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Prospective Study of the World Aluminium Industry

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FOREWORD

A series of Industrial models have been developed by the Institute for Prospective Technological Studies (IPTS) aiming at studying in detail the technological perspective of several energy intensive industries. This paper describes one of such a simulation model for the aluminium industry at global, regional as well as national levels.

The aluminium model simulates the technology evolution of the industry from 2000 to 2030, exploring the alternative development trends in energy consumption, emissions, technology, retrofitting options and trade. Several future technologies foreseen in the primary aluminium production are considered and projected in the model allowing different scenarios to illustrate the technology dynamics of the sector's future. Scrap recycling is one of the key components of the aluminium industry and is crucial to the sustainable development of the sector. The model, thus, also explores the possible perspective of scrap availability and recycling potentials. Furthermore, based on the demand and supply trend of aluminium, the model also analyses the evolution of bauxite mining and the alumina refining industry.

The model is designed to be a flexible tool in accommodating policies to address different environmental issues such as GHG emissions, material use, and waste recycling. The aluminium industry of the European Union is given more detailed analysis to address the main environmental issues such as the GHG emissions.

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1 INTRODUCTION

1.1 Background

The aluminium industry is the largest non-ferrous metal industry in the world economy. Since its industrial production, demand for aluminium has been continuously increasing to around 45 million tonnes in 2004 and its application has extended to variety of economic sectors. The production of the primary aluminium from bauxite is electricity intensive process and consumes majority of the energy used in the sector. Furthermore, primary aluminium production process emits carbon dioxide and two kinds of perfluorocarbon gases (PFCs), which are all important greenhouse gases (GHGs). Therefore energy price and GHGs reduction policy has great influence on the technology evolution and the economy of the sector. In order to understand the possible development of the aluminium industry and the potential impact of energy and environmental policy on the sector, the present model is developed at IPTS.

This report discusses the structure and the results of the aluminium model. Chapter 2 gives an overview of the current status of the aluminium industry as well as the key economic and environmental issues in the sector. Chapter 3 summarise the technology development of the sector and identifies the alternative and future technologies that will impact the industry. In the Chapter 4, the structure of the model as well as the necessary assumptions and the mathematical formulation are described in detail. In the last chapter, Chapter 5, the results of the model simulation are discussed.

1.2 Definition

Aluminium, whose chemical symbol as Al, can be produced from natural resource, i.e. bauxite, or from recycled scrap metal. The first process is called the primary production, and the latter secondary production. The application of aluminium is almost always in the form of alloy despite it being primary and secondary metal and the demand for aluminium alloy make no distinction as to the origin of the metal. For a better understanding of the data and information presented in this paper, the following definitions apply:

- *Primary aluminium*: aluminium produced by the primary production process using alumina from bauxite

  Aluminium oxide, also known as alumina, is the main component of bauxite, the principal ore of aluminium. The bauxite ore is made up of impure Al_2O_3, Fe_2O_3, and SiO_2. Through the Bayer process, Al_2O_3 is first dissolved in sodium hydroxide, then precipitates as $Al(OH)_3$ and through calcination, $Al(OH)_3$ decomposes back to Al_2O_3.

  $Al_2O_3 + 3H_2O + 2NaOH + \text{heat} \rightarrow 2\ NaAl(OH)_4$

  $2\ Al(OH)_3 + \text{heat} \rightarrow Al_2O_3 + 3H_2O$

  Alumina is then further reduced via electrolysis process, the so-called Hall-Héroult process, to liquid aluminium metal.

  $2\ Al_2O_3 + 3\ C \rightarrow 4\ Al + 3\ CO_2$

- *Secondary aluminium*: aluminium produced by the secondary production process using the old scrap and new scrap (excluding the so-called run around scrap or internal scrap)

- *Aluminium scrap*: scrap comes from either post consumption products containing aluminium, i.e. *old scrap*, or from the dross during the production process, and cut offs during semi and final fabrication of products, *new scrap*. Scrap from semi product fabrication is mostly remelt on site, i.e. internal scrap, therefore is often not recorded in trade of scrap and also often considered as part of primary aluminium. For this reason, internal scrap is not discussed in this paper.

- *Aluminium consumption*: as aluminium is mainly used as input material to other industries, its products can be distinguished by semi products, ingots, sheets, etc., and final products, window frame, beverage cans, etc. The consumption in this paper refers to the quantity of aluminium in final products. In order to produce one tonne of final product, the needed input of aluminium is often much more than one tonne (the source of off-cut new scrap). Therefore, in order to satisfy the aluminium final product consumption, the *aluminium demanded* and *production* are always higher in quantity.

- *Bauxite resource and reserve*: according to The U.S. Geological Survey (USGS), resource refers to the concentration of naturally occurring bauxite in such form and amount that economic extraction of bauxite from the concentration is currently or potentially feasible. And the part of the resource which could be economically extracted or produced at the time of determination is considered as reserve.

2 OVERVIEW OF THE ALUMINIUM INDUSTRY

Aluminium is the third most abundant element in the earth's crust and the most abundant metallic element. It never occurs as a free element in nature. Aluminium smelting as an industrial activity is the youngest and largest activity of the non-ferrous metal industry, as it began only about a century ago. 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. In 1997, the EU aluminium industry directly represented a workforce of about 200.000 people and its annual turnover was 25 billion Euros.

2.1 Consumption

The world consumption of aluminium in total, both primary and secondary, has grown at an average rate of 3,1% yearly in the 90s, from 29 Mt in 1994 to 38 Mt in 2000; however, the growth in consumption accelerated in the last few years at about 5% annually reaching 45 Mt in 2004 according to the aluminium industry. The more pronounced growth rate per year was observed in Asia at about over 6% before 2000 and 12% after 2000 and the lowest in eastern European countries at 1% at this time. Consumption of primary aluminium was approximately 32 Mt in 2005, with Asia taking the largest share of 45% followed by North America and the EU-27 with 22-23%, as details shown in Figure 1. Primary aluminium consumption in Asia again has the highest increase and followed closely the trend in growth rate of total aluminium. China, as the region's principal country, quadrupled its consumption from 1994 to 2005 and accounts for 22% of world's total consumption, see Table 1. While the share has kept relatively unchanged for most of the principal countries, the relative share of 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.

Figure 1 Primary aluminium: consumption share by regions

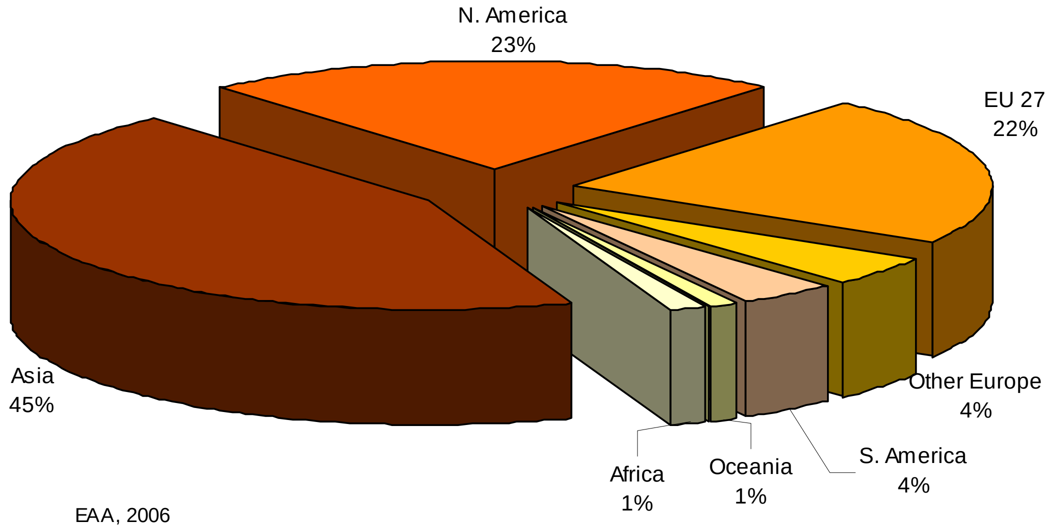


Table 1 Primary aluminium: consumption (in kt) and share of principal markets

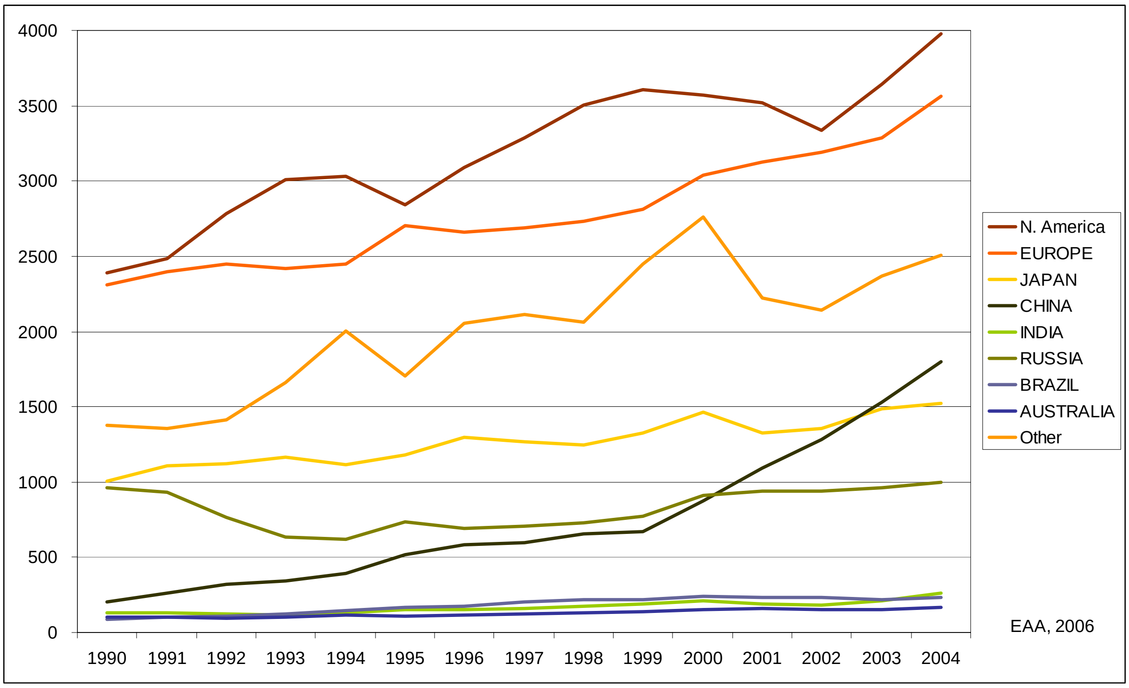
	1994	2005	1994	2005	1994 (kg/pop)	2005 (kg/pop)
USA	5557	6360	28%	20%	21,3	22,4
China	1500	7105	8%	22%	1,2	5,3
Japan	2346	2405	12%	8%	18,8	18,9

Germany	1370	1846	7%	6%	16,9	22,5
Russia	470	940	2%	3%	3,4	6,7
ROK	604	1140	3%	4%	13,6	23,6
Canada	559	805	3%	3%	19,9	25,7
France	736	810	4%	3%	12,7	13,5
India	474	930	2%	3%	0,5	0,9
Brazil	414	683	2%	2%	2,6	3,7
Spain	352	640	2%	2%	9,0	16,3
United Kingdom	565	500	3%	2%	9,7	8,4
Taiwan	355	470	2%	1%		
Belgium/Luxemburg	329	425	2%	1%	31,3	39,8
OCEANIA	393	415	2%	1%	14,0	12,7
Sub total	16024	25474	81%	80%		
TOTAL WORLD	19868	31801	100%	100%		

Source: EAA, 2006

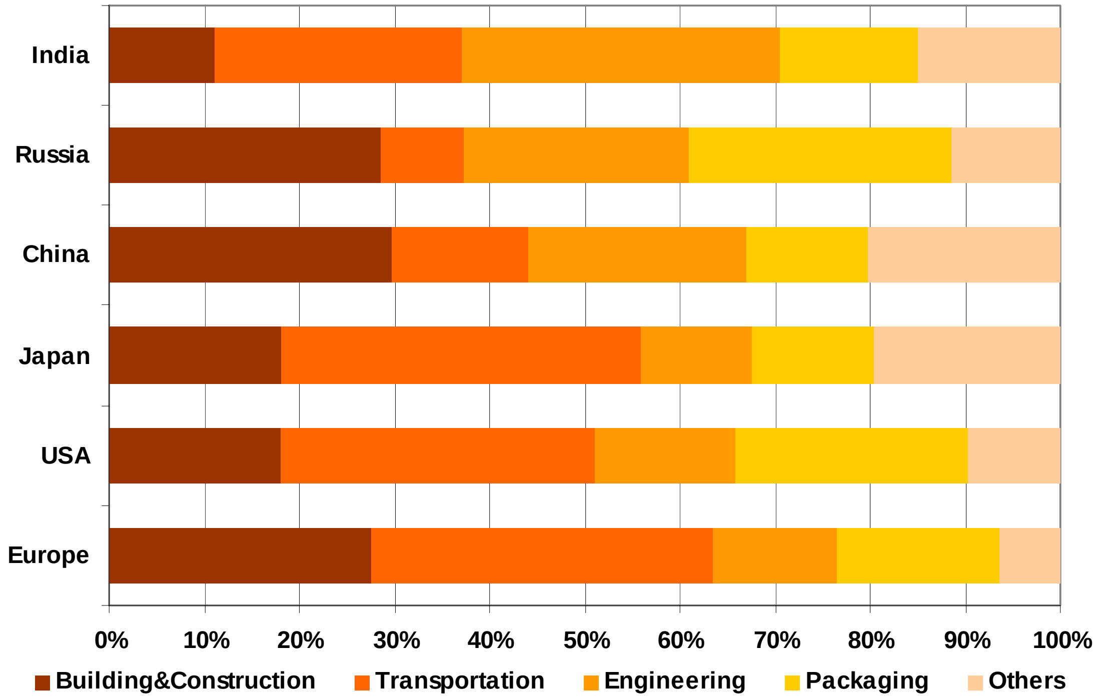
The estimated consumption of secondary aluminium, based on reported data, indicates an increasing trend in all regions in the last decade (see Figure 2). Europe and North America accounted for a dominant share of 50% in the 2004 world total. Again the growth in China is most prominent, being more than doubled between 2000 and 2004. The consumption of secondary aluminium in Europe increased at an annual average of 3% in the same time period.

