hydroxide) at high pressure and temperature. This becomes a liquid containing a solution of sodium aluminate and undissolved bauxite residues containing iron, silicon and titanium. Gradually, these residues sink to the bottom of the tank where they are removed. These residues are known as "red mud". The resulting clear sodium aluminate solution is fed to a precipitator to extract particles of pure alumina. These are further passed through a rotary or calciner to drive off chemically combined water. A white powder of pure alumina is the end result [13].

3.1 Alumina production

The largest share of world alumina production is found in Australia, Europe and on the American continent, as displayed in Figure 3.2. As for bauxite production, Australia is by far the largest single producer.

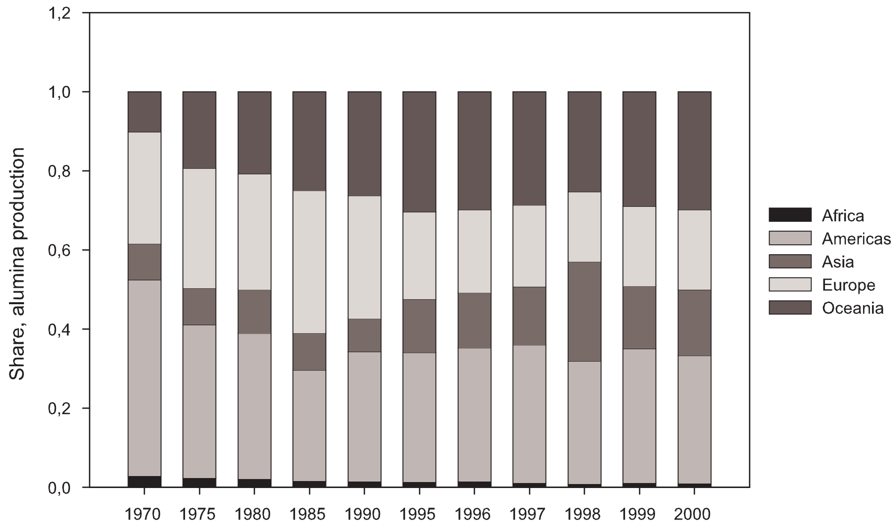


Figure 3.2: Different regions share of world alumina production [25].

Costs of refining bauxite into alumina is ten times that of mining bauxite, at US$^{1995}150/t$_{Output}$. Table 3.1 shows distribution of operating costs as well as investment costs.

Table 3.1: World average operation and investment costs for alumina refining, in US$^{1995}/t$_{Output}$ [24].

Total operating costs	
Bauxite	34%
Labor	13%
Electricity	3%
Other energy	22%
Caustic soda	13%
Other operating costs	15%
Capital costs	
Upgrading	$16 – $24
Brownfield expansion	$35
Greenfield expansion	$70

With regards to operating costs, 59% are related to energy costs and raw material costs. Only 12% of energy costs are from electricity.

Alumina production facilities are found in all parts of the world. For alumina production capacity and production, the main regions are the Americas and Oceania, as shown in Figure 3.3.

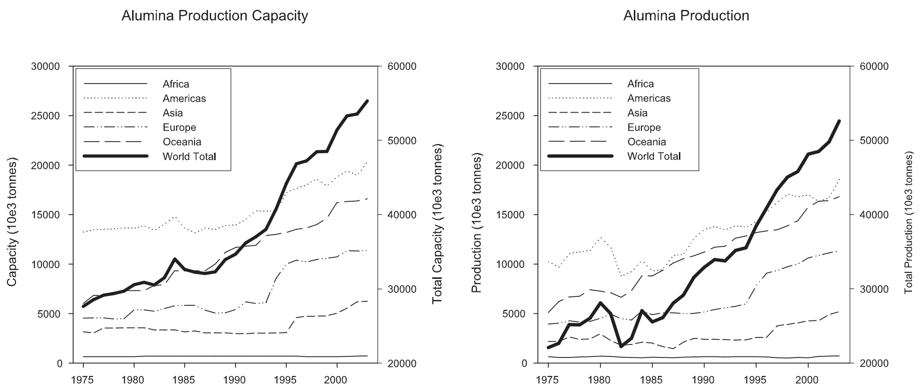


Figure 3.3: World alumina production capacity and production volumes [25], [28], [14].

The largest alumina producers are Australia, China, United States, Jamaica and Brazil, in ranked order. Together these countries' alumina production compounded 60% of world alumina supply in 2002 [28]. As can be seen from Figure 3.3, world alumina production volume and capacity have been growing steadily for the last three decades, with the exception of a short decline in production for the first years of the 1980s. The same main trends are shown for the three most important regions, while the African continent has shown little signs of growth, and the same applies to Asia until the mid 1990s. The recent growth in Asian alumina production is mainly due to rapid growth in the Chinese industry. The case of present Chinese growth will be further discussed later.

3.2 Alumina refining - Environmental impacts

In 1998, the International Aluminium Institute initiated a project for collection of life cycle inventory for the production of primary aluminium, and the results were presented in a report in 2003 [15]. The survey coverage represented approximately 60% of world primary production, with China and Russia being the largest sources of lacking information. Main inventory results for alumina production is found in Table 3.2 [15].

Table 3.2: Alumina refining inventory for world average production of 1,925 kg alumina (in order to produce 1 tonne of primary aluminium) [15].

Input	*Alumina Refining*	*Unit*
RawMaterials		
Bauxite	5,168	kg
Caustic Soda	159	kg
Calcined Lime	86	kg
Fresh Water	6.4	m^3
Sea Water	6.5	m^3
Fuels and Electricity		
Coal	185	kg
Diesel Oil	1.2	kg
Heavy Oil	221.4	kg
Natural Gas	233	m^3
Electricity	203	kWh
Output	*Alumina Refining*	*Unit*
Air Emissions		
Particulates	1.2	kg
CO_2-equivalents	1,908	kg
NO_x (as NO_2)	2.24	kg
SO_2	10.2	kg
Mercury	0.00020	kg
Water Emissions		
Fresh Water	6.4	m^3
Sea Water	6.6	m^3
Oil/Grease	0.13	kg
Suspended Solids	1.43	kg
Mercury	0.0018	kg
By − products for external recycling		
Bauxite residue	2.3	kg
Other by-products	3.5	kg
Solid Waste		
Bauxite Residue (red mud)	1,905	kg
Other Landfill Wastes	47.5	kg

Amounts of inputs and outputs in Table 3.2 correspond, on average, to the production of one tonne of primary aluminium, hence the extraction of 5,168 kg of bauxite is needed to produce this amount of primary aluminium. Caustic soda and calcined lime are used as input reactants, and water as a cooling agent. The alumina refining is not very electricity intensive, but relies of consumption of fossil fuels like coal, heavy oil and natural gas, which combined account for nearly 80% of CO_2-emissions. Bauxite residues, known as red mud, are substantial. The amounts generated varies greatly, depending on the type of bauxite used, as do its chemical and physical properties. The figure presented in Table 3.2 is the average value. Table 3.3 demonstrates the range in chemical composition that can be found in residues from different types of bauxite [13].

Table 3.3: Range of chemical composition in bauxite residues [13].

Component	*Range*
Fe_2O_3	30 – 60%
Al_2O_3	10 – 20%
SiO_2	3 – 50%
Na_2O	2 – 10%
CaO	2 – 8%
TiO_2	Trace - 10%

Apart from alkalinity imparted by liquids in the refining, the residues are regarded as chemically stable and non-toxic, most often disposed of on land. Once these sites are decommissioned they can be used to grow crops or other vegetation [13].

Chapter 4

Aluminium smelting

The process used in modern primary aluminium smelting is based on the Hall-Héroult Process. Alumina is dissolved in an electrolytic bath of molten cryolite (sodium aluminium fluoride) within a large carbon or graphite lined steel pot (cell). An electric current is passed through the electrolyte at low voltage, but very high current. The electric current flows 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 [13].