Figure 2 Secondary aluminium: consumption and trend by region 1990-2004



As already mentioned, aluminium is widely used as an input material in several industrial sectors. An estimate of the sectoral consumption of aluminium in the principal markets, Figure 3, shows that transportation, and building and construction accounted for the majority share of over 50% in Europe, Japan and the USA, while in China and Russia, building and construction sector took the largest share. However, the shares can vary significantly from one country to another as a consequence of their different industrial economic structure. Among all the principal countries, scattered data indicate that the share for transportation shows a more pronounced increase than that of all the other sectors and has doubled since 1997 in the case of China (*Roskill, 2003*).

Figure 3 Aluminium consumption: sectoral consumption

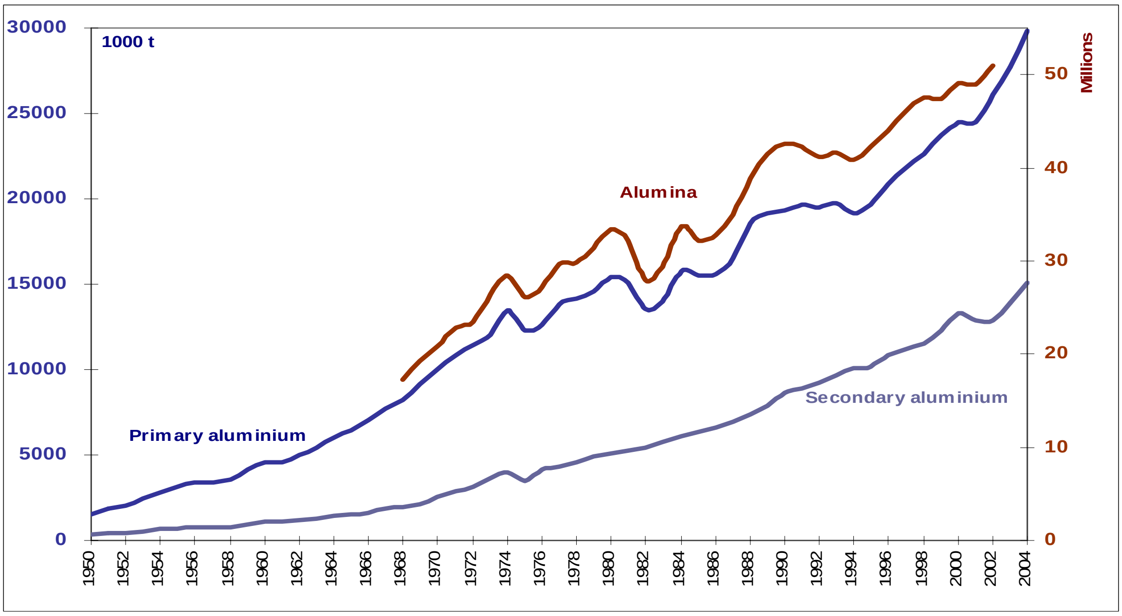


Source: EAA, 2006

2.2 Production and trade

Aluminium is produced in both primary form from alumina (Al_2O_3) and secondary form from scraps. The history of world production, as presented in Figure 4, shows a strong increasing trend for the production of both aluminium and alumina since the 50s.

Figure 4 Alumina and aluminium production 1950-2004



Source: EAA, 2006, USGS, 2006

Primary aluminium is produced by the reduction of alumina which is converted from bauxite, see also Chapter 3. On average, 100 tonnes of bauxite produces 40-50 tonnes of alumina which then generates around 20-25 tonnes of aluminium (*CRU, 2002-2003*). Bauxite resources are estimated to be 55000-75000 Mt, located in South America (33%), Africa (27%), Asia (17%), Oceania (13%) and elsewhere (10%) (*USGS, 2006*). Shown in Table 2, the current bauxite reserve (currently and marginally economic) amounts to 25000 Mt. The origins of the bauxite reserve and their respective production of alumina are also presented in Table 2. Although South America has the highest reserve, production of both bauxite and alumina is by far the highest in Australia. There are several alumina production facilities in the EU, which used to produce roughly the same amount of alumina that was needed for its primary production though increasingly insufficient in the recent years. In 2004, there are 56 alumina refineries and 200 primary aluminium smelting plants worldwide, of which seven and 38 respectively are located in Europe. There are some 100 reported production sites in China, of which a considerable number are small scale primary producers accounting significantly to the country's capacity and production. It is estimated that currently Europe has around 286 refiners/remelters, most with an annual capacity of above 1000 tonnes. Another 137 and 77 refiners/remelters in North America and Japan, and together with the rest of the world, the recycling industry numbers 1200 plants (*EAA, 2006 and CRU, 2003*).

Table 2 Bauxite and alumina: reserves and production, 2004

	Bauxite reserve		Bauxite production		Alumina production	
	Mt	share	Mt	share	Kt	Share
Guinea	7400	30%	16	10%	670	1%
Australia	5700	23%	56,6	36%	16382	30%
Jamaica	2000	8%	13,3	8%	3631	7%
Brazil	1900	8%	18,5	12%	3962	7%
India	770	3%	11,3	7%	2800	5%
China	700	3%	15	9%	5450	10%
Guyana	700	3%	1,5	1%		
Greece	700	3%	2,4	2%		
Surinam	580	2%	4	3%	1900	4%
Kazakhstan	350	1%	4,7	3%		
Venezuela	320	1%	5,5	3%	2100	4%
Russia	200	1%	6	4%	3131	6%
EU-25					6249	12%
USA	20				4340	8%
Others	3400	14%	4	3%	9634	6%
Total	**24740**	100%	**159**	100%	**54000**	100%

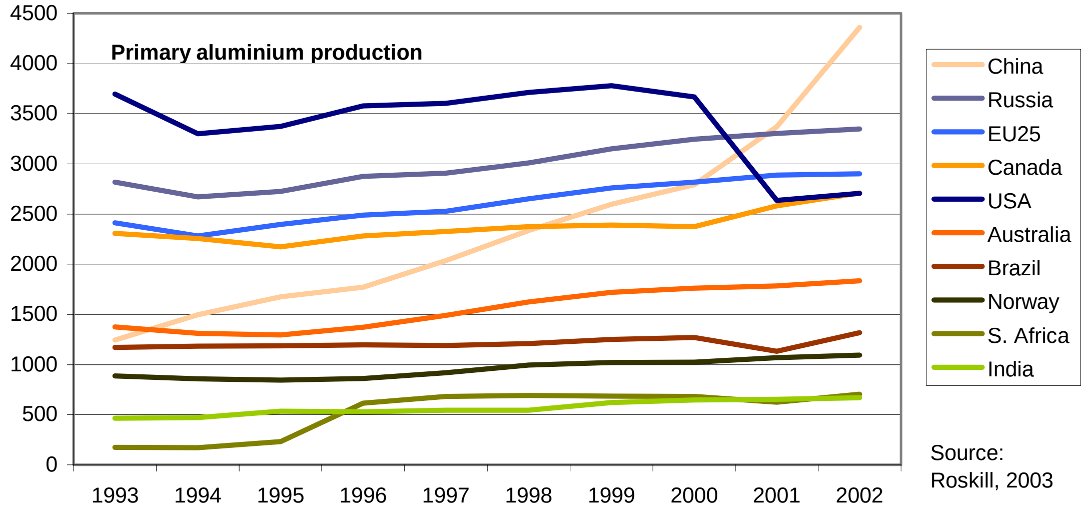
Source: Roskill, 2003 and USGS website, 2006

The world total primary production grew at an average rate of 2,3% per year between 1990-2000, and sharply increased to more than 5% after 2000 (*EAA, 2006*), and as result, the reported total world production of primary aluminium was approximately 30 Mt in 2004. The principal production countries can be characterised as strong growth in China at an 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 5 and by the IAI statistics (*IAI, 2006*). In 2004, the EU-25 accounted for 14,5% of the world's primary production, and has had a yearly average growth rate of 2% in production since 2000. The share of primary production in China increased from 12% in 2000 to 23% by 2004.

An approximate comparison to the consumptions, presented in Table 1, indicates that the EU-25 and USA are clearly the importers of primary aluminium, and Russia, Canada and Australia are the major exporters, while China and India appear to be just self-sufficient. In total, world trade of aluminium (both primary and secondary) accounted for nearly 50%, i.e. 15,5 Mt, of the world total consumption. The trading activity of primary aluminium is rather concentrated. The main exporters, Russia, Canada, Australia, Norway, Brazil, the United Arab Emirates and South Africa, accounted for around 60% of world’s total export in 2000 and 2001 with 20% originating from Russia alone. The USA and Japan were in turn being the largest importers and together accounted for more than 35% of world’s total import. The other main importers are

Germany, the Netherlands, South Korea, and Italy. Trade between these major exporters and importers represents about 30% of the world trade. The EU-25 accounted for approximately 10% and 33% of the world's export and import respectively.

Figure 5 Primary aluminium: production by principal countries/regions, 1993-2002

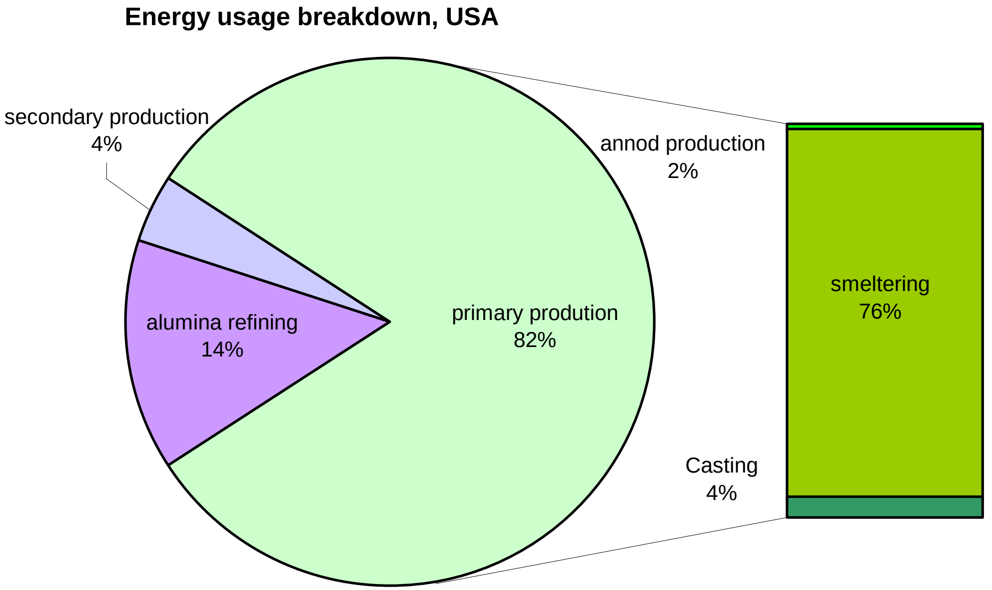


Source: Roskill, 2003

2.3 Energy consumption

Alumina refining mainly requires thermal energy for bauxite digestion and calcinations, which is reported to be less than 20% 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 whole primary production process (incl. alumina refining). An estimated breakdown of the energy consumption in the USA as an example is shown in Figure 6.

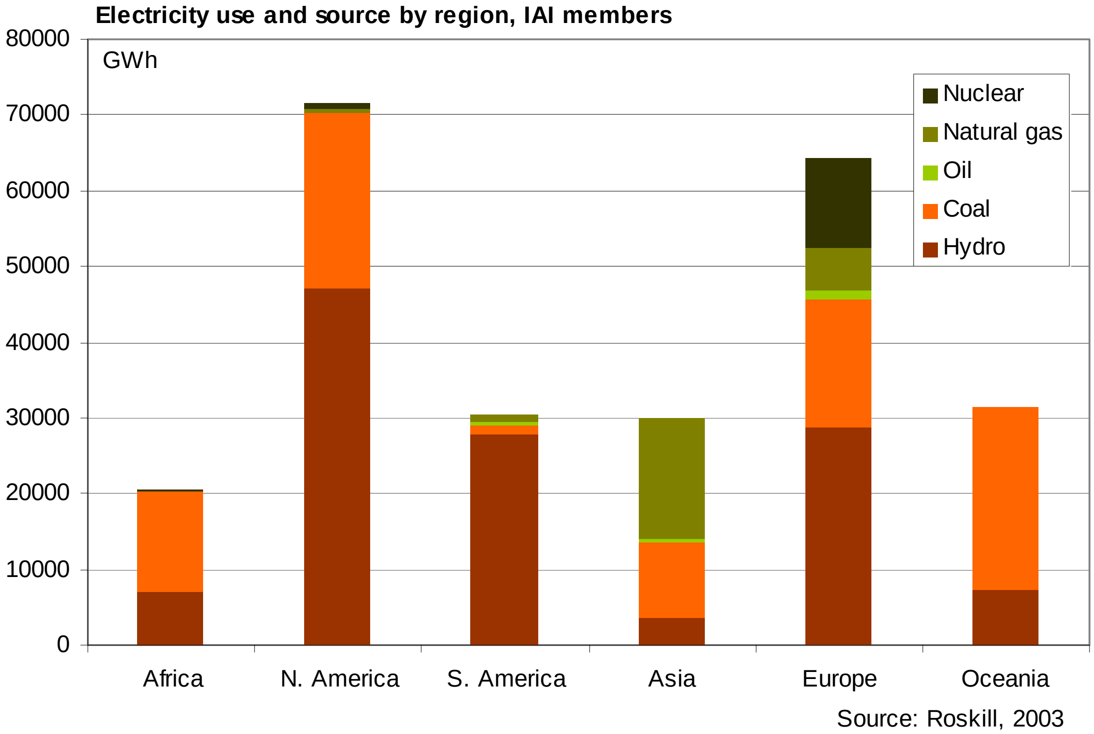
Figure 6 Aluminium production: energy usage (per tonne aluminium) by section



Source: ENERGETICS, Maryland, USA, 1997

In 2001, the world's total power consumption of all the primary smelters was 350GWh, of which 28% was self generated; however, such a share ranged from 0% in Africa to 95% in Southeast Asia. The source of electricity for the members of the International Aluminium Institute (IAI), which in total accounts for more than 70% of the world primary production, is illustrated in Figure 7. While the fuel mix varies significantly from region to region, overall, hydro electricity plays a great role as a source of power in the primary production, accounting for nearly half of the total power consumed in the reporting members and followed by electricity from coal at 36%. While the USA and Canada relies primarily on power from hydro and coal, electricity fuel in Asia is mainly coal, gas and nuclear and accounted for 18% of the power supply to the sector in Europe.

Figure 7 Primary production: electricity use and source, 2001



Source: Roskill, 2003

2.4 Key environmental issues

The main environmental concern of the industry is related to primary aluminium production, where GHGs including two perfluorocarbons (PFCs), CF_4 and C_2F_6, are generated as a result of the anode effects during electrolysis. Both PFCs have a global warming potential much higher than CO_2. As already mentioned, primary aluminium production is electricity intensive, therefore CO_2 emissions of the industry highly depend on the primary fuel for electricity generation. According to a study from International Energy Agency (IEA), total GHG emissions of the aluminium industry were around 390 Mt of CO_2 equivalent in 1990 and decreased by 7% by 1995, mainly due to the reduction of process related PFC emissions. A breakdown of the GHG emissions shows that primary aluminium production accounts for 72% of the sector's total and 26% from the alumina production, while secondary production contributed to around 1%. Based on the world production data, it is estimated that GHG emissions in 2000 were slightly more than 155 Mt CO_2 equivalent as direct emissions from the sector, including primary production and fuel combustion (for heat as well as self power generation). The indirect emissions from grid power generation are around the same level. Together, the world's aluminium industry contributes to approximately 1% of the total anthropogenic GHG emissions.

There are also large amounts of solid waste, such as undissolved bauxite known as red mud, generated during the extraction of alumina. An alumina refinery with a capacity of 1 Mt per annual produces more than 1Mt of red mud on dry basis per year. The insoluble mud is generally alkaline containing 3 – 12 kg of NaOH per tonne of alumina production, therefore it needs to be neutralised before being discharged. Current practice is to deposit the treated mud on or near the site in specially designed, sealed ponds.

Environmental issues related to the secondary aluminium production are relatively less significant. However, emissions to air consist of particulates with traces of metals, chlorides, hydrochlorides, as well as organic hazardous compounds including dioxins. The type and quality of scrap has the major influence on the emissions. Various techniques, e.g. hood, baghouses, cyclones are used to capture the fumes/gases and control air emissions to meet the standards. Filter dust collected is deemed to be hazardous and is currently land filled or partly recycled. Salt slag, a mixture of salts, aluminium oxide, aluminium metal and impurities, is a typical residue from aluminium scrap melting, and there can be as much as 500 kg of salt slag generated per tonne of metal production. The salt slag is now being completely recovered and reused on site for the same purpose. Meanwhile, aluminium metal is also recovered and the remaining residues are, whenever possible, used in cement production or land filled.

3 INDUSTRY PROCESS AND TECHNOLOGY

The aluminium industry as a whole consists of four subsectors each having their own distinguished characteristics, production processes, technologies, resources and energy demand:

- bauxite mining
- alumina refinery
- primary aluminium smelting
- scrap recycling and secondary aluminium refinery

3.1 Bauxite mining

Bauxite mainly consists of aluminium hydrates and the bulk of its known reserves are located in countries of the southern hemisphere, e.g. Guinea, Australia, Jamaica, etc., as detailed in Table 2. Nearly all bauxite currently mined is produced by open-pit mining because underground mining tends to be more costly. Bauxite is extracted from a site by removing the overburden and loosening the bauxite deposit with explosives, depending on its hardness and other local conditions. In some cases, the bauxite is crushed with dust control equipment, and/or treated with water to remove impurities, and dried prior to shipment to the alumina refinery. The mining site residues and wastes are then treated and the site is restored. Bauxite mining and trade are not included in the present model.

3.2 Alumina refining

There are four different processes identified in the current alumina production, the Bayer process, and three alternative processes, i.e. the Sinter process, the combined/parallel Bayer-Sinter process and the Nepheline-based process. The Bayer process is the most widely used form of alumina extraction. The method was developed in the late 1800s and has been the conventional and most efficient process for alumina hydroxide manufacturing.

The **Bayer process** can be summarised as the following as illustrated in Figure 8:

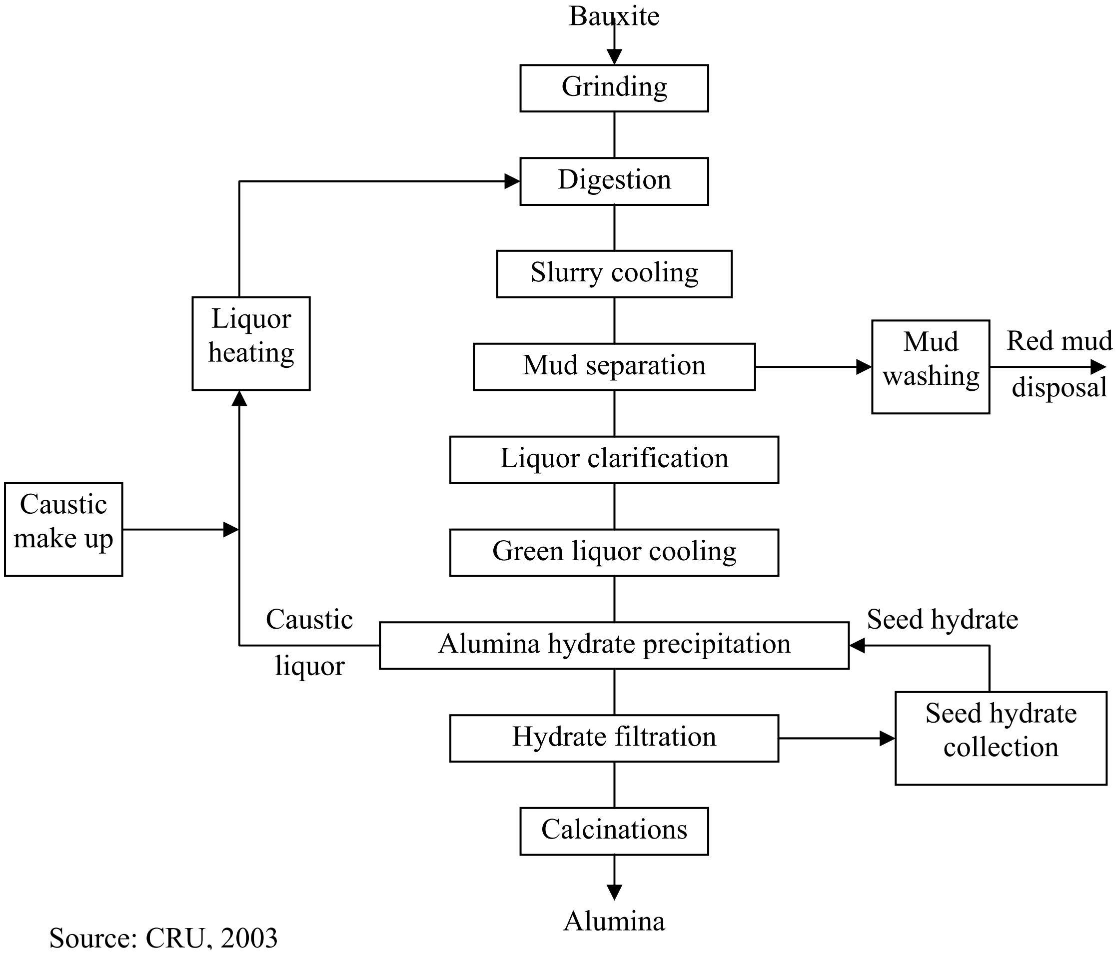
- the bauxite is ground and combined with hot caustic liquor either in ball or rod mills, to form slurry. Caustic soda is added to the slurry and the mass is then steam heated in digesters. The solution is approximately 30% NaOH at a temperature between 150 and 230 ^{o}C

- the resulting liquor contains a solution of sodium aluminate and undissolved bauxite residues which contain 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 60-75 ^{o}C, and fine particles of alumina are added to seed the precipitation pf pure alumina particles as the liquor cools. Seed hydrate crystals are added to the solution to promote the growth of alumina hydrate crystals. The precipitate sinks to the bottom of the tank, is settled and filtered off

- finally, the washed crystals are dried and calcinated in fluid bed or rotary kiln calciners at a temperature of around 1000 ^{o}C.

Figure 8 Bayer process



Source: CRU, 2003

In total the alternative processes produce 17% of the world's alumina, and majority of them are located in China and Russia. The alternative processes mainly aim at accommodating different raw materials and improving the recovery rate of alumina. Due to the variety of aluminous materials used in alumina production, the **Bayer-Sinter process** is favoured in China. However, high energy consumption has been the drawback of the Sinter process, which requires 30-40 GJ/tonnes alumina in comparison to 11GJ/tonne for the Bayer process. The Sinter process typically results in the production of large amounts of leached residue which can be used for cement production, and combined alumina and cement production could reduce the cost of mud disposal significantly as is the case in China.

Because of the lower alumina content of nepheline ore (a silica-undersaturated aluminosilicate, $Na_3KAl_4Si_4O_{16}$), the **Nepheline-based process** requires the handling of a greater volume of material (4.8 tonnes to one tonne of alumina) and results in various by-products of substantial amounts. Consequently, this process has a much higher cost than the Bayer process and only becomes economically viable when all the by-products can be sold. Currently, production of alumina from nepheline ore exists only in Russia and Iran, totalling 1,3 Mt of alumina in 2002.

3.3 Primary aluminium production

Primary aluminium is produced entirely through the Hall-Héroult process, which involves the electrolysis of alumina dissolved in a bath of molten cryolite (Na_3AlF_6) at a temperature of 960 ^{o}C. The electrolytic cells comprise a carbon cathode, insulated by refractory bricks inside a rectangular steel shell, and a carbon anode suspended from an electrically conductive anode beam. The cells are connected in series to form an electrical reduction line. A direct current is passed from a carbon anode through a bath to the cathode and thence, by a busbar to the next cell.

Alumina content in the molten bath is maintained at 2-6% and computer controlled addition is common in a modern plant. When alumina content in the electrolyte bath falls too low, the bath itself would start the electrolytic reaction with the carbon in the anode, the so-called anode effect, producing two types of PFC gases, i.e. CF_4 and C_2F_6. Furthermore, fluoride compounds, mostly as aluminium fluoride (AlF_3), are added enabling the cells to be operated at a lower temperature. Currently, most cells are now operated with the AlF_3 content of the bath significantly in excess of the stoichiometric cryolite composition, consequently with potentially increased fluoride emissions.

Liquid aluminium is deposited at the cathode in the bottom of the cell and oxygen combines with carbon anode, to form carbon dioxide. The carbon anodes are therefore continuously consumed during the process. The molten aluminium is periodically withdrawn from the cells by vacuum siphon into crucibles. The crucibles are transported to the casting plant and the aluminium is emptied into heated holding furnaces. Alloying additions are made in these furnaces with controlled temperature.

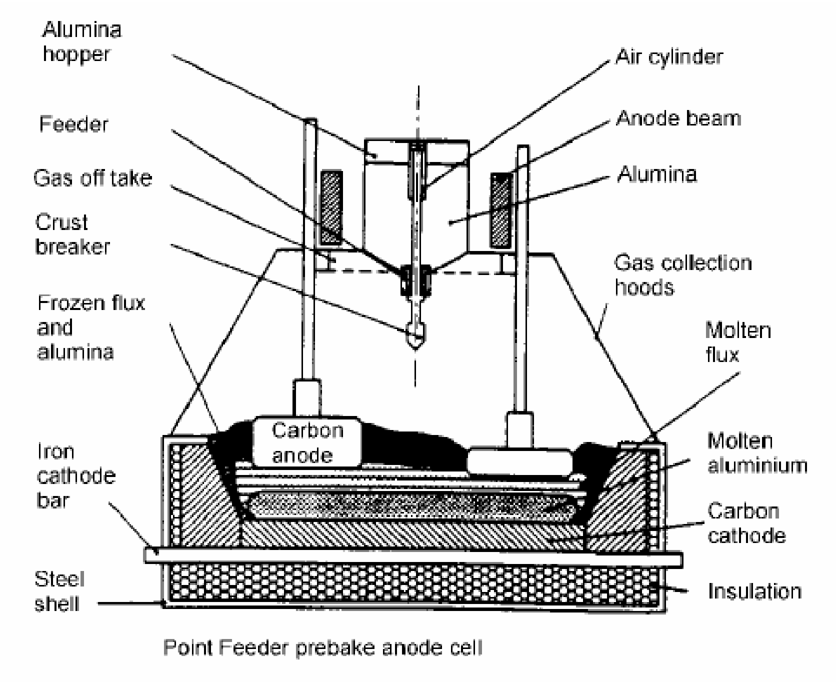
Primary aluminium technologies are differentiated by the type of anode used and the method by which the pot is worked or the anode is introduced into the cell. The two major technologies are Prebake and Søderberg.