4.1 Technology

All modern primary aluminium smelting plants are based on the Hall-Héroult process, invented in 1886. Alumina is reduced into aluminium in electrolytic cells, or pots. The pot consists of a carbon block (anode), formed by a mixture of coke and pitch, and a steel box lined with carbon (cathode). An electrolyte consisting of cryolite (Na_3AlF_6) lies between the anode and the cathode. Other compounds are also added, among those are aluminium fluoride and calcium fluoride. The latter to lower the electrolyte's freezing point. This mixture is heated to approximately 980 C. At this point the electrolyte melts and refined alumina is added. Reduction of aluminium ions produce molten aluminium metal at the cathode and oxygen at the anode, which react with the carbon anode itself to produce CO_2. This process is shown in Equation 4.1.

$$2Al_2O_3 + 3C - - > 4Al + 3CO_2 \tag{4.1}$$

There are two main types of aluminium smelting technologies, known as Prebake and Söderberg. The principal difference between them are the type of anode used. Söderberg technology uses a continuous anode which is delivered to the cell in the form of a paste, and which bakes in the pot itself. Prebake technology, on the other hand, uses multiple anodes in each cell. These anodes are pre-baked

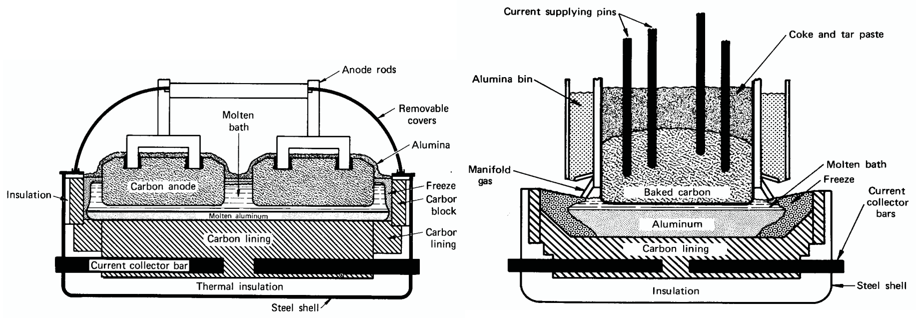


Figure 4.1: Illustrations of Prebake (left) and Söderberg (right) cells for aluminium smelting [17].

in a separate facility and then suspended in the cell [13]. Figure 4.1 shows an illustration of a Prebake and a Söderberg cell [17].

Söderberg is the oldest technology and is being phased out 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. All new plants and most plant expansions are using Prebake technology [13]. Regarding world production, 27% was produced using Söderberg technology in 2001 [12]. Energy represents about 25% of the costs associated with primary aluminium production, so the higher electricity consumption of Söderberg plants make upgrading economically attractive as well as lowering the indirect emissions caused by electricity production [16], [24]. Table 4.1 shows the worldwide smelter technology distribution as of 2001 [12].

Table 4.1: Technology distribution of worldwide primary aluminium production [12].

Technology	*Prebake*	*Söderberg*
PFPB (Point Feeder Prebake)	58%	
CWPB (Center Work Prebake)	9%	
SWPB (Side Work Prebake)	6%	
HSS (Horizontal Stud Söderberg)		9%
VSS (Vertical Stud Söderberg)		18%
Total	73%	27%

As can be seen from Table 4.1, 73% of world primary aluminium capacity was provided by Prebake technology in 2001.

4.2 Electricity consumption

In addition to lower direct emissions from the smelting process, Prebake technology also has lower electricity consumption. Being a very energy intensive industry, lowering the consumption for the smelting process is important for the industry, knowing that approximately 96% of electricity consumption for producing primary aluminium is related to this process (approximately 3% for alumina and 0.6% for bauxite mining) [24].

The average consumption is approximately 16.6 MWh/tonne for Söderberg 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. Table 4.2 contains an overview of electricity consumption for different smelting technologies [24].

Table 4.2: Electricity consumption in aluminium smelting (MWh_{el}/t_{output}) [24].

Technology	MWh_{el}/t_{output}
Söderberg	16.6
CWPB	15.5
SWPB	14.6
PFPB	14.4
All existing plants 1995	15.5
Upgrading and brownfield expansion	
PFPB	13.8
Greenfield expansion	
PFPB	13.3

Electricity consumption from smelting plants in Table 4.2 are in compliance with present estimates. The International Aluminium Institute estimates the average world consumption to be 15.7 MWh/tonne [13], while an LCI-study performed on behalf of the same organization finds it to be 15.4 MWh/tonne [15], and their statistics collected from members (comprising 75% of world primary aluminium production) suggest 15.2 MWh/tonne [14]. Electricity consumption differs somewhat in different regions, due to different technology mixes. Electricity consumption by region is shown in Table 4.3 for 2002 [14].

Table 4.3: Electricity consumption for primary aluminium production in different regions (MWh_{el}/t_{output}) [14].

Region	MWh_{el}/t_{output}
Africa	14.6
Americas	15.2
Asia	15.4
Europe	15.4
Oceania	14.5

The results for some developing countries seem surprisingly low, which is explained by a younger industry and the use of more recent technology for expansion and new capacity [16].

There has been continuous improvement in energy efficiency of smelting. In the 1950's the world average electricity consumption for primary aluminium production was about 21 MWh/tonne, and the last two decade's improvement is shown in Figure 4.2, [13], [14].

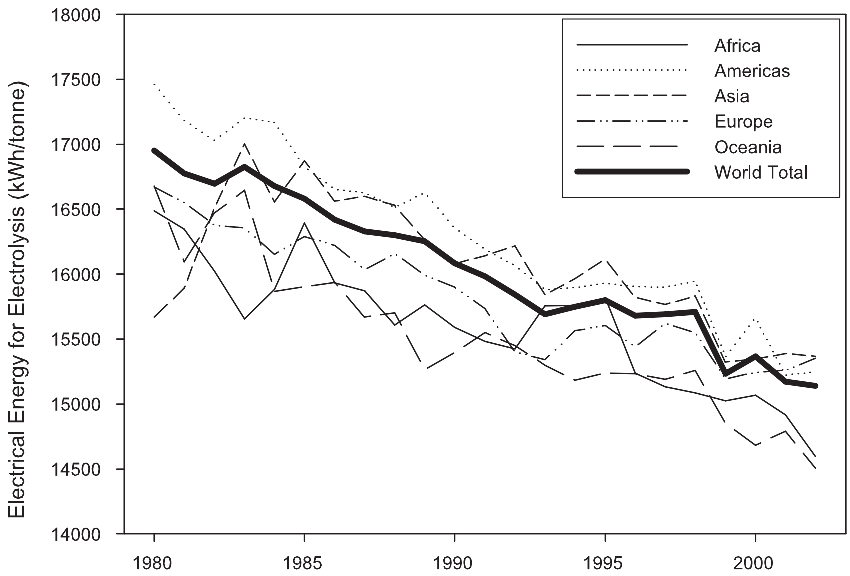


Figure 4.2: Energy efficiency improvement in world primary aluminium production [14].

The world average electricity consumption for production decreased from about 17 MWh/tonne in 1980 to 15.2 MWh/tonne aluminium output in 2002, with Europe and Asia having the lowest efficiency due to older technology.

Aluminium production is located in areas with access to abundant power resources, like hydropower, coal and natural gas. The International Aluminium Institute publishes annual statistics for, among others, consumption of electrical power for primary aluminum production [14]. In statistics for 2002, hydropower is the energy source for 50% of world electrical power in the aluminium industry. Figure 4.3 shows the energy sources of electrical power used in primary aluminium production in different regions of the world in 2002.

Hydropower is the main energy source for aluminium production on the American continent, in Europe and for the world total, while coal is dominating in Africa and Australia. Hydropower is far above the world average in certain countries like Brazil, Canada, Norway and Russia (Russia 80% and Norway 100%) [16].

4.3 Aluminium production

Ranking of the main primary aluminium producing countries have changed since the mid 90's, with China, Russia and Canada surpassing The United States as the biggest producer. China is presently the largest producer, followed by Russia and Canada. The United States and Canada presently produce about the same

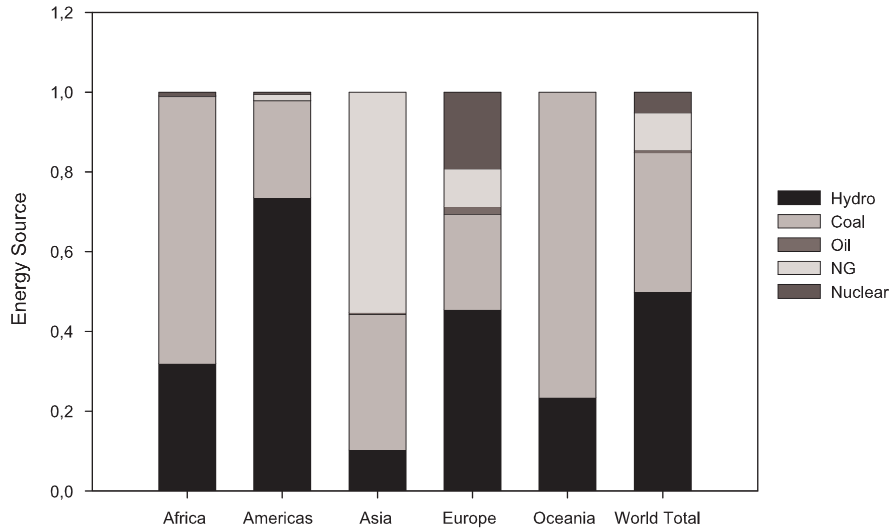


Figure 4.3: Energy sources for electrical power in primary aluminium production, 2002[14].

annual output, but while Canada has a positive growth the opposite is the fact for The United States. Together with the next three countries, Australia, Brazil and Norway, these constitute 67% of world production output, all of them with seven figured annual production rates. Norway is the smallest of these with an annual output of approximately 1,150 tonnes in 2003 [25]. Primary aluminium production is shown in Figure 4.4 for different regions as well as world total.