3.3.1 Prebake

In the prebake cells, the pots use multiple anodes that are formed and baked prior to consumption in the pots. The prebake technology has essentially two variants based on how alumina is fed to the cell, i.e. where the pot working (crust breaking and alumina addition) takes place: Centre Worked Prebake (CWPB) and Side Worked Prebake (SWPB). In the CWPB cells, alumina is fed along the longitude centre line of the cell, whereas in SWPB technology, alumina is added along the longitudinal sides of the cells. A third variant of the prebake is defined as Point feed Prebake (PFPB, see Figure 9) to represent the state-of-the-art technology in primary production. In comparison to CWPB, PFPB has a distinct method of feeding alumina into the cell, i.e. a point feed system, which enables more precise process control of alumina concentration in the bath, produces less sludge and stabilises the temperature. These features allow higher current efficiency, lower energy consumption, and lower emissions. All the new plants are using point feed.

Prebaked anodes are manufactured from the mixture of calcined petroleum coke and coal tar pitch in a separate anode plant, which is often an integral part of the primary aluminium plant.

Figure 9 Prebake cell

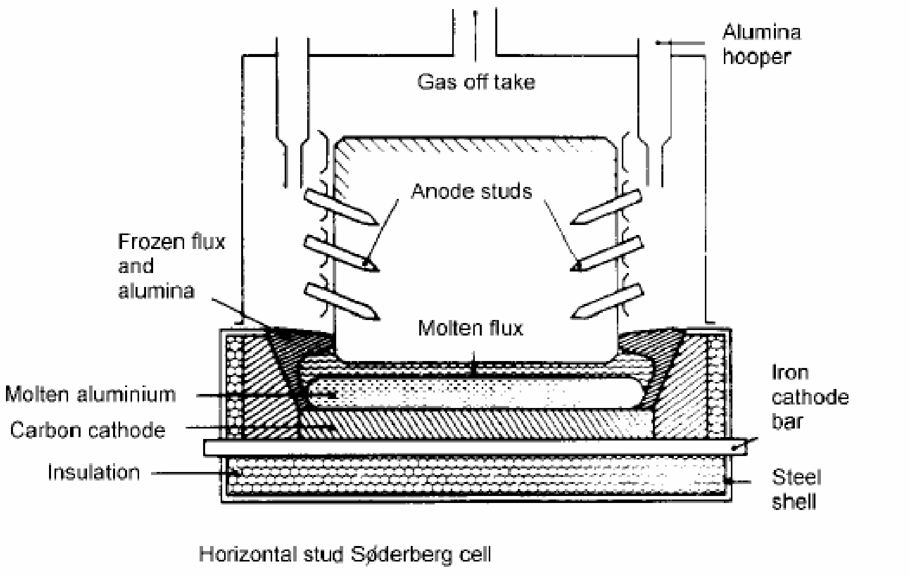


Source: IPPC, 2001

3.3.2 Søderberg

Søderberg cells use a single, monolithic, carbon anode that is added as paste and baked in the cell itself through the heat arising from the molten bath. Søderberg technology has two variants based on how the electricity is introduced to the cell, i.e. Vertical Stud Søderberg (VSS) and Horizontal Stud Søderberg (HSS). In a VSS cell, the electrical connectors or studs are placed vertically into the top of the anode, while in an HSS cell, it is placed horizontally into the anode along the longitudinal length on both sides of the cell. Søderberg cells, popular from the 1940s to the 1960s, in general are less efficient than prebake cells in terms of capture and collection of fluoride fumes and hydrocarbons generated from the process. Therefore it has become more costly to comply environmental and health regulations and are gradually being replaced by prebake technology.

Figure 10 Søderberg cell



Source: IPPC working document, 2000

As already mentioned, primary aluminium production is very electricity intensive. The theoretical minimum energy needed for the electrolysis is 6,34kWh/kg of Al. Currently, the lowest can be reached at is 13kWh/kg Al in a modern production line with a high amperage, state-of-the-art computer system, and point feed cells, and they can achieves energy efficiency of 50%. Around 45% of the energy input is lost as heat exchanged to the surroundings, e.g. pot shell, anodes and crust. Anode changing is routine for prebake cells and is the greatest thermal disturbance in the production. The application of new technology (state-of-the-art point feed) and better process control could reduce an estimated 10% of energy consumption. It is believed that only a radical technology breakthrough, e.g. the inert anode/cathode could result in significant improvements in energy efficiency.

3.4 Secondary aluminium production

Secondary aluminium is produced from recycled scrap that is either generated at the smelter and fabrication plants or collected post consumption. Thus the aluminium scrap is categorised as: new and old, due the distinction of pre or post consumption.

Sources of new scrap are the production plant of primary aluminium and plants that use aluminium as the input material. Usually there is no need for sorting of the new scrap and it can be used on-site at the smelter or transported directly to a secondary refiner or remelter. Pre-treatment is only needed when the new scrap includes alloys. Old scrap is waste material that has a high aluminium content, such as electronic appliances, automobile parts, construction material, packaging material, etc. Secondary producers are usually distinguished as refiners and remelters. Refiners produce casting alloys and deoxidation aluminium from scrap of varying composition, and are able to add alloying elements and remove certain unwanted elements after the melting process. Remelters produce wrought alloys from mainly clean and sorted wrought alloy scrap.

The secondary aluminium production process from old scrap includes: old scrap collection and sorting, scrap pre-treatment, and melting and refining. The main feature of the production process is the diversity of raw materials encountered and the variety of furnaces used. The type of raw material and its pre-treatment is therefore used to judge the best type of furnace to be used for a particular type of scrap with its size, oxide content and degree of contamination among others. Therefore, the choice of process technology, in most cases, varies from plant to plant, and there are potentially many possible strategies to set up the process for the treatment of similar input material. An overview of the production process can be described as the following:

Scrap pre-treatment: pre-treatment operations include sorting, shredding, and cleaning. These steps aim at minimising the losses of aluminium in the smelting furnace as well as reducing the furnace emissions of air pollutants and other toxic substances. After sorting aluminium scrap from other scraps and metal pieces, it is shredded down to a smaller size which will promote quicker melting. The cleaning process will remove oils, organic coatings, and other contaminants and this is done through a carefully controlled burning or, in some cases, by using hydrometallurgical technique. The design of the pre-treatment process is essential to the quality of the scrap and it depends fundamentally on the type of the waste material to be treated.

Melting and refining: this stage of operation includes melting, adding fluxing agents, removing magnesium, degassing, alloying, and skimming. There are a number of melting technologies in use, and the choice among them is dictated by the characteristics of the scrap, mostly how clean the scrap is after the pre-treatment. Most of the furnaces used for melting can thus be differentiated into high emitting furnaces and low emitting furnaces.

High emitting furnaces usually refers to those that can process a large amount of contaminated scrap, such as insulated wire, oily borings and turnings, used beverage cans (UBCs), and coated or painted aluminium foil. Reverberatory melting furnaces with side-charge wells and rotary barrel furnaces are used for such types of scrap and usually with the use of chlorine or other agent containing hazardous substances for damaging/degassing. The standard reverberatory furnace is the most common technology in secondary aluminium production and generally employed to treat large volumes of smaller size scrap.

Low emitting furnaces are defined as any furnace designed to process only clean scrap without fluxing, and without the use of hazardous agent for demagging and degassing. The “clean” scrap includes delacquered UBCs, fried borings and turnings, uncoated aluminium siding and foil, sweated aluminium and new scrap from primary production and foundries. The common furnaces in this category are induction furnaces for scrap with fewer surfaces (larger size) and the Meltower process.

3.5 Technology development of the industry

The status of the currently prevailing technologies of the industry are well developed and widely accepted. They are readily accessible to any new producers and are adaptable in various economic conditions. Alumina and aluminium production requires certain economies of scale and is a capital intensive industrial activity. While efficiency has been improving continuously, especially in primary aluminium production, there has been no technological revolution in the past decades.

Retrofitting options

Because the cost of energy in primary production is high, improving efficiency has been the driving force for the technology evolution in the industry. While some of these technological improvements are specific to the aluminium industry, others reflect rather the overall progress of industries. In the European Commission's adopted BREF document on Non-Ferrous Metals Industry (*IPPC, 2001*), various technical options and good practices are described to improve the aluminium processes. Here are some examples of the key technology developments:

Options to improve the Bayer process: as mentioned, the Bayer process is the prevalent technology for converting bauxite to alumina. Two main options are currently available to increase energy efficiency, i.e. calcinations with fluidised bed kilns replacing the rotary kilns, and the application of cogeneration. The first option allows both a more desirable grade of alumina and a reduction of fuel demand by two-thirds. The second option could save 15% of the primary fuel consumption of the plant, and in fact, it is believed that in order to compete in the world alumina market, cogeneration would have to be integrated.

Options to improve secondary aluminium production: one of the first issues to be addressed in the secondary production is scrap collection, which determines the availability of scrap and sets the limitation of secondary production. Infrastructure is needed for collection and, equally important, the environmental awareness of a society is crucial. Technology aiming at increasing metal recovery efficiency during the production is possible in three key areas. The first is the dross metal recovery, which makes it possible to separate dross, for recycling aluminium component, from salt cake, for recovering the salt fraction. This technology, currently still new, would avoid a large amount of solid waste to landfill, and result in energy savings from 1,5% to 8% depending on the scrap type. The second is the innovative decoating equipment, which decreases the loss of furnace melt (dross) and utilises the organics present in the scrap as a source of energy. Therefore, the adoption of this technology is expected to bring 12% of energy savings. The third one is to replace the side-well of the reverbatory furnace by equipment such as DC plasma arc melting technology and the vertical floatation melter. This will reduce dross formation and save up to 35% of energy.

Options to improve the primary electrolysis process: since electricity accounts for one-third of the energy cost in primary production, the effort for the industry has been to focus on improving the efficiency of the Hall-Hèroult Process. As already mentioned, the electricity intensity (kWh/t) has decreased at an average rate of 1,5% per year since the start of industrial application of the technology at the beginning of the century. In the early 1980s, technology broke through with a point feed and system control was achieved (see the next paragraph) and since then optimal engineering design continues to decrease the electricity consumption. Apart from electricity cost, the environmental compliance cost, especially related to the GHGs, is and will continuously serve as a driving force for technological retrofitting. The current widely adopted technical options are described as the following:

The point-feeding system with computer control: conversion to the state-of-the-art PFPB technology is the most accepted route for increasing operational and environmental efficiency for both CWPB and SWPB. Even for Søderberg cells, this conversion holds one of the most feasible retrofitting options although with a relatively high cost. Unit electricity consumption reduction can be achieved from 10 to 30% depending on the starting technology and cell design.

Optimisation of the electrolysis process: potential improvement of the existing cell performance includes several measures, e.g. the composition of chemical bath, carbon anode design, cell pot material, etc. aiming at reducing heat losses, anode consumption, etc. Optimal parameters vary from one pot (line) to another, thus these measures are implemented only after extensive computer modelling and large-scale testing. Optimisation of the process has been ongoing since the beginning of the industry. The potential energy intensity reduction is between 15 and 30%.

Advanced technologies

In the last 20 years, R & D has not given any viable alternatives for primary aluminium production other than the currently prevailing electrochemical process, and advanced technology innovations are not expected in alumina production. However, some advanced technical improvements on primary and secondary processes are under research development and some are expected to be commercially available in some 20 years time. These potential improvements, taken from various sources, are summarised here:

Lower the electrolysis temperature (PBRTE): currently the electrolysis is performed under an average temperature of 1220K which is far above the melting point of aluminium (933K), which implies a high heat loss. Several approaches for temperature reduction have been investigated and the promising results come from new additives for electrolyte. Theoretically, a reduction of temperature to around melting point could decrease electricity use by 1-1,5 kWh/kg. It is assumed that this option could become available in 2010, saving 0,7 kWh/kg (5%).

Drained-cell technology (wettable cathode): this option involves the development of an inert titanium diboride (TiB_2) cathode (also called wettable cathode) which allows the cell design in ways that the molten aluminium can be drained from the cathode to collection sites in the cell, thus eliminating the magnetically induced turbulence, and enabling the cell operation at a much reduced interelectrolyte distance, therefore achieving better energy efficiency. The potential energy savings are estimated to be as high as 15-20%. This technology has been field tested; however, benefits are not desirable due to cell design and heat balance constraints. Nevertheless, if a break-through can be made, this technology is expected to become commercially viable in 10-20 year's time.

Inert anode (PBANOD): the development of inert, non-carbon anodes that would not be consumed in the electrolysis process is a major potential advancement in primary aluminium production. However, cell design and heat balance constraints are to be overcome. Furthermore, there has been no suitable anode material to sustain in the corrosive and high temperature of the cell environment. Energy efficiency would improve in the range of 10-25% and commercial availability is expected by 2020. When an inert anode is combined with the wettable cathode, higher efficiency gains can be achieved. Due to the absence of carbon, the cost of anode replacement would be saved and no CO_2 and PFCs will be generated in the electrolysis process.

From the point of scrap to secondary production, two technologies related to the sorting of automobile scrap are the focus of research and development given the fact that scrap availability from the automobile sector is expected to increase largely in the next 10-15 years due to the end of life of the current automobiles with a high aluminium content. Furthermore, with recent trends pointing towards a growing demand for sorting and separating different alloyed aluminium, industrial commercialisation of these technologies appears imminent.

Alloy separation with laser/x-ray: the laser-induced breakdown spectroscopy (LIBS) technique is an adaptation of the optical emission spectroscopy chemical analysis technique tested currently for aluminium alloys separation. Instead of using a direct current arc to vaporise a small region of the sample for analysis as in the conventional method, a laser performs this task, resulting in a higher potential rate of processing. The spectrum of each sample is analysed and its chemical composition determined, which allows alloy identification piece-by-piece. According to recent reports, up to 50 shredded pieces per second can be analysed by this method. In order to be effective, this technique requires surfaces to be cleaned of all paint and protective coatings, so a de-coating step is required prior to the LIBS analysis. The technology is already in an advanced stage of development.

The selective etching plus colour sorting technique: utilises treatment of the shredded pieces by a caustic etch. Since different aluminium alloys will react differently to an etch based on their alloying constituents, they can be sorted by the resulting colour of the etched pieces. Alcoa has patented a process that enables the separation of alloys into three distinct categories: "bright", which consists of pure Al and binary Al-Mg alloys; "grey", which consists of Al-Mg, Al-Si, and Al-Mg-Si alloys; and "dark", consisting of alloys containing Zn and Cu. Subsequent to etching, a camera performs the sorting function.

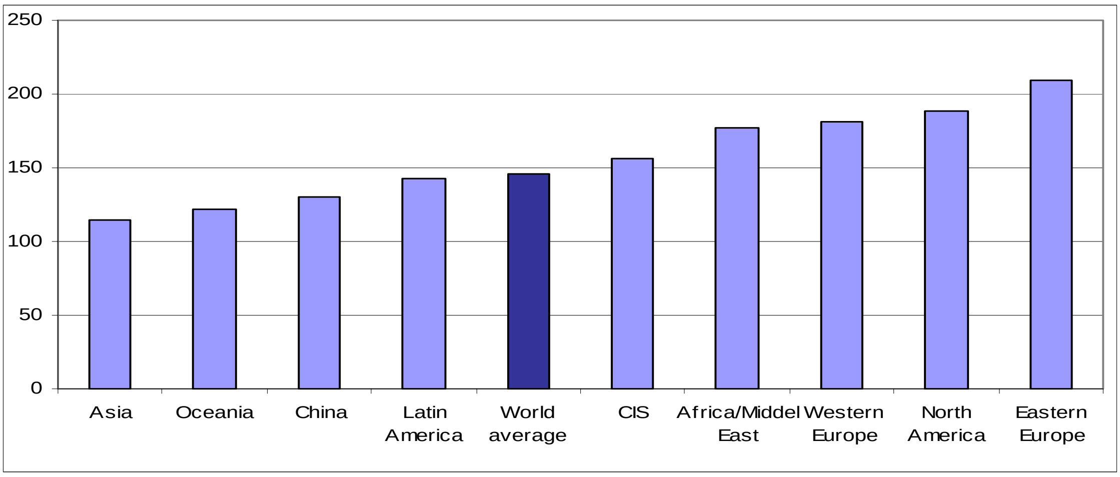
3.6 Costs and prices at world level

Production costs of the different sub-sectors of the aluminium industry are interlinked, and are usually strongly affected by the price of aluminium at world level. In practice, the cost of the essential raw materials and inputs, i.e. alumina and electricity for primary production, are contracted in relation to the primary aluminium price.

3.6.1 Alumina production cost

The average cost of alumina production was estimated to be 145,7 nominal USD/tonne in 2002, falling slightly from the previous year. By region, shown in the Figure 11, Asia, excluding China, and Oceania have the lowest production cost as a result of their own low cost bauxite resource plus relatively lower energy prices. The cost disadvantage of using traded bauxite is reflected in the case of Western Europe and North America. On average, bauxite (24%) and energy, both heat and power (35%), accounted for more than half of the production cost, while caustic soda takes 13% and labour 10%.

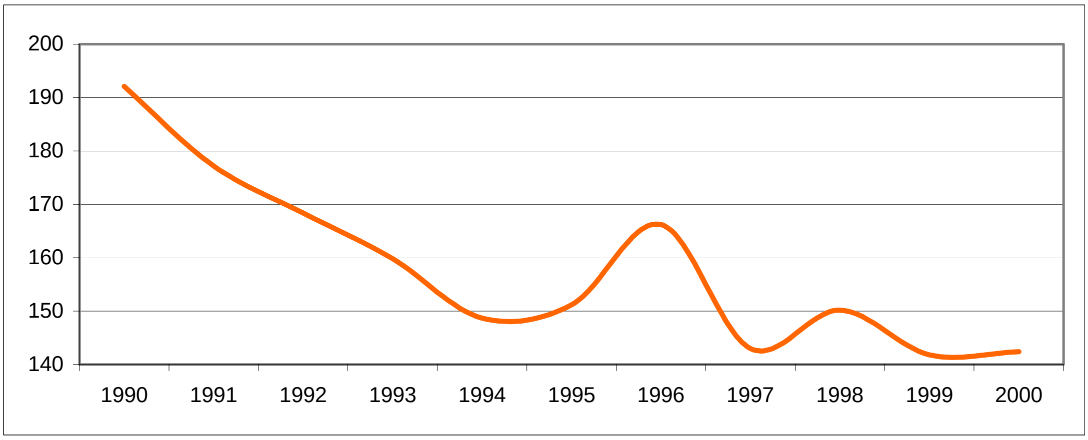
Figure 11 Alumina production cost by region (nominal USD/tonne, 2002)



Source: CRU, 2003

In the last decade, the full operating cost of alumina production has decreased at a rate of 5USD/tonne yearly since 1990 reflecting a combined effect of, on the one hand, the decline in the price of caustic soda and the low metal price, and on the other hand, the increase in energy cost, as shown in Figure 12.

Figure 12 Alumina production: full operating costs, 1990-2000 (2002 USD/tonne)

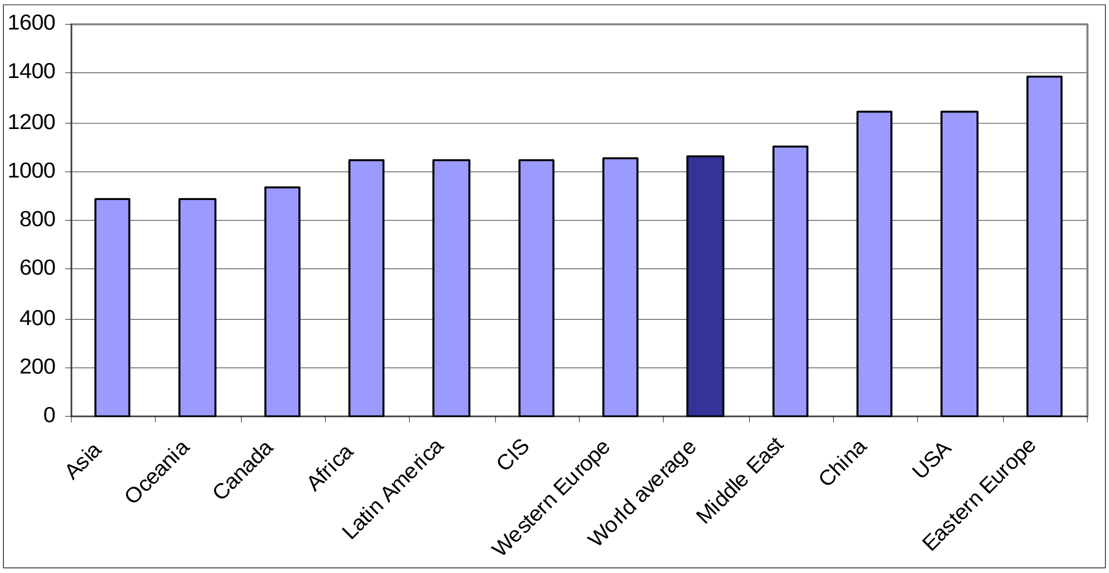


Source: CRU, 2003

3.6.2 Primary aluminium smelting costs

The world average operating costs of the aluminium smelters was 1060 nominal USD/tonne in 2001, a decrease of 90 USD/tonne from that of 2000. Comparison among the main production regions, as given in Figure 13, shows that the cost difference of approximately 500USD/tonne could be observed between Asia and Eastern Europe. The contracted alumina price and power tariff are the main attributions to the cost variation among the regions and together they accounted for around 60% of the average cost in 2001 while labour and other materials (including carbon) totalled to another 37%.

Figure 13 Primary aluminium production costs by region (nominal USD/tonne 2001)

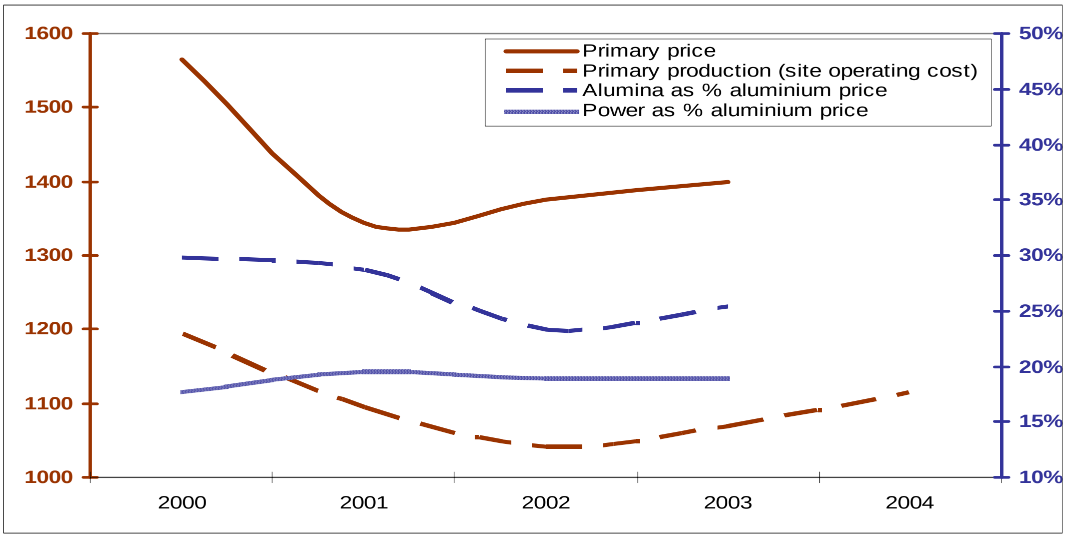


Source: CRU, 2003

As already discussed, alumina and electricity are the main cost factors in primary aluminium production. Most aluminium smelters have one-year or medium to long term contracts with alumina suppliers in the form of alumina being priced as a percentage, 10,5%-14,5%, of the prevailing London Metal Exchange (LME) 3-month price of aluminium and such a relationship can be illustrated by the production cost of alumina as a percentage of the primary price, as in

Figure 14. Similarly, about 25% of primary aluminium is produced with the electricity purchased under fix term contract with power supplier and the tariff of electricity is linked to the primary metal price. This implies that the cost of aluminium production is influenced, strongly in the short term, by the price of metal.

Figure 14 Interrelation between primary aluminium price and production costs (US$)

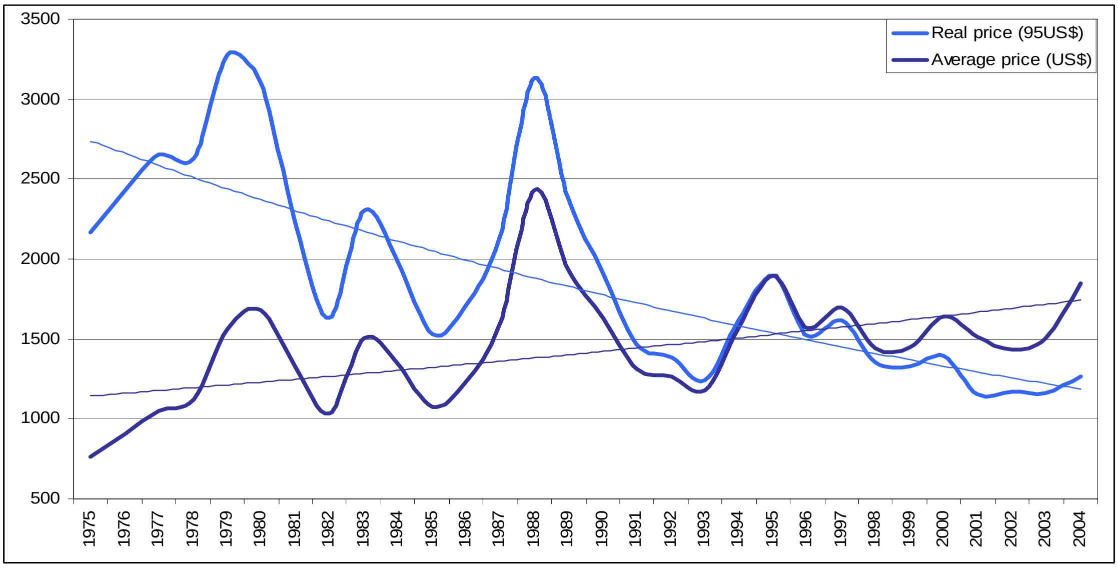


Source: CRU, 2003

3.6.3 Price

The great bulk of high grade aluminium and aluminium alloy, of which the latter could equally come from both primary and secondary production, is traded on the basis of long-term contracts between producers and consumers. The prices at which these transactions are conducted are almost invariably based on those set daily by the LME, which provides the principal reference or benchmark price. The physical amount of trading is reflected by the movement of LME stocks at several warehouses across the world. The volume of LME stocks is reported daily and has an important impact on the price as it affects the short term supply of aluminium, and as a result, the aluminium price increases when stocks go down and vice versa. However, in the long term, the metal price is expected to reflect the production cost. Figure 15 shows the metal price development in the USA since 1975. While the yearly average price (nominal price) has increased, the real price of primary aluminium has decreased in the same period.