From Figure 4.4, Europe has surpassed the American continent and is presently the main region for aluminium production. However, looking at the growth rates, Asia will surely change this and become the largest producer, with China being responsible for this rapid growth. The importance of China's growth is reflected in the curve for total world production, showing a similar form to that of Asia.

4.4 Aluminium consumption

Aluminium is presently the second most commonly used metal and new areas of application raise the consumption, as do increased use in existing applications. Figure 4.5 displays primary aluminium consumption by end use for the Western World and for the world in total.

Both the world total and the western world consumption pattern show approximately the same distribution, due to the western world's dominant share of total primary aluminium consumption, with countries classified as developed countries accounting for nearly 75% of world consumption [25]. The consumption

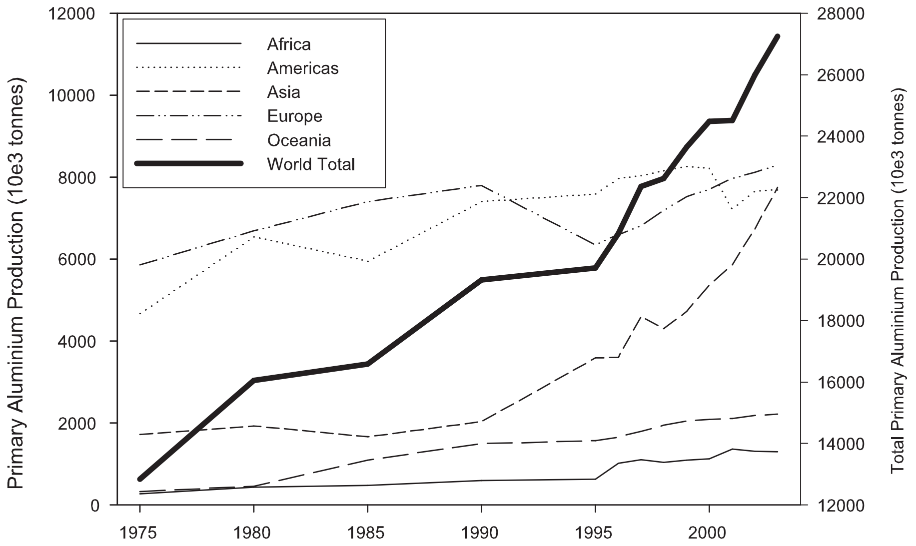


Figure 4.4: World primary aluminium production output [25], [23], [28].

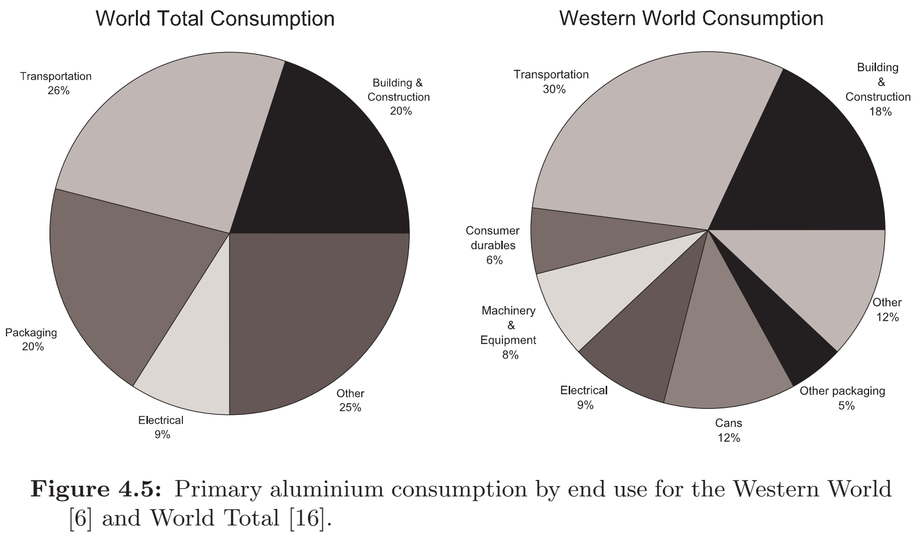


Figure 4.5: Primary aluminium consumption by end use for the Western World [6] and World Total [16].

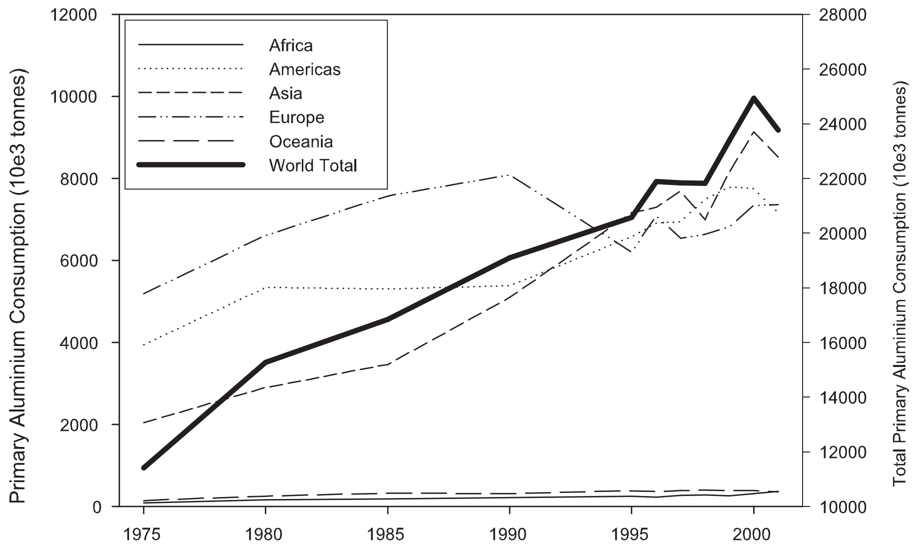


Figure 4.6: World primary aluminium consumption [25], [28], [23].

distribution for different regions is shown in Figure 4.6.

The regions with the highest consumption are Asia, Europe and the Americas. A drop in world consumption is shown for 2001. The same is true for world production, as shown in Figure 4.4, although the decrease is smaller. However, the gap between production and consumption has been growing in the recent years, leading to larger stocks. Without strong economic growth inventories may not decline [23]. The aluminium industry expects aluminium consumption to increase further, and their forecasts are relatively in accordance with each other on a long term horizon. On a global basis, Hydro Aluminium estimates the long term annual growth rate for aluminium consumption to be 3% in one statement [27], and as high as 4%-4.5% in another [22]. However, other sources agree on something in between, closer to 3%-3.5% [23], [3].

The most important use of aluminium is in transportation and construction, which presently make up nearly half of total consumption. The extensive use in these applications is due to the favorable material properties. Its low weight allows for weight reduction and smaller engines. An aluminium body on a small commercial vehicle may weigh 45% less than a corresponding steel body and therefore saves fuel consumption and emissions, as each kilogram of automotive aluminium replacing traditional higher density materials can save a net 20 kilograms of CO_2 equivalents over the lifetime of the vehicle. At the same time it is strong and also absorbs kinetic energy well, making it safer for passengers in case of a collision. Maintenance need is lower and lifetime longer since aluminium has a corrosion rate 1/25th that of high-resistance steel. Aluminium is also widely used in the aerospace industry, for sea freight and rail transportation as well. Modern aircrafts use aluminium as the main material, comprising about

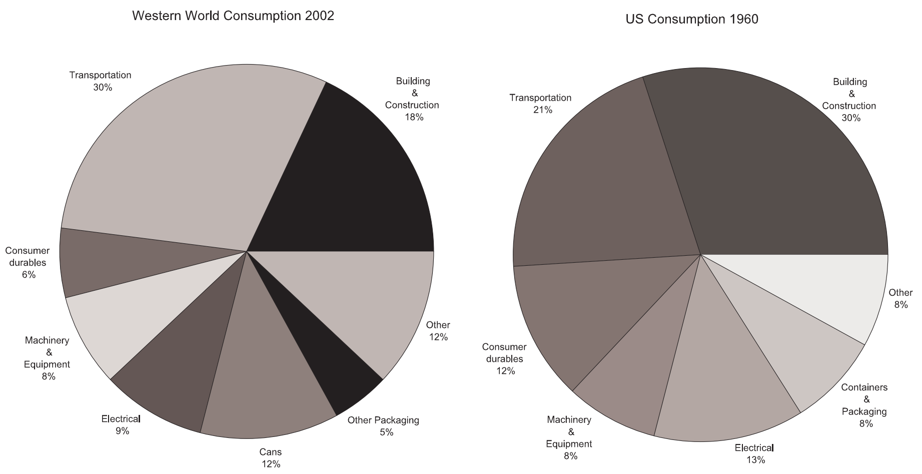


Figure 4.7: Primary aluminium consumption by end use for the Western World 2002 and US 1960 [7].

80% of the unladen weight. Demand for commercial aircrafts is forecasted to increase by 60% over the next decade.