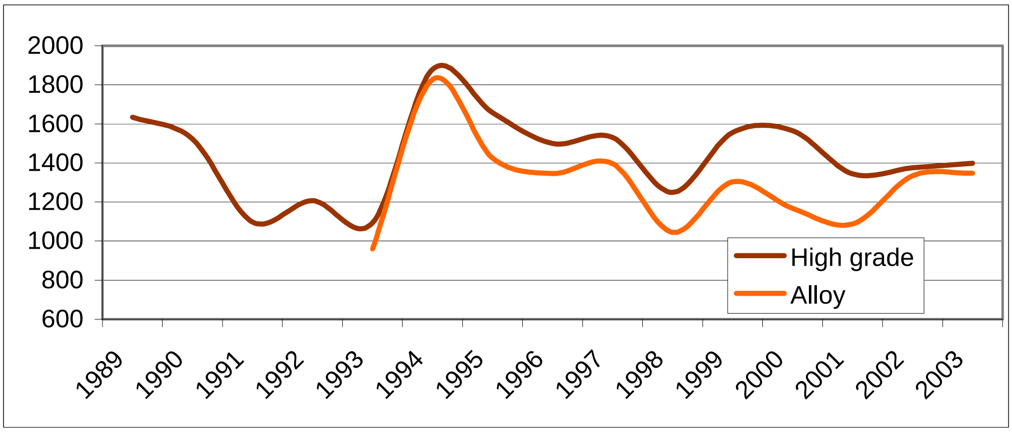
Figure 15 Aluminium price, 1975-2004



Source: USGS website, 2006, U.S. Department of Labour, website, 2006

As shown in Figure 16, the price for aluminium alloy has been slightly lower than that of high grade aluminium until 2002 when they were becoming closer. While high grade aluminium is mostly from primary aluminium, the aluminium alloy price is considered the best available information to reflect the price of secondary aluminium.

Figure 16 Aluminium price – high grade vs. alloy (annual average USD/tonne)



Source: Roskill, 2003

3.7 Scrap supply and price

3.7.1 Overview

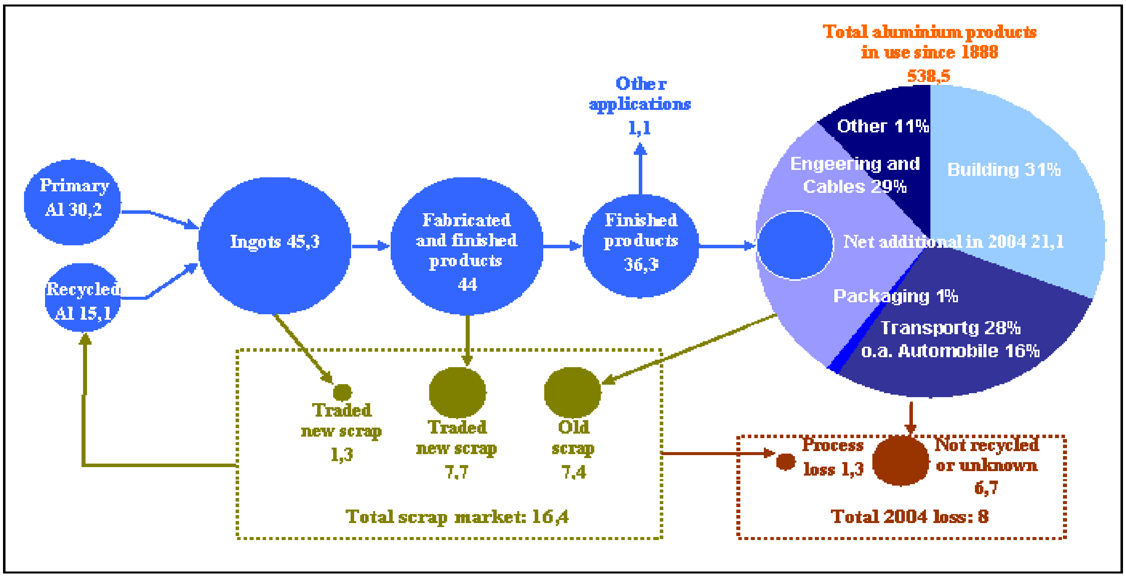
All products containing aluminium are potential sources of scrap. However, due to the nature of the product and its application, the life time and availability for recycling vary. The supply of scrap is considered one of the important factors affecting the price of secondary metal. As already mentioned, scrap is differentiated as new and old scrap. New scrap, before consumption, is nearly 100% recycled either inside a plant or directly by a remelter. Therefore, old scrap is the key issue in recycling and scrap supply.

It is worth to clarify here several concepts related to the discussion on recycling. At the end of life time, aluminium containing products become the source of scrap. Part of the yearly scrap generation is being collected and usually goes directly to the recycling loop (including reuse) and the rest is considered lost. The *end-of-life recycling efficiency rate* refers to metal recycled in a year as percentage of metal available for recycling in that year, and this efficiency is the combined result of the *rate of old scrap collection*, the percentage of the collected scrap in the total of yearly scrap generation, and the *rate of old scrap recovery* (rate of recovery), the amount of secondary aluminium produced as percentage of the yearly scrap generation. As a general indicator, *sector recycling rate* refers to the share of the secondary aluminium produced, from both new and old scrap, in total aluminium consumption of the sector per year.

An estimated overview of the global flow aluminium (illustrated in Figure 17, adapted from EAA data) indicates the place and the quantity of scraps that are generated, stored or lost. In total, around 7 Mt of old scrap and 9 Mt of new scrap were reported in 2004. The estimated old scrap generation of the same year was 15 millions which made the overall recycling rate 41% at world level and the end-of life recycling efficiency rate close to 50%. There is also a significant amount of internal scrap generated at the foundries, and this is being remelted directly in the plant or close by. This part of the scrap is often not included in statistics and is not taken into account in this model.

The flow shows that currently there are around 540 Mt of aluminium stocked in various aluminium applications and the stock is increasing, and, as result of that, the yearly generation of old scrap is also expected to increase, shown as an overview in Figure 17.

Figure 17 Global aluminium flow in 2004 (Mt)

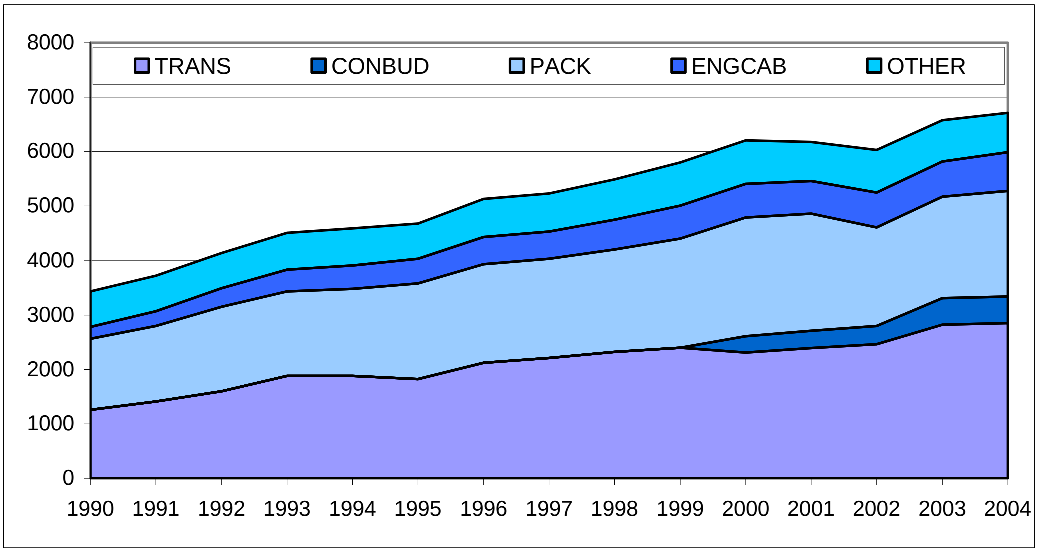


Source: EAA (adapted), 2006

3.7.2 Scrap generation by sector

Different final products have their distinctive life time, means of waste collection and separation, as well as different rates of recycling. According to historical data, the transportation sector and packaging aluminium have been, and still are the main sources of old scrap. The building sector, due to its very long life time, has contributed little in scrap supply; however, since the year 2000, its share in total scrap generated has become accountable and is increasing (see Figure 18). In order to estimate the limitation in the supply of scrap, it is important to understand the process from the end of life (becoming waste) of these products containing aluminium to marketable scrap. A few key sources of scrap are examined sector-wise in detail in the following sections. Due to the fact that numerous references are used to compile the following summary and to check the consistency of the data and information, the references are only listed in the Reference Chapter.

Figure 18 Origins of secondary aluminium



TRANS: transportation; CONBUD: construction and building; PACK: packaging; ENGCAB: engineering, electronics and cables; OTHER: others
Source: EAA, 2006

Transportation sector

As already discussed, the transportation sector is one of the main consumers of aluminium, although, depending on the industrial structure of a region/country, this situation may vary significantly. Aluminium is used as a component in cars, commercial vehicles, aeroplanes, trains, ships, etc. Currently, the transportation sector accounts for 44% (~3Mt) of the total recycled aluminium. With the sector's consumption of aluminium being around 10 Mt, an overall rate of recycling at approximately 30% is estimated. Based on past data and information, it is estimated that there is around 150 Mt of aluminium stored in the entire transportation sector.

The automobile industry is by far the largest market for aluminium in this sector. When a car has come to its end of life, it is collected and dismantled with the aluminium parts being separated (and partially reused). Further processes of the dismantled car will provide a second separation of aluminium alloy from the other metal content. In the end, all aluminium scrap will be transported to a refiner/remelter. The scrap that is collected depends on the yearly number of end-of-life-vehicles (ELVs) and their aluminium content. The average life time of vehicles is estimated to be 12-15 years; however, many vehicles may be in use longer, especially in developing countries and in the case of exported used cars from Europe, therefore making the estimation of the generated amount of scrap difficult. The amount of scrap collected can be best calculated with the statistics from collecting and dismantling companies of ELVs. Furthermore, different generations and vehicle types contain varying percentages of aluminium. Data show that the average aluminium content per vehicle has increased most significantly since 1990 from about 50 to 100 kg/vehicle in Western Europe and to 120 kg/vehicle in North America by the end of 2000. Statistics show that the EU, Japan and the USA together produce more than 70% of cars and 60% of light commercial vehicles of the world. An estimate of the ELVs in these countries is presented in Table 3. Using the average aluminium content of a light vehicle produced in 1990, the collected aluminium scrap (based on the number of cars recycled) is around 1.5 Mt per year, half of the sector's total contribution to recycled aluminium.

Table 3 ELVs in selected region/countries

Annual based	EU	Japan	USA
Cars in production (light vehicles)	16-18 million	9-10 million	15-17 million
Cars in use	200 million	~50 million	200-210 million
New cars registered	14-14,5 million	5-5,5 million	15-15,5 million
Cars deregistered	11-12 million	~5 million	13,5-14,5 million
Cars recycled	7-8 million	4-4,5 million	12,5-13,5 million
Cars exported	3-3,5 million	0,5-1 million	n.a.
Average weight	1000-1200 kg	1000-1200 kg	1200-1400 kg
Aluminium content (average in 1990)	50,8 kg	61,2 kg	74,8 kg
Potential scrap generated (excl. export vehicles)	~400 kt	~300 kt	~1,100 kt
Scrap collected	355,6 kt	244,8 kt	936 kt
Rate of scrap collection	90%	81%	85%

Source: ICGS, 2004

Building and construction sector

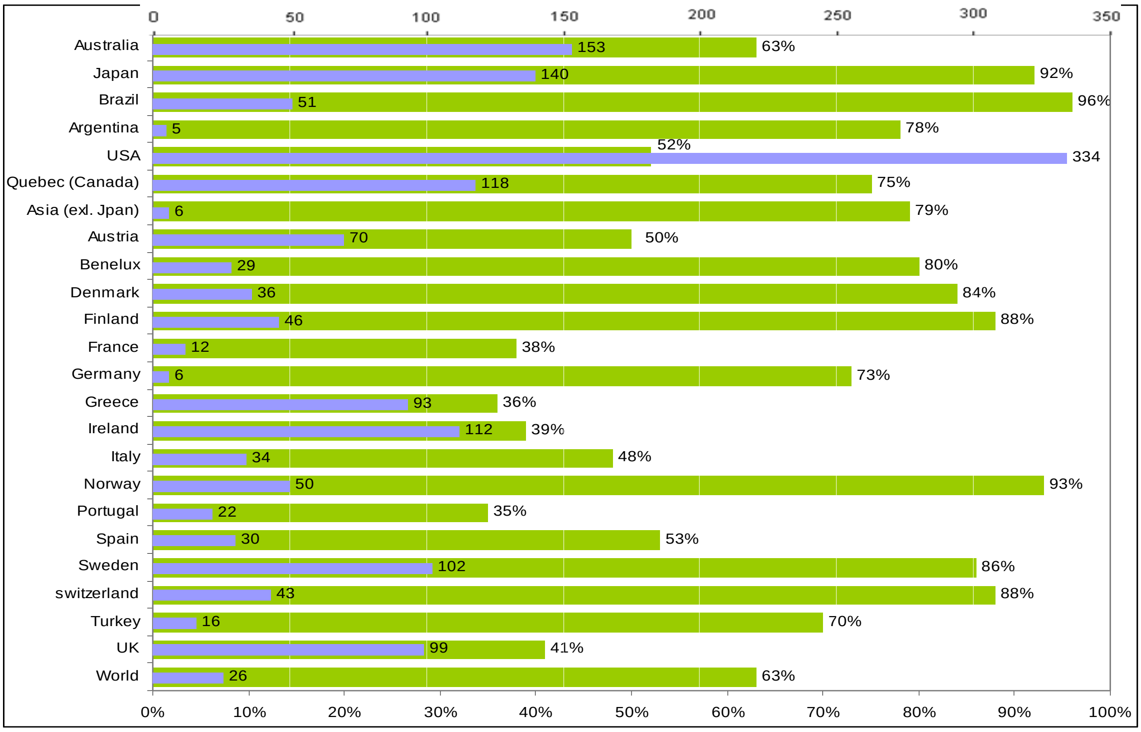
In countries without an automobile industry, the building and construction sector is probably the largest markets of aluminium, consuming some two and nine million tonnes of aluminium products per year in Europe and the world respectively. However, it may vary considerably from country to country due to the level and type of sector activities, which implies that the scrap generated at the end of life of the building will also be different. The total stored aluminium in the sector is the largest since the beginning of the industrial use of aluminium, amounting to nearly 170 Mt worldwide. However, as already mentioned, due to the very long life times of buildings, their contribution to recycled scrap was only 7% in 2004, i.e. around 0,5 Mt in total.