As in transportation, aluminium's strength, weight and versatility are important qualities in buildings and constructions. Applications are windows, facades, roofs, walls etc. Aluminium building products help keeping buildings cool in summer and warm in winter. Comparing the western worlds present consumption to that of the US in 1960 shows that the transportation and construction sector together constitute approximately the same share of consumption, although transportation are gaining relative to construction, as displayed in Figure 4.7. The reason for this is a higher growth rate for aluminium used in transportation.

Aluminium is also used for a wide range of other applications. A large share of consumption is presently processed into aluminium foil and thereafter used for making cans for beverages and for food packaging. The same combination of properties as in transportation and construction makes it very attractive for these purposes, in addition to qualities important for use as a packaging material. Aluminium is impermeable and keeps out air, light, odour and bacteria in order to preserve the content. This also makes it useful for preserving cosmetics and pharmaceutical products [13].

4.5 The structure of the aluminium industry

The aluminium industry directly employs over a million people worldwide. In addition, four times as many jobs are created indirectly downstream and in service industries. Production is often located in remote areas where job opportunities are otherwise scarce, i.e. in Norway, with Norsk Hydro Aluminium's smelting plants in Årdal, Høyanger and Sunndalsøra in Norway. In some countries the industry is also an important source of foreign currency, i.e. Jamaica, Suriname and Cameroon, where the aluminium industry is responsible for 50%, 70% and 65% of exports, respectively. The contribution from the industry is substantial also in more developed countries. The Norwegian aluminium industry generates 2% of GNP, while in Australia aluminium is the second largest commodity export [16].

Most companies are single metal companies, and only 20% are involved with other metals. Large vertically integrated companies represent over half the world's production, involving both recycling and mining of bauxite. Production capacity is present on almost every continent [16]. The primary aluminium industry is relatively compact with 20 companies representing 65% of world production. Including only the top ten these account for 51% and the top five for 38% in 2003. In 1995, the same figures were 41% and 26% respectively. Table 4.4 presents further information on this [23].

Table 4.4: Main producers of primary aluminium and their contribution to world production in 2003 [23].

Company	*Share* 2003	*Company*	*Share* 1995
Alcoa	12.4%	Alcoa	7.7%
New Alcan [1]	11.6%	Alcan	6.6%
Alcan	8.5%	Reynolds	4.1%
RusAl	7.9%	Krasnoyarsk	3.8%
Norsk Hydro	5.4%	Bratsk	3.7%
BHP Billiton	3.9%	Pechiney	3.5%
Pechiney	3.1%	Alumax	3.3%
Rio Tinto	2.9%	Norsk Hydro	3.1%
Chalco	2.7%	CAV	2.7%
Sual Holdings	2.3%	Rio Tinto	2.6%
Dubal	2.0%		
Total	51.1%	*Total*	41.1%

Signs of consolidation within the aluminium industry can be observed from the table, since larger parts of the production is concentrated on fewer companies. Norwegian company Norsk Hydro has climbed from a production share of 3.1% in 1995 to 5.4% in 2003, making it the 4th largest company for primary aluminium production. The emergence of Chinese aluminium industry can be seen by the appearance of Chalco as the 8th largest producer in 2003.

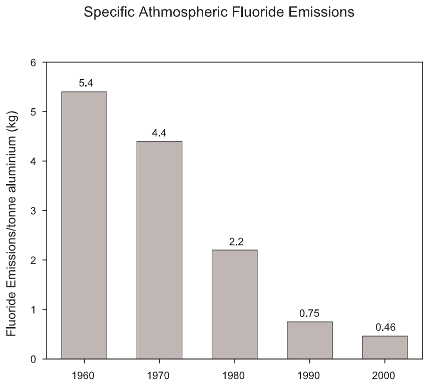
4.6 Aluminium smelting - Environmental impacts

Molten aluminium is produced by dissolving alumina in a molten cryolite bath, passing electric current through this solution and thereby decomposing the alumina into aluminium and CO_2. The process requires use of anodes. Inventory results for aluminium smelting by electrolysis and corresponding production of anode to produce aluminium in liquid form are presented in Table 4.5, along with data for ingot casting to produce primary aluminium [15].

[1] Alcan acquired Pechiney in Dec. 2003, Total Production

Table 4.5: Inventory for world average production of 1,000 kg primary aluminium [15], [10].

Input	*Anode*	*Electrolysis*	*Ingot*	*Unit*
RawMaterials				
Alumina		1,925		kg
Petrol Coke	349			kg
Pitch	92			kg
Aluminium Fluoride		17.4		kg
Cathode Carbon		6.1		kg
Alloy additives			20	kg
Chlorine			0.068	kg
Fresh Water	0.5	2.95	3.15	m^3
Sea Water	0.001	20.8	0.2	m^3
Refractory Materials	5.5	6		kg
Steel (for anodes)	1.4			kg
Steel (for cathodes)		5.5		kg
Fuels and Electricity				
Coal	0.9			kg
Diesel Oil	1.4		0.1	kg
Heavy Oil	6.2		10	kg
Natural Gas	23		52	m^3
Electricity	62	15,365	81	kWh
Output	*Anode*	*Electrolysis*	*Ingot*	*Unit*
Air Emissions				
Fluoride, Gaseous (as F)	0.02	0.55		kg
Fluoride Particulate (as F)	0.004	0.5		kg
Particulates	0.1	3.3	0.08	kg
CO_2 (eq)	374	1,626	368	kg
NO_x (as NO_2)	0.13	0.35	0.12	kg
SO_2	0.7	13.6	0.2	kg
Total PAH	0.02	0.13		kg
BaP	0.0001	0.005		kg
CF_4		0.22		kg
C_2F_6		0.021		kg
HCl			0.067	kg
Water Emissions				
Fresh Water		3.2	3.8	m^3
Sea Water		20.9		m^3
Fluoride (as F)		0.2		kg
Oil/Grease		0.008	0.009	kg
PAH (6 Borneff components)		0,00377		kg
Suspended Solids		0.21	0.02	kg
By − products for external recycling				
Dross			13	kg
Filter Dust			0.57	kg
Other by-products	2.8	5.1		kg
Refractory Material	3.1	0.5	0.5	kg
Scrap sold			2.2	kg
SPL Carbon fuel/reuse		9.9		kg
SPL Refr.bricks/reuse		5.5		kg
Steel	1.7	6.9		kg



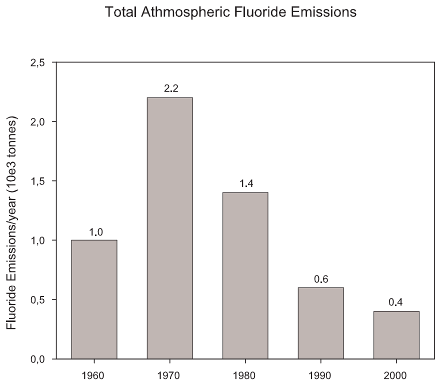


Figure 4.8: Fluoride emissions, Norwegian aluminium smelting industry 1960-2000 [16].

Input	*Anode*	*Electrolysis*	*Ingot*	*Unit*
Solid Waste				
Carbon Waste	2.4	4.6		kg
Dross - Landfill			7.7	kg
Filter Dust - Landfill			0.4	kg
Other Landfill Wastes	2.7	7.3	1.3	kg
Refractory Waste - Landfill	2.5	1.2	0.7	kg
Scrubber Sludges	0.8	13.7		kg
SPL - Landfill		17.3		kg
Waste Alumina		4.7		kg

Production of primary aluminium requires 441 kg of anode material to be consumed per tonne of output. The dominant role of the electrolysis process for electricity consumption is clearly shown in Table 4.5, with nearly 15.4 MWh_{el}/t_{output}. Including alumina production, smelting comprises 97.8% of total electricity consumption, leaving a nearly negligible 1.3% to alumina production and even less for anode production and ingot casting. Energy use for bauxite mining is mainly related to diesel oil for mechanical equipment.

Emissions of fluorides from the smelting process, in gaseous and particulate form, are shown in Table 4.5 to be modest. Emission of these substances were earlier considered to be the most important pollutants from smelting. These substances can cause severe damage to coniferous trees, as seen in Norway, as well as accumulate in vegetation and in ruminants feeding on this. Modern control systems to remove and recycle fluorides through gas collection and wet/dry scrubbing systems have largely eliminated the problem. 1st generation plants (1940-1955) had emission intensities of 12-15 kg/$tonne_{output}$, reduced to 2-6 kg/$tonne_{output}$ for the 2nd generation (1955-1975) and 0.5-1 /$tonne_{output}$ for the present 3rd generation plants. The individual differences are of course considerable. Figure 4.8 demonstrates the decrease in specific fluoride emissions in Norway for the last decades, and the total emissions to the atmosphere for the same period [16].