The main use of aluminium in this sector is to provide materials for roofing and cladding, and window and door frames, as well as small applications such as shutters, door handles, ceiling partitions, etc. A study on the collection of aluminium scrap from building deconstruction and demolition in six European countries indicates that the collection rate was between 92 and 98% even though the aluminium content in buildings (mass based) is below 1%. While the collection of the small items depends largely on the demolition method, the large items are often collected separately in order to be directly sold for reuse or sent for recycling. Insufficient data on annual deconstruction and demolition means that an estimation of the rate of aluminium scrap collection in this sector is impossible. Taking into account the sector's consumption, the yearly recycling rate of the sector is around 5%, and it is increasing due to the incremental use of aluminium in the past.

Packaging sector

Aluminium packaging waste is a large short term source of scrap. Most of the products used in food packaging have less than a one year life time. The current consumption at world level is close to five Mt per year. The sector contributes to nearly 28% of the recycled aluminium, second after the transportation sector. The overall rate of recycling of aluminium in the sector is around 36%, mainly from beverage cans.

Figure 19 Aluminium beverage can domestic consumption (unit per capita) and rate of recycling



Source: EAA, 2006

Two different types of aluminium products are usually distinguished in this sector, i.e. rigid and semi-rigid, and flexible packaging, with the first one having high aluminium content and the latter low in aluminium content. Used beverage cans (UBCs) are the most recycled aluminium products of the sector, while the others are rarely recovered. Per capita, the world's average use of aluminium cans is 26 units; however, it ranges from six in Germany and Asia to 334 in USA. The difference is due to the fact that in some countries the alternatives, steel and paper cans/cartons, are more popularly used. The UBC recycling technology has been well established and the rate of collection reached 60% as the world average and 46% in Europe in 2002. Brazil, Japan and Norway have reported a collection rate of more than 90%. The USA, being the single largest consumer, potentially generates half of the scrap of this sector, though its collection rate is just over 50%, as detailed in Figure 19.

Engineering equipment, electronics and cables, and other sectors

As already discussed, aluminium is also widely used in electrical applications, machinery and equipment. These sectors, here called as the engineering, electronics and cable sector, represents around 18% of the market and is responsible for 10% of the recycled aluminium at the global level. The life time of products in this sector varies from a few years to some 50 years, making the estimation of scrap supply very difficult. Taking the recent data as an indication, the average recycling rate of the sector is 10-12%. Similarly, the rest of the applications, here referred to as the other sectors, takes 16% of the market share and provides another 10% of recycled aluminium.

4 STRUCTURE OF THE ALUMINIUM MODEL

The aluminium model presented in this chapter is constructed upon the industry structure and the information described in the previous chapters. It consists of the following interconnected elements, as shown in Figure 20:

Aluminium consumption in each region is considered to be closely related to the GDP and population. The world total aluminium consumption is split into the demand for primary and secondary aluminium substituting each other depending on the price and substitution elasticity. Since aluminium is traded worldwide, the world primary aluminium demand is then to be satisfied by the total world primary aluminium production, which is distributed to different production regions based on their production capacity and costs. The cost of alumina to the primary smelter is, in most regions, specified in medium term contracts as a percentage of the primary aluminium price. The secondary aluminium demand is also to be met by world production which is mainly constrained by the availability of scrap. The potential of scrap generated at world level is determined by the amount of products containing aluminium reaching their end of life per year in each main sector and the ever increasing rate of collection under each economic condition. Such a relationship between demand and the supply potential of both primary and secondary aluminium is the key factor influencing the world market price of aluminium. The evolution of primary aluminium production technology is driven by electricity efficiency, which will not only affect production costs and energy consumption, but also reduce both process and energy related emissions.

4.1 Notation

In the aluminium model, the world is divided into 47 regions, and for the convenience of reporting, these regions are aggregated into continent based larger regions, as detailed in Table 5 in the Chapter 5. The model is composed by a modelling software package named VENSIM, which is a visual modelling tool that allows conceptualising, documenting, simulating, analysing, and optimising the models of dynamic systems.

4.1.1 Subscripts

- Time: *t*
- Regions: *region*
- Technology: *tech, i, j*
- Bauxite source: *source*
- Fuel: *fuel*
- Emissions: *gas*
- Sector: *sector*

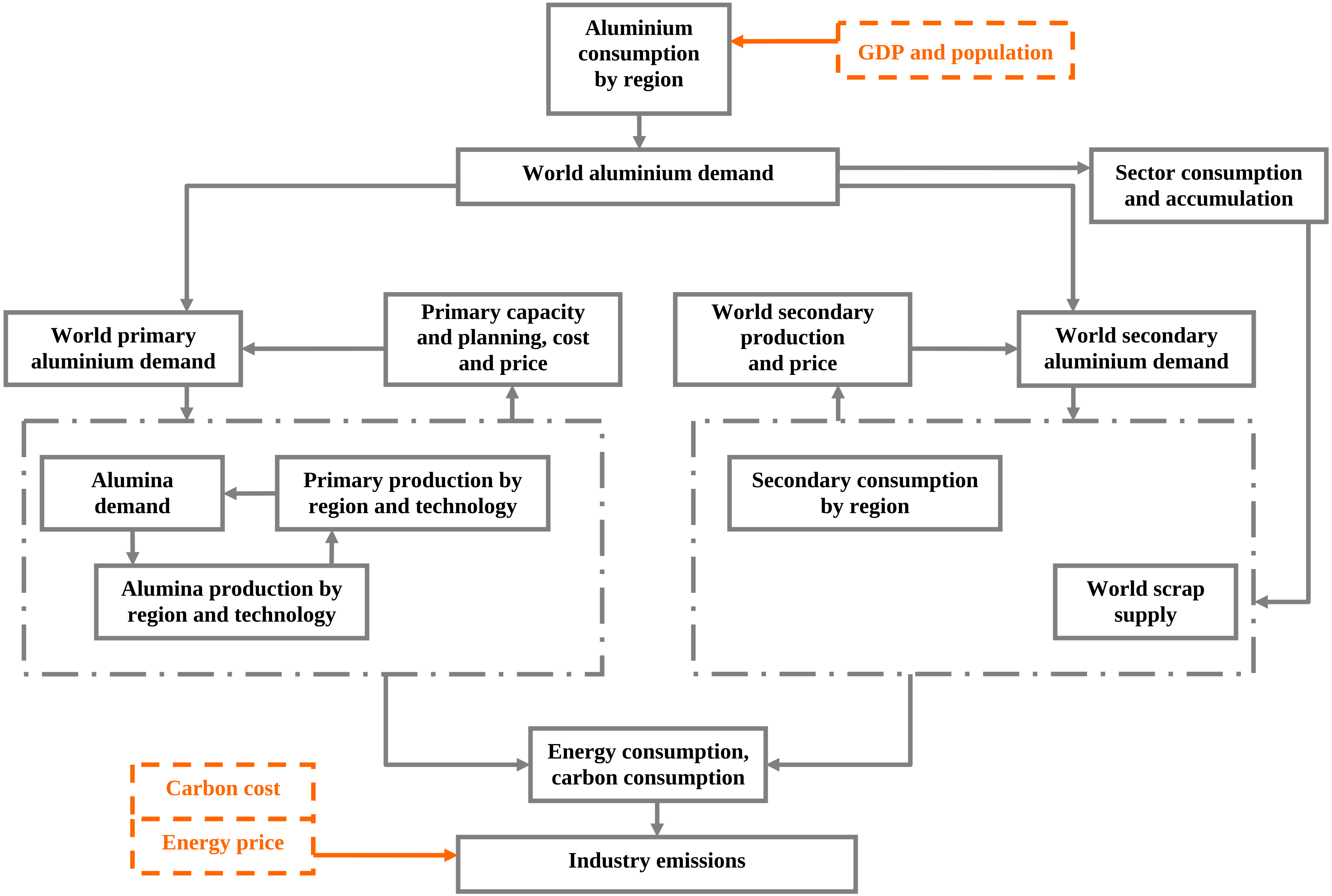
4.1.2 Variables

Table 4 List of variables

Variables	Description
GDP_{region}	Gross domestic production
POP_{region}	Population
$GDPPOP_{region}$	GDP per capita
Consumption related	
$PGCONALU_{region}$	Aluminium consumption per GDP and population
$CONALU_{region}$	Total aluminium consumption
TOTCONALU	World total aluminium consumption
$CONALUPRI_{region}$	Total primary aluminium consumption
$CONALUSEC_{region}$	Total secondary aluminium consumption
$CONALA_{region}$	Total alumina consumption

DEMBAU_{region}	Demand of bauxite
$\mathrm{SHARESECTOR}_{region,sector}$	Share of aluminium consumption by sector
Price related	
ALUPRIPRICE	Price of primary aluminium
ALUSECPRICE	Price of secondary aluminium
$\mathrm{BAUPRICE}_{region}$	Price of bauxite
Production related	
$\mathrm{TONALUPRI}_{region}$	Total primary aluminium production
$\mathrm{PROALUPRI}_{region,tech}$	Primary aluminium production by technology
$\mathrm{SHPROALUPRI}_{region,sector}$	Share of technology in total primary aluminium production
$\mathrm{CAPALUPRI}_{region}$	Primary aluminium capacity
$\mathrm{REMCAPALUPRI}_{region,tech}$	Remaining primary aluminium capacity
$\mathrm{RETCAPALUPRI}_{region,tech}$	Retired primary aluminium capacity
$\mathrm{RTFCAPALUPRI}_{region,tech}$	Retrofitted primary aluminium capacity
$\mathrm{INSTLCAPALUPRI}_{region,tech}$	Installed primary aluminium capacity
TONALA_{region}	Total alumina production
$\mathrm{SHALATECH}_{region,tech}$	Share of alumina technology in relation to source of bauxite
CAPALA_{region}	Alumina capacity
$\mathrm{NEWCAPALA}_{region,tech}$	New alumina capacity
$\mathrm{REMCAPALA}_{region,tech}$	Remaining alumina capacity
$\mathrm{BAURATIO}_{source}$	Bauxite to alumina ratio
Cost related	
$\mathrm{COSTPROALUPRI}_{region,tech}$	Primary aluminium production cost by technology
$\mathrm{CF}_{region,tech}$	Cost of fixed variables
$\mathrm{CFOM}_{region,tech}$	Fixed operation and maintenance cost
$\mathrm{CFIV}_{region,tech}$	Fixed investment cost
$\mathrm{CV}_{region,tech}$	Cost of variables
$\mathrm{CVOM}_{region,tech}$	Operation and maintenance cost
$\mathrm{CVENG}_{region,tech}$	Energy cost
$\mathrm{CVRM}_{region,tech}$	Raw material cost
$\mathrm{AVCOSTBAU}_{region, source}$	Average bauxite cost
$\mathrm{AVTRANSBAU}_{region, source}$	Average bauxite transport cost
Scrap related	
$\mathrm{ALUPOOL}_{sector}$	Aluminium containing product pool
TOTSCRAPGEN	World total scrap generation
TOTSCRAPLOSS	World total scrap loss
Energy related	
$\mathrm{SELEDALUPRI}_{region,tech}$	Specific electricity demand for primary aluminium production
$\mathrm{EELEALUPRI}_{region,tech}$	Electricity efficiency of primary aluminium production
$\mathrm{SHSELF}_{region,tech}$	Share of self generation in electricity demand for primary aluminium production
$\mathrm{FCNELALU}_{region}$	Non-electricity energy consumption of the aluminium industry
$\mathrm{NWPRFDALU}_{region,fuel}$	New primary fuel demand of the aluminium industry
$\mathrm{NELPRFDEMALU}_{region,fuel}$	Non-electricity primary fuel consumption of the aluminium industry
$\mathrm{PRFSHALU}_{region,fuel}$	Share of primary fuel in non-electricity energy consumption
$\mathrm{PRFSELFDEMALU}_{region,fuel}$	Share of primary fuel in energy demand for self generation
Emission related	
$\mathrm{EMIFACTOR}_{tech,emission}$	Emission factors
$\mathrm{GHGPROEMISSION}_{region, emission}$	Process GHG emission
$\mathrm{CFUELEMISSION}_{region, emission}$	Fuel induced carbon emission in carbon equivalent
$\mathrm{CO2EMISSION}_{region, emission}$	Emission in CO_2 equivalent

Figure 20 Main features of the aluminium model



4.2 Aluminium consumption and demand

As discussed in the previous chapters, global consumption of aluminium has been increasing since the 50s and at a 4% growth rate annually since the 90s. As a commodity and one of the important input materials to a variety of industries, aluminium consumption responds to economic activity. Therefore, the demand for aluminium and the commodity intensity (commodity consumption per unit of GDP per capita) can be assumed to correlate to GDP and population. Although this function varies among regions and material, it has been proven to follow often an inversed U-shape curve, the so-called Intensity of Use Hypothesis. The inverted U shape can be explained in terms of superposition of three different trends of the changes in the commodity requirements (*Van Vuuren et al. 1999*):

- changes in different phases of the economic transition from agriculture to manufacturing and construction and then to services
- changes as a result of substitution
- changes as a result of technological development.