Specific fluoride emissions from the Norwegian aluminium industry are reduced to approximately 8.5% of the 1960 level. The impacts from this are reflected in the reduction in total fluoride emissions for the same period, as aluminium production increased from 185,000 tonnes in 1960 to 1,030,000 tonnes in 2000. Comparing fluoride emissions in Norwegian aluminium industry with the world average figures in Table 4.5 shows an emission intensity less than half that of world production.

Present and recent concern about environmental impacts from aluminium smelting is related to reduction of Greenhouse Gases (GHG).

Chapter 5

Greenhouse gases

In 1995, about 1% of worldwide energy related CO_2 emissions were caused by the production of primary aluminium [24]. Emissions of greenhouse gases are mainly related to the smelting process.

5.1 PFC emissions

Primary aluminium production has been identified as a major anthropogenic source of two perfluorocarbon compounds (PFCs), tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). These compounds are very potent global warming gases with long atmospheric lifetimes. Global warming potential, measured in CO_2 equivalents, is 6,500 and 9,200, respectively. 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. To counter this, the aluminium industry has taken measures towards reducing anode effect frequency and duration through better process control. These measures have proven effective, with significant emissions reductions. 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. In 2000, 66% of world production was covered in the survey, the remaining being assessed by technology and production weighted estimates. Table 5.1 shows the worldwide improvement in PFC emissions from aluminium smelting in the period 1990 to 2000 [11].

Table 5.1: Worldwide emissions of GHG (% of total CO_2 equivalents), world total emissions and aluminium production (10e6 tonnes) [11].

$Year$	CO_2	PFC	$World\ CO_2\ eq.$	$Production$
1990	27%	73%	117	19.500
2000	42%	58%	92	24.250

Total world GHG emissions have decreased by approximately 21% during the period, although world primary aluminium production has at the same time increased by 24%. The focus on PFC reduction is further demonstrated by the composition of total CO_2 equivalents, with PFC contribution declining significantly.

PFC emission intensities vary considerably for different technologies as well as for individual plants, with Prebake technology performing significantly better than Söderberg type plants. Table 5.2 presents improvements in specific PFC emissions for different smelting technologies in the period 1990 to 2000, for participants in the International Aluminium Institute's PFC emissions survey, covering 60%-70% of world production [11].

Table 5.2: Technology specific emissions of PFC compounds (kg/tonne) and total emissions (tonnes) [11].

$Year$	$CWPB$	$PFPB$	$SWPB$	VSS	HSS	$Average$
CF_4						
1990	0.42	0.37	1.37	0.52	0.54	0.54
1998	0.24	0.13	1.45	0.37	0.57	0.28
1999	0.24	0.11	1.37	0.37	0.49	0.26
2000	0.21	0.11	1.06	0.36	0.51	0.22
Amount 1990	1,112	1,887	1,987	952	466	tonnes
Amount 2000	243	1,260	929	797	240	tonnes
C_2F_6						
1990	0.054	0.048	0.137	0.023	0.054	0.057
2000	0.027	0.014	0.106	0.016	0.051	0.021
Amount 1990	143	243	199	42	47	tonnes
Amount 2000	31	162	93	35	24	tonnes

Prebake technologies have the largest improvements in PFC emission intensity, especially the PFPB technology which is the present state of the art technology. Söderberg technology is being phased out, and emissions reductions are not very considerable. Less effort is put into improving old technology. China and the Russian Federation rely more on HSS and VSS technology, respectively, than the world average. Average specific CF_4 emissions could be further reduced from 0.22 kg/tonne to 0.15 kg/tonne if facilities operating above the median emission level improved their performance to the median performance. Emissions of PFCs and CO_2 could eventually be eliminated in the future, by the introduction of inert anodes and replacement of carbon anodes [11].

Average emission intensity varies between regions, and an overview of this is given in Table 5.3 for the 1994 to 1997 period. However, these figures do not comprehend total world production, as indicated by the participation rates [8].

Table 5.3: Specific emission rates of CF_4 (kg/tonne) for different regions, and participation rates (%) [8].

Year	*Africa*	*N. America*	*L. America*	*Asia*	*Europe*	*Oceania*
1994	0.42	0.39	0.32	0.32	0.40	0.14
Part.	57%	83%	63%	27%	32%	87%
1995	0.41	0.38	0.27	0.29	0.38	0.11
Part.	62%	85%	65%	33%	32%	86%
1996	0.23	0.40	0.30	0.31	0.44	0.08
Part.	100%	90%	84%	39%	35%	91%
1997	0.34	0.36	0.31	0.22	0.36	0.06
Part.	92%	91%	83%	44%	37%	100%

Participation rates varies substantially, with Asia and Europe having the lowest ones. Emission rates are decreasing, with Oceania as the best performer. Apart from this region, emission rates are quite similar. Classification of countries into categories based on the Kyoto protocol's Annex 1 and non-Annex 1 countries, supports this, with specific CH_4 emissions rates of 0.31 kg/tonne and 0.29 kg/tonne, respectively, in 1997 [8]. Annex 1 countries are developed countries with specific GHG reduction targets, while non-Annex 1 countries refer to countries without specific targets. Voluntary agreements between governments and industry has been a major contributor to PFC emissions, and new investments in developing countries will also spread more efficient technology. This might explain the good performance of non-Annex 1 countries.

5.2 Total CO_2 emissions

Total CO_2 emissions consist of both PFC compounds and CO_2, characterized and presented as CO_2 equivalents. An overview of total CO_2 emissions for the different primary aluminium production processes is provided Table 5.4 [10].

Table 5.4: Emissions of greenhouse gases from primary aluminium production unit processes (kg CO_2 equivalents) [15], [10].

	Bauxite	*Refining*	*Anode*	*Smelting*	*Casting*
Process	0	0	45.70%	16.61%	0
Electricity	0	5.85%	7.42%	59.25%	20.90%
Fossil Fuel	33.33%	79.51%	15.90%	1.36%	42.10%
Transport	66.67%	6.16%	0.94%	0.04%	37.00%
Ancillary	0	8.48%	30.04%	0	0
PFC	0	0	0	22.74%	0
Total (kg)	48	991	849	9,789	368
Per tonne Al	248	1908	374	9,789	368

Aluminium smelting is by far the most dominant process of primary aluminium production's GHG emissions, mainly because of electricity consumption, which amounts to 46% of total CO_2 emissions, all processes accounted for. The second most important source is PFC compounds from the smelting process. Looking closer at electricity, the electrolysis accounts for approximately 96% of total

CO_2 emissions from electricity production. Specific emissions from electricity production are expected to decrease in the future, and there are three main reasons for this [24]:

- Lower CO_2 emission rates for electricity generated from fossil fuels
- Replacement of old Söderberg plants with more energy efficient PFPB technology (see Table 4.2)
- The production of primary aluminium is being shifted to regions with larger share of electricity production relying on hydropower

As described in the last point, CO_2 emissions from primary aluminium production depends on localization as well as technology, because of the different energy carrier mix present in different regions. Schwarz et. al provide regional emission factors for electricity production and primary aluminium production for 1995 and forecasts for 2010 [24]. The figures shown in Table 5.5 is based on a scenario with moderate growth for aluminium demand of 1.9%.

Table 5.5: Regional CO_2 emission factors for electricity production (t_{CO_2}/MWh_{el}) and specific regional CO_2 emissions from electrolysis (t_{CO_2}/t_{Al}) [24].

	(t_{CO_2}/MWh_{el})		(t_{CO_2}/t_{Al})	
Region	*1995*	*2010*	*1995*	*2010*
USA	0.61	0.54	9.5	7.6
Canada	0.19	0.18	2.8	2.5
Brazil	0.05	0.03	0.7	0.4
Rest of L. America	0.48	0.31	7.3	4.3
Germany	0.67	0.58	10.3	4.3
Rest of EU	0.38	0.32	5.4	4.5
Rest of W. Europe	0.00	0.01	0.1	0.1
Former Soviet U.	0.64	0.50	11.6	6.9
Rest of E. Europe	1.10	0.91	16.7	13.1
Africa	0.71	0.55	10.3	7.8
Near/Middle East	0.68	0.50	10.3	7.0
India	0.98	0.71	15.0	9.9
China	1.06	0.66	15.9	9.1
Rest of Asia	0.42	0.34	6.3	4.7
Australia	0.82	0.75	12.1	10.4
World	*0.56*	*0.45*	*8.7*	*5.9*

As displayed in Table 5.5, there is great variation in both t_{CO_2}/MWh_{el} and t_{CO_2}/t_{Al} when looking at specific regions. However, the figures are decreasing for the world average as well as for all individual regions. The strong relationship between CO_2 emissions from electricity production and primary aluminium production is demonstrated by looking at the ranking for both parameters in Table 5.5. High emission rates from electricity are reflected in the aluminium production. China is presently the world's largest producer of primary aluminium, and has the largest specific emissions. The fourth largest producer is the US, and because of its reliance on fossil fuels the country ranks at the level of the Former Soviet Union, Africa and the Middle East concerning t_{CO_2}/MWh_{el}. Brazil and the region "Rest of Western Europe" have by far the lowest emissions, due to their dominant proportion of electricity production from hydropower. Canada, being the third largest producer, is also the third best performer in terms of specific emissions.

Chapter 6

Recycling

Aluminium's material properties make it excellent for recycling, contributing to more efficient use of energy resources and raw materials. Energy demand of recycling is only 5%-10% that of primary aluminium production, reducing environmental damage from electricity production as well as from raw materials extraction and processing. All aluminium can be melted and recycled repeatedly without downcycling and property losses. Therefore it also has significant economic value, and it is recognized as the most cost effective material to recycle. The extensive use of aluminium for more applications as well as increased use in existing ones, leads to generation of increasing volumes in stocks, which is thereby represents a considerate source for future aluminium demand. The recovery and use of secondary aluminium is already an important component of metal supply in several countries [16], [20], [2].

The aluminium recycling industry is growing faster than the primary production industry, at an estimated annual rate of more than 4%, and already produces substantial outputs from both old and new scrap [27]. The European Aluminium Association (EAA) reports an annual production of recycled aluminium of nearly 10 million tonnes worldwide, which is more than one third of world demand [2]. Recycled material's share of consumption will increase further in the years to come [27]. The International Aluminium Institute reported the sources of scrap recycling in 1998 as shown in Table 6.1 [13].

Table 6.1: Sources of aluminium recycling from old and new scrap (1998)[13].

Source	*Share*
Transport	38%
Building	32%
Packaging	17%
Other	13%

The transport sector is the main source of aluminium for recycling, a position that is likely to be strengthened by the passing of the End-of-Life directive (ELV) into European law in 2000. This directive imposes quantitative recycling requirements for the automotive industry, as outlined in Table 6.2.

Table 6.2: Recycling requirements in the ELV directive (by weight) [27].

Year	*Material recovery*	*Energy recovery*	*Disposal*
2006	80%	5%	15%
2015	85%	10%	5%

In accordance with future requirements, the recycling ability in new cars should be 95% from 2005. In Europe, the average use of aluminium car components is estimated to increase from 85 kg per car in 1998 to 180 kg per car in 2010, further enhancing recycled amounts from this industry [27]. Recycled aluminium already accounts for 85% in auto castings and 11% in sheet and extrusions, according to 1999 figures [10]. However, in terms of environmental gains, the ELV directive may contribute to counter the automotive industries efforts to reduce weight, because of the per weight recyclability requirement. A car with light weight recyclable materials might not pass the legislation, while the same car with heavier recyclables (95% of total weight) will, given the same amount of non-recyclables [2].

Aluminium is widely used in construction, as displayed in Table 6.1. Reports have suggested recycling rates of approximately 95% in selected West European countries [2]. This figure seems very high, and Hydro Aluminium estimates the same recycling rate to be 69% in 2010, for Western Europe in general [27]. However, there is no doubt that considerable amounts of aluminium is tied up in building stocks, and that this will continue to be a major source of recycled material.

Aluminium scrap is a valuable resource, and the competition for this material is increasing, pushing secondary material prices. China is an important and growing net importer of scrap, taking considerable amounts out of the US and European scrap markets. Low Chinese labor costs make scrap separation more economical [6], [27]. The increased competition is leading to a restructuring of the recycling industry, from small facilities to fewer and larger units. Figure 6.1 displays this development for the European secondary industry, and also shows the growth of secondary material processing capacity for Hydro Aluminium [27].

From 1995 to 2000 the number of small refiners with annual capacities below 1,000 tonnes were reduced to nearly one third, while the largest facilities increased by more than a factor of 3. Combined, this increases transportation need, although it also increases efficiency. This trend is likely to continue, since 2/3 of process scrap is bound in closed loops with customers, making it harder for small independent refiners to acquire scrap material [27].

The increasing importance of secondary aluminium is also shown in Figure 6.1, using Hydro Aluminium as an example. From constituting less than 1/3 that of primary production capacity in 1992, secondary production capacity's higher growth rate made them nearly equal in 2001.

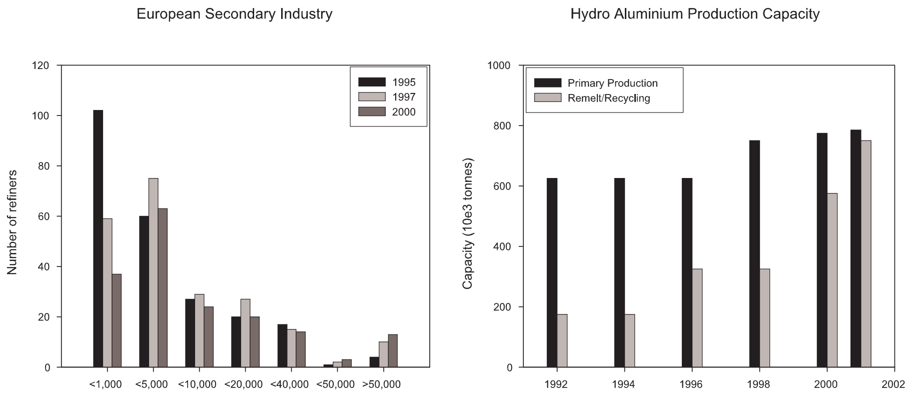


Figure 6.1: Restructuring of European secondary industry 1995-2000, and the growth of recycling capacity for Hydro Aluminium [27].

Chapter 7

The case of China

During the past decade, both aluminium production capacity and consumption have grown rapidly in China, and the country is a major participant in global aluminium trade. Between 1995 and 2002 China accounted for 40% of the total net increase in world aluminium production, and for the first three quarters of 2003 the same figure was 60%. This is due to the strong economic growth in the Chinese economy. Over the past five years, China has accounted for 10% of global economic growth, reaching 4% of world GDP in 2003 and placing it as the worlds seventh largest economy [6]. However, if cost of living differences are adjusted for in terms of Purchasing Power Parity (PPP), China is presently the 2nd largest economy with 12% of world GDP, only second to the US, as displayed in Table 7.1.

Table 7.1: China's position in the world economy measured in GDP and PPP-adjusted GDP in 2003 [21].

Country	*Share of GDP*	*Country*	*Share of* GDP_{PPP}
US	31.1%	US	19.2%
Japan	12.0%	China	12.0%
Germany	6.9%	Japan	6.3%
UK	5.1%	Germany	3.9%
France	4.9%	UK	2.9%
Italy	4.3%	France	2.9%
China	4.0%	Italy	2.7%

One of the main contributors to the strong economic growth is extensive amounts of foreign direct investment in the country. In 2002 this amounted to more than US$50bn, approximately 18 times that of Russia. Other contributing aspects are massive government investment in infrastructure in cities and less developed regions of the country, and a growing domestic consumption as a result of higher income and lower prices for large consumer durables following sharp falls in import duties imposed by the World Trade Organization (WTO) as a condition for membership [6], [21].

7.1 Bauxite and alumina

As described in Table 2.1, China has extensive bauxite resources. However, the quality is low, so China has developed a soda-lime sinter process which uses more energy and larger quantities of soda per tonne of alumina produced than an average Western plant, raising both costs and environmental impacts. No metallurgical-grade bauxite is exported from China, and most of the production is supplied to Chalco, which is a state-controlled company owning all the six alumina refineries in the country, and 20% of primary smelting capacity. Together these make China the second largest alumina producer with 5.4 Mt of output in 2002, which is still only a third of Australian production. Since 1995, however, China's alumina production has had a compounded annual growth rate (CAGR) of 13.6%, but the country is still a net importer of alumina. Expectations of continued growth has led to plans for capacity expansion, which is due to reach 8 Mt in 2005, and a further 3 Mt increase later on. However, alumina demand is expected to exceed 16 Mt by the middle of the present decade, the gap between domestic alumina production and local requirements continuing being filled by imports, presently at 5.61 Mt in 2003. Thus, about 50% of demand is covered by imports, mainly from Australia and India, with 73% and 10% respectively [6], [7], [18].

Chinese bauxite production costs are higher than the world average, and to some extent, the same applies for alumina production. Full operating costs (FOC) are above the world average of US$151/t (in 2002) for four plants, while one is roughly the same and the last one below. Still, FOC remains below long-term alumina contract price and above alumina spot price. China's dependency on purchasing alumina on the spot market instead of having long term contracts or succeeding in establishing ownership in alumina producers is a major contributor to higher costs and increased vulnerability. China's growing requirements presently comprise more than 25% of world free market alumina, contributing to push the spot price further. Other important alumina buyers are CIS (former Soviet Union/Commonwealth of Independent States), Hydro Aluminium and Dubal, with 12%, 7.5% and 6 %, respectively [6].

7.2 Trade flows

China's primary aluminium capacity has increased substantially for the last decade, and is presently about 6.5 Mt. The recent increase has, however, resulted in more modern smelters. More than 77% of the capacity rely on Prebake technology. In comparison, there is about twice as much Söderberg capacity in the Western World and in Russia. Most Chinese smelters use Söderberg technology, but the technology is related to small smelters, while the fifteen largest smelters, comprising 45% of production, use Prebake technology [6].

Primary aluminium capacity has increased due to higher domestic consumption as a result of strong economic growth, and so has the production output. During the last half of the previous decade, China's position as a net importer of unwrought aluminium came to an end. For the last couple of years, the country

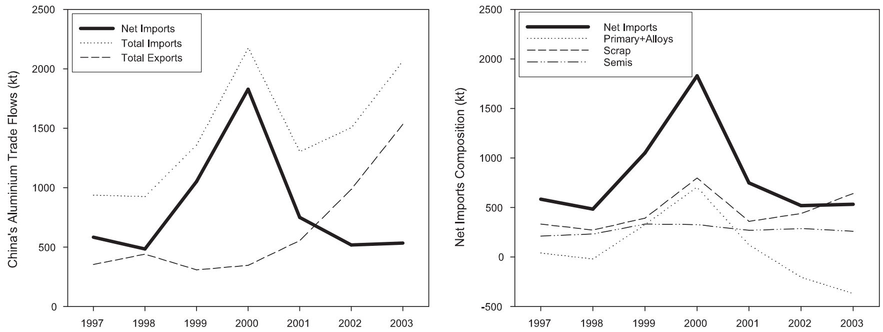


Figure 7.1: Chinese trade flows and net imports composition [6].

has instead registered significant net exports of primary aluminium. Figure 7.1 gives an overview of Chinese trade flows and composition of net imports for the recent years.

Looking at net import of primary aluminium, a substantial decrease is shown, resulting in negative figures, i.e. net export. However, this is offset by net imports of scrap and semi-fabricated products, giving an altogether positive net import. Total imports and exports are both increasing, indicating growing consumption and production.

China's scrap recycling rate is approximately 80%, but this still accounts for only 25% of scrap demand. Scrap import constituted 70% of total domestic demand in 2003, mainly from the US (33%) and Hong Kong (25%). Low Chinese labor costs make scrap separation more economical [6]. Higher energy costs do not offset this because of aluminium's low energy demand for recycling, 5%-10% that of primary aluminium energy demand.

Net import of semi-fabricated products have been fairly stable, as seen in Figure 7.1. A considerable proportion of Chinese primary aluminium does not conform to international standards and requirements, and is thus unsuitable for further processing in high-speed rolling mills. This makes China an exporter of bars, rods and extrusions, and an importer of processed products like sheets, plates and foil. However, the quality of Chinese aluminium is improving [6].

7.3 Chinese aluminium production and consumption

As a consequence of the rapid economic growth in the period 1995-2004, both consumption and production of primary aluminium have increased substantially. Industrial activity in general has had a very high growth rate, but the corresponding growth in primary aluminium consumption has been even larger and about 1.2 times that of industrial production. Table 7.2 presents compounded annual growth rates (CAGR) of production and consumption [6], [7], [21].

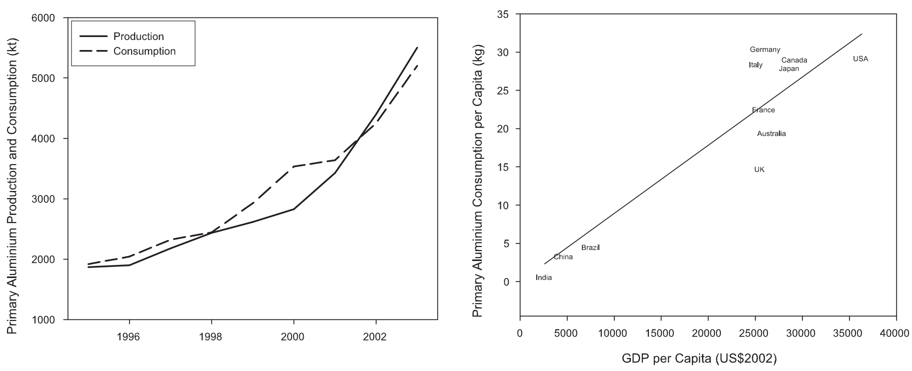


Figure 7.2: Chinese primary aluminium production and consumption, and consumption/Capita vs. GDP/Capita [6], [4].

Table 7.2: Chinese compounded annual growth rate 1995-2003 [6], [21].

	1995-2000	*2000-2003*
Production	8.6%	25.6%
Consumption	13.0%	14.5%

Production CAGR is higher than for consumption, as capacity is increased to keep pace with the growing demand. The higher growth rate for aluminium relative to industrial output is not surprising. For the last four decades, developing countries have experienced aluminium consumption of 1.3-1.5 times the CAGR of industrial production. As industrialization takes place, manufacturing, construction and other materials-intensive activities expand, hence aluminium consumption is determined not only by growth in industrial production, but also by the intensity of use. When the need for capital investments like these move towards satisfaction, a decline in consumption growth is likely to occur due to a shift to a less materials-intensive service industry [6].

China is already the world's largest primary aluminium consumer, overtaking the US in 2001 [1]. Still, it has an aluminium consumption per capita of only about 12% that of industrialized countries. Figure 7.2 displays Chinese production and consumption in recent years, as well as aluminium consumption per capita vs. GDP per capita for selected economies [6], [21], [4].

Considerable growth for both production and consumption are shown, with production output overtaking consumption in recent years, as indicted by the CAGR-values of Table 7.2. Figure 7.2 shows correlation between aluminium consumption per capita and GDP per capita, indicating growth in the former variable as GDP per capita grows. This is experienced earlier in developing economies. Measuring China's GDP in terms of purchasing power parity (PPP), the country's economy is at the level which other Asian countries like Taiwan, Korea and Japan were when their economies started to accelerate.

China's aluminium consumption by end use is displayed in Figure 7.3, and shows significant differences from the Western World consumption pattern [7].

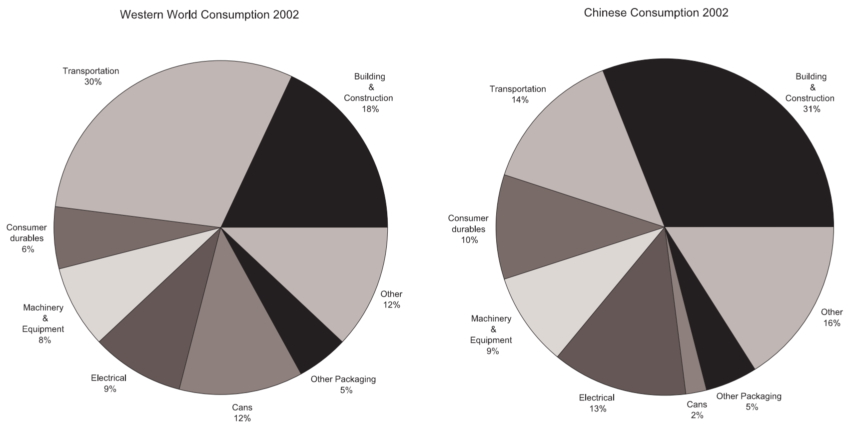


Figure 7.3: Aluminium consumption by end use for the Western World and China in 2002 [7].

China has a larger share of consumption related to building and construction, electrical products and consumer durables than the Western World, while the opposite is true for transportation, cans and other packaging. Both residential and non-residential construction activity is high, especially in the major cities, and is expected to remain high as well. The main drivers for this are continued growth in per-capita incomes, foreign direct investment, domestic fixed investment and general improvement of the economy. In addition non-residential construction activity and corresponding aluminium demand will be further stimulated by the 2008 Beijing Olympics and Shanghai's 2010 EXPO. For the Olympics only, 42 stadiums and about 50 hotels are planned.

Aluminium for transportation purposes is significantly lower than for the Western World, but this about to change. Transportation is by far the fastest growing market for aluminium. China is not only increasing in terms of cars per capita, but also emerging as an automotive producer, both of automotive parts as well as vehicles. Major international automotive manufacturers like General Motors, Volkswagen, BMW, Honda, Toyota and Nissan are all increasing their production capacity in China [6].

In general, the present aluminium consumption pattern of China strongly resembles the end use distribution of the US in 1960, as seen in Figure 4.7.

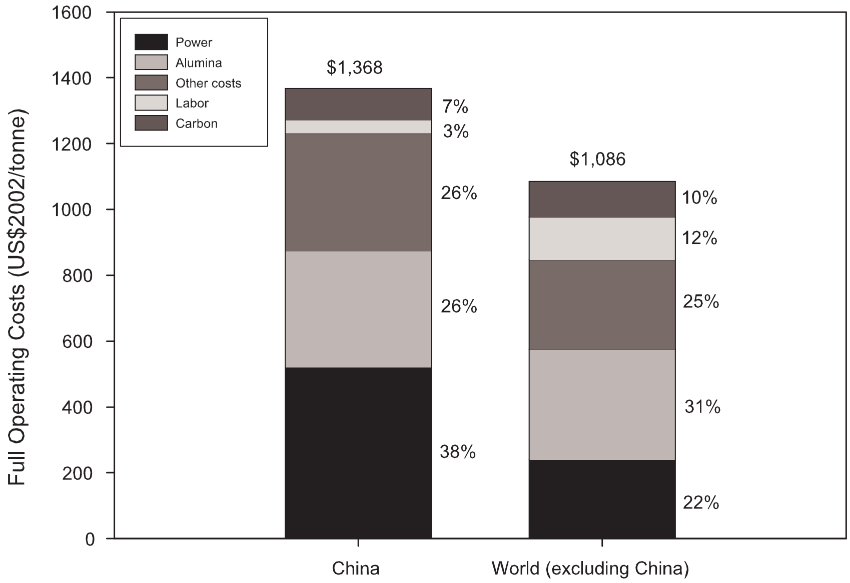


Figure 7.4: Components of full operating costs as of 2002 [6].

7.4 Energy and operating costs

The cost structure of Chinese primary aluminium production is different from the world average. The full operating costs (FOC) are higher as well, being 26% above the average in 2002. All top ten Chinese smelters have FOCs above the world average. Figure 7.4 displays the cost structure of Chinese and World production [6].

The main differences between China and the rest of the world are related to power and labor costs. Chinese labor costs account for only 3% of FOC, compared to 12% for the world average. However, this is more than offset by the power costs, constituting 38% of FOC. China is the second largest power producer in the world, but still experiences power shortages and high costs. While electricity purchased from the grid costs between US$30/MWh and US$43/MWh in China, the world average is in comparison US$19/MWh. The power production is mainly coal-based. Table 7.3 shows capacity and production from different sources in 2002 [6].

Table 7.3: Chinese power situation in 2002 [6].

Energy source	*Capacity*	*Production*
Coal	74%	82%
Hydro	24%	17%
Nuclear	2%	1.5%
Total	355.85 GW	1,600 TWh

The non-renewable and CO_2-intensive, coal-based share of production is even higher than for the capacity, on behalf of the more environmentally preferable hydropower alternative. Although production is very high, it still increases substantially, growing at an annual 8% for the last 20 years, and forecasted by the government to grow by a conservative 6% in the next five years. This corresponds to an annual increase of 25 GW, or 1.4 the capacity of the Three Gorges project. However, the general economic growth, rural electrification and proliferation of energy-intensive industry create an estimated annual demand of 40 GW. For 2005, power demand is expected to increase by 15%, and already, energy shortages are reported to affect some smelters and lowering production output [6], [1].

7.5 Energy shortage and over-supply

Due to emerging power shortages and a general concern for aluminium over-supply, Chinese authorities have specified policy measures to curb growth in aluminium capacity, focusing on:

- Accelerating the phase-out of Söderberg plants that are neither economically nor environmentally sustainable

- Restricting alumina imports for smaller smelters

- Centralizing the power to approve new projects

- Loans to new projects by state banks are banned unless approved by central government

Stronger central governmental control is needed to fulfill a policy of closing down all environmentally unacceptable smelters by 2007, as laid out by the central government itself. This will mainly affect Söderberg technology plants, and especially the smaller ones. However, this has not been easy, since most of these smelters are owned by local governments, more interested in preserving employment and tax revenues. Attempts to close down this capacity have not been very successful, and sometimes resulted in expansions to boost output above minimum levels. This is why restricting alumina supply is proposed by the central government, and some signs of this are already present.

State banks will no longer finance new aluminium smelter projects, and domestic financial institutions are warned of the potential risks of involvement in such projects due to the perception that there already is excessive production capacity. Foreign investment will still be allowed, although subjected to stricter screening procedures. China will prefer to encourage existing aluminium industry in developing into more centralized major aluminium enterprise groups with global competitiveness [6], [1].

Chapter 8

Future primary aluminium demand

Primary aluminium demand is expected to increase in the years to come, for the world in general as well as for the different regions. In order to make projections about this future demand, macroeconomic relationships between aluminium consumption and national income is utilized. Primary aluminium demand (PAD) is econometrically estimated as a simple logarithmic function of GDP for individual regions, attempting to capture the effect of ”market saturation” with rising income, as described by Harnisch et. al [5]. Equation 8.1 shows the relationship between GDP and PAD.

$$PAD = \alpha + \beta lnGDP \tag{8.1}$$

α and β is found by regression. GDP projections for different regions are provided by UNCTAD [25], while Wilson et. al [29] provides the same for China and India. India and China are examined on their own due to their large populations and potential growth. Figure 8.1 shows projected PAD for different regions as well as the world total.

The demand curves in Figure 8.1 are all increasing, and world PAD is estimated to nearly double for the next fifty years. Europe will by far experience the largest demand, followed by North America and China. However, looking at growth rates, both Europe and China will experience substantially higher growth than North America, which actually have the lowest growth of all regions. The region of Middle East and Africa has the highest growth of all, followed by India and China. PAD in 2050 is displayed in Table 8.1 for all regions relative to the 2000 level, showing that developing countries will have the strongest growth.

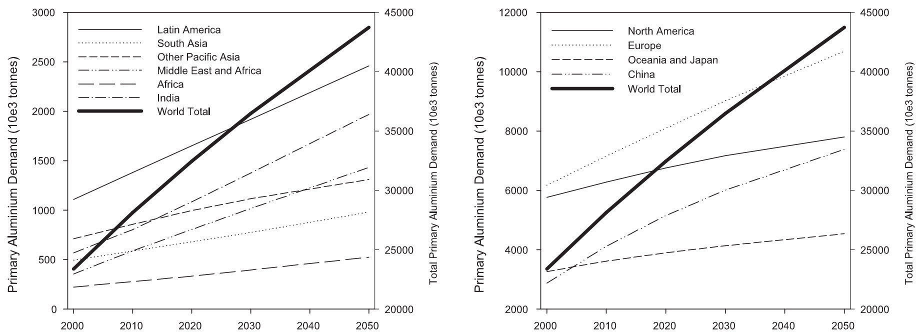


Figure 8.1: Projections of future primary aluminium demand [25], [5], [29].

Table 8.1: Growth in PAD for the period 2000 to 2050, displayed in % of 2000 level.

Region	*PAD Growth*
Middle East and Africa	403%
India	346%
China	257%
Africa	236%
Latin America	222%
South Asia	198%
Other Pacific Asia	185%
Europe	173%
Oceania and Japan	139%
North America	135%
World Total	*187%*

Some regions have fairly equal growth rates over the entire period, while others, like China, increases more rapidly in the beginning. This might be due to higher saturation concerning aluminium demand, and a sign of PAD growing in pace with the economy for Europe and North America (when measured as annual percentage increase), while for China PAD growth will be higher than economic growth in the beginning, and eventually slow down as the market becomes more saturated. The less developed countries will be able to have strong PAD growth for a longer period than the western economies, as an expanding economy is more materials intensive than a more developed and service oriented economy.

PAD projections are performed by regression of figures for the last three decades, using 5 years intervals from 1970 to 2000. China has been experiencing very strong growth for the last five to ten years, far more than the earlier part of the regression period. The importance of this is somewhat offset and underestimated by using the entire period of 1970 to 2000 instead of the last ten years. By using the last ten years only, projected PAD growth would be higher, which would probably be more representative for the near future. However, in the long run, the projections from 1970 to 2000 presented in Figure 8.1 might be more accurate. The reliability of the regressions performed for 1970 to 2000 to estimate future primary aluminium demand is displayed by the R^2 values in

Table 8.2, indicating the degree of variance in the plots used for the regression. The corresponding α and β values are also listed.

Table 8.2: α, β and R^2 values for different regions.

Region	α	β	R^2
India	−3907.3	342.78	0.97
Oceania and Japan	−32001	2322.9	0.96
Latin America	−12807	978.86	0.92
Europe	−78685	5281	0.92
South Asia	−3333	289.05	0.91
Other Pacific Asia	−4068.3	344.92	0.87
Middle East and Africa	−9286.8	708.48	0.82
China	−13969	1212.4	0.79
North America	−35583	2609.4	0.78
Africa	−2172.3	187.36	0.70

Table 8.2 shows generally high R^2 values, making the projections in PAD more reliable and useful for further work.

Chapter 9

Conclusions

Both primary and secondary aluminium production is growing, with the strongest growth taking place in China, due to its recent strong economic improvements. At the same time, secondary aluminium from recycling of old and new scrap is increasing even more due the release of more material from the substantial stocks in different products and applications, increased focus and improvements in recycling systems and the lower costs and environmental stress from the recycling process.

Aluminium is finding its way into new applications and segments, as well as increasing its importance in existing products, with the transportation sector being the fastest growing one. However, the use of aluminium in different applications vary within different regions of the world, but with development patterns showing similar trends.

Environmental implications from aluminium production is mainly related to the smelting, or electrolysis, process. 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.

Through relations between GDP forecasts and aluminium consumption, projections of future primary aluminium demand are estimated, indicating a nearly doubling of world demand in 2050, with developing countries such as China and India in the lead.

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