Changes in economic structure from manufacturing to services result in material decoupling, occurring when the demand for a certain material starts to decrease for the generation unit GDP per capita. Technology development in terms of efficiency improvement often contributes to the material decoupling. Historical data exhibit that such decoupling has been observed for instance in the case of iron and steel. Data on past aluminium consumption have not shown the occurrence of material decoupling; however, this is not surprising since the production and utilisation of aluminium in comparison to iron and steel is still recent and is supposed to be increasing (the left side of the inversed U curve). Several materials, mainly iron and steel and plastics, are competing with aluminium in various applications. It is not possible for the current model to investigate such substitutions and trends in detail and to make the corresponding estimation of the impact of each on the aluminium industry. However, the past relationship between aluminium price and demand reflects, to a certain extent, the relative market competitiveness of aluminium.

Based on such a philosophy, it is expected that developing countries with low GDP per capita would be located more on the left side of the curve while developed countries tend to appear on the right. However, it should be noted that among countries with similar levels of GDP per capita great differences in aluminium consumption may exist due to their own economic structure, for example, the importance of their automobile industry. In this model, the aluminium consumption pattern is determined for each region with its own set of parameters. The consumption of aluminium per unit of GDP and population, *PGCON* (kg/million EUR & population), can be estimated by the following equation, Eq. (1):

$$(1)\quad \begin{aligned} Ln(PGCON_{t,region}) &= R + \alpha \ln\left(PGCON_{t-1,region}\right) \\ &+ \beta \ln\left(GDPPOP_{t,region} / GDPPOP_{t-1,region}\right) \end{aligned}$$

Where R, α and β are the parameters of the curves, and *GDPPOP* is the GDP per capita (€/inhabitant). Values of the parameters are calibrated via a regression programme, i.e. to best fit to the actual data of the last 10 to 12 years. Naturally, the more the historical data are available, the better the calibration of the parameters. The R-square varies for each of the regions and its average value of the 47 regions is about 0,7. Similarly, the Durbin-Watson (DW) statistic, which measures the serial correlation in the residuals (as a rule of thumb, if the DW is less than 2, there is evidence of positive serial correlation), has an average of 2. With the forecasted GDP and population as exogenous inputs, the consumption of aluminium can be calculated for the modelling period.

Total aluminium consumption and demand can basically be satisfied by its production from both primary and secondary aluminium. Most aluminium alloy products can be made from both primary and secondary aluminium, and it is not possible to distinguish their individual demand based on the end uses. Furthermore, the production technology of secondary aluminium continues to advance and makes wider application of secondary aluminium possible. However, two constraints need to be taken into account. First, secondary production is limited by the availability of scrap. Scrap collection and recycling in developed countries has improved progressively in the past 20 years and is well integrated in the metal industry. Further improvement in scrap recycling implies advanced technology and higher costs. The amount of scrap generated each year also depends on the consumption of aluminium, especially in the short term the consumption of products with short life times and in the long term the net addition, due to primary production, to the aluminium pool (as shown in Figure 17). Second, secondary aluminium could reach fairly high purity after proper treatment; however, uncertainty of trace elements will remain and these elements may also accumulate with the number of recycling loops completed, implying potentially higher costs in scrap treatment. As a result, the rate of recycling in the long term will maximise; however, the cost and the supply, i.e. the aluminium pool, will limit its growth. In the short term, due to the strong increase in demand for aluminium and the room for improvement in recycling, such constraints should have little effects. Therefore, in the model, it is assumed that primary aluminium and secondary aluminium can increasingly substitute each other; however, their supply and production are independent of each other limited by the availability of different types of resources. In order to project the future consumption of these two 'substitutable commodities', the Constant Elasticity Substitution (CES) function is employed and parameters are calibrated based on consumption data from 1990 to 2002. The use of this function tries to resolve, at a given level of total aluminium consumption, the optimal supply (at minimised cost) from primary and secondary aluminium. In this function, the price of the two substituting elements is of crucial importance, and is discussed later in Section 4.5.2.

$$CONALUPRI_t = (CONALU_t / \alpha F) \times (1-\gamma)^{\sigma} \times ALUPRIPRICE_t^{-\sigma} \times \\ [\gamma^{\sigma} \times ALUSECPRICE_t^{(1-\sigma)} + (1-\gamma)^{\sigma} \times ALUPRIPRICE_t^{(1-\sigma)}]^{(\sigma/1-\sigma)} \tag{2}$$

$$CONALUSEC_t = (CONALU_t / \alpha F) \times \gamma^{\sigma} \times ALUSECPRICE_t^{-\sigma} \times \\ [\gamma^{\sigma} \times ALUSECPRICE_t^{(1-\sigma)} + (1-\gamma)^{\sigma} \times ALUPRIPRICE_t^{(1-\sigma)}]^{(\sigma/1-\sigma)} \tag{3}$$

where alpha (αF) is a weighing factor between primary and secondary aluminium in a region, gamma (□) is the distribution parameter of secondary aluminium, and sigma (□) is the elasticity of substitution between primary and secondary in the CES function, which in the case of primary and secondary aluminium, it is calibrated and set at the value of 2. Calibration results show that for most regions/countries the value of alpha is between 1 and 2, with industrialised countries, where high recycling rate are observed, around 2 and developing regions varying from 1 to 1,6, and the values for gamma mostly range from 0,05 to 0,4 with industrialised regions at the higher value end. The model also assumes that both alpha and gamma will converge and slowly increase their value year by year, i.e. especially the regions with currently lower recycling rate will gradually generate more scrap in the future.

4.3 Primary aluminium production and technology

The total primary aluminium consumption and demand can thereafter be calculated. Since aluminium is a world-traded commodity, it is assumed in this model that the demand of aluminium in a given region can be totally or partially satisfied by the production from another region disregard the geographical location and, in the case of primary aluminium, this means that the production and capacity planning of a producer depends on their share in the world market. The size of such market share is the combined result of the following elements which are crucial to the production price of a region/country:

- the alumina cost: the alumina price and the distance to the alumina resource are reasonable approximates to the future raw material supply and cost

- the electricity cost: primary production is electricity intensive. Therefore a stable low electricity tariff is crucial to competitiveness. Many smelters have long term contracts with industrial power providers and some generate electricity by themselves
- current production costs: other costs, such as labour and administrative costs, also vary from region to region and correspond to the overall economic structure and development of a region/country
- capacity: existing and planned capacity is a constraint to the production, and sets a limit to the maximum share of a region/country in the world market, which will in turn affect capacity planning, e.g. increasing demand (due to a region's low production cost) stimulates producers in the region to install new capacity. This is discussed in Section 4.4.

In VENSIM, an allocation function, *ALLOCATE BY PRIORITY*, is considered to be suitable to allocate the world primary aluminium demand by production region/country. The *ALLOCATE BY PRIORITY* function is an implementation of the Wood algorithm. This algorithm has five desirable properties, to ensure both realism and flexibility, as in Eq. (4):

- committed capacities of all the technologies must sum to the total demand, under all conditions
- all commitments and market shares must be positive
- no technology can commit more than its capacity
- under conditions of extreme excess demand, each technology should use its entire capacity
- under conditions of limited demand, unattractive technologies should use little or nothing. If there is a uniquely attractive technology with a high capacity, it should win virtually the entire market, shutting out its competitors.

$$
\begin{aligned}
& TONALUPRI_{i} = ALLOCATE\ BY\ PRIORITY\ (CAPALUPRI_{t\text{-}1,\,region}, \\
& PRIORITYALUPRI_{t\text{-}1,\,region}, \\
& SIZE, \\
& WIDTHALUPRI_{t\text{-}1,\,region}, \\
& TOTCONALUPRI_{t})
\end{aligned}
\tag{4}
$$

Where, $TONALUPRI_i$ is the production of primary aluminium in region i, $CAPALUPRI_i$ is the production capacity in region i. $TOTCONALUPRI_i$ is the total demand of primary aluminium to be shared out by the regions. $PRIORITYALUPRI_i$ is a parameter reflecting how attractive region i is in comparison to the other regions. This parameter is a weighted average value inversely calculated based on the current production cost justified by the region's alumina supply and electricity tariff. $WIDTHALUPRI_i$ provides a motion of the typical deviation of the distribution of production costs in region i and the potential amount of capacity that is close to the region's $PRIORITYALUPRI_i$. *SIZE* is the number of regions to share the total demand.

The basis of the Wood algorithm is shown in Figure 21. The simplest case (with one single region as producer) is illustrated in the upper part of the figure. Faced to a total demand equal to "C", the algorithm "auctions" the production capacity from the cheapest production costs to the more expensive ones by moving along the "attractiveness" axis from right to left until the point in which the total area under the capacity curve matches the demand "C".

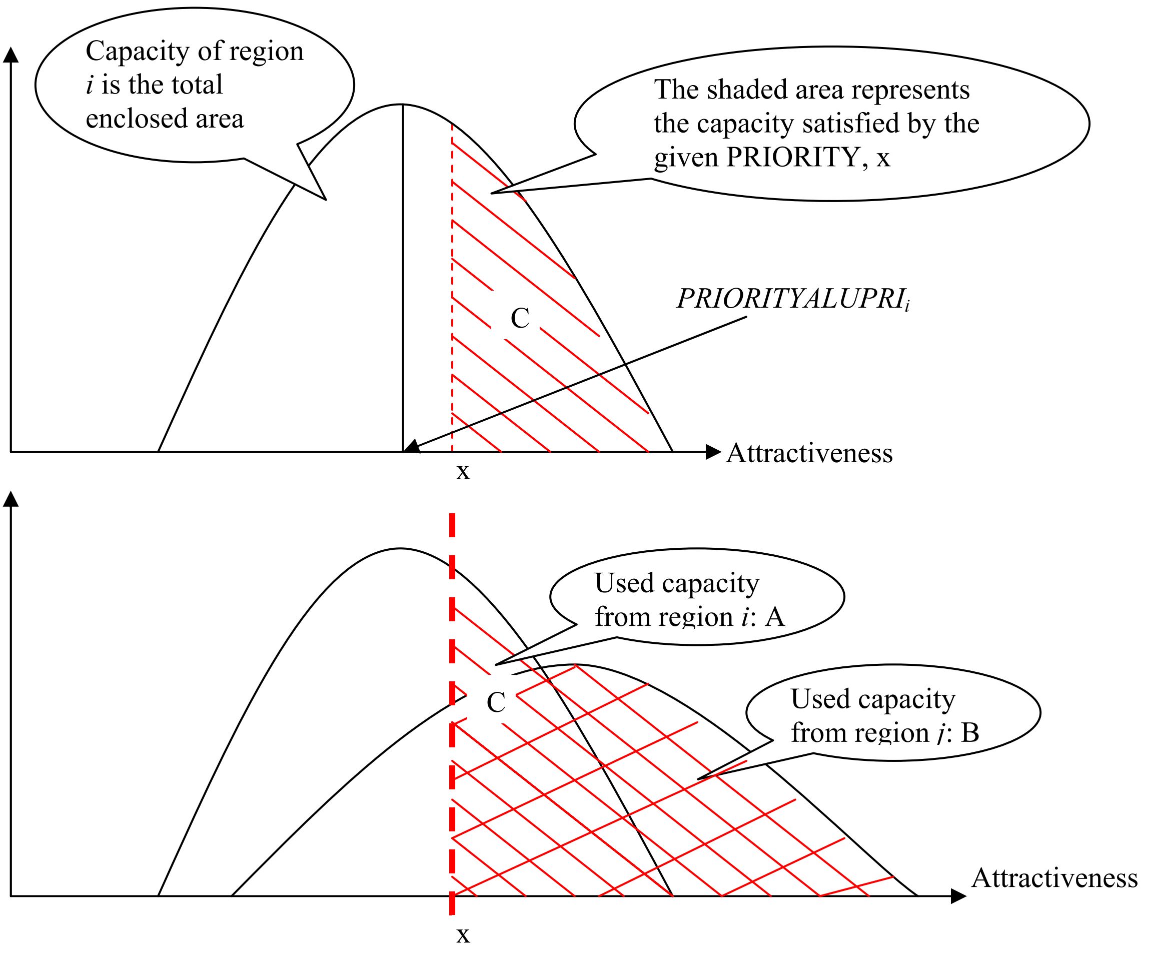
When more regions are competing for the overall demand "C" (as shown in the lover part of Figure 21), each of them is characterised by a cosy distribution (i.e. an "attractiveness" pattern). Basic parameters for each of them will be its average value ($PRIORITYALUPRI_i$), its shape (either rectangle, triangular, parabolic, gaussian) and a notional typical deviation ($WIDTHALUPRI_i$). The algorithm "auctions" the production moving from right to left along the "attractiveness" axis until the sum of the areas under the both curves (A+B) matches the total exogenous demand "C".

Knowing the production share of a region, the next step is to determine the technology makeup of its production. Most of the smelters have only one or two technologies installed. In many cases, one older technology was installed at the initial start up of the plant and retrofitted gradually to the modern prebake technology, i.e. PFPB. As already discussed, two major future technologies are considered in the model; however, due to their uncertainty, they are presented in the model as one possible alternative scenario. The technologies are detailed in the Section 4.4 in relation to capacity planning. Production by technology is estimated with another allocation function of VENSIM, *ALLOCATE AVAILABLE*, i.e. to allocate a fixed demand among available technologies. Similar to Eq. (4), explained above, Eq. (5) is also an implementation of the Wood algorithm and is, in fact, a generalisation of the *ALLOCATE BY PRIORITY*.

$$\begin{aligned}(5)\qquad & PROALUPRI_{t,region,tech} = ALLOCATE\ AVAILABLE\,(CAPALUPRI_{t,region,tech}, \\ & SHAPE_{region,tech,\,ptype}, \\ & TONALUPRI_{t,region})\end{aligned}$$

Where *PROALUPRI* stands for production by technology in a given region, *CAPALUPRI* is the capacity of the technology in the region, and *TONALUPRI* is the total desired production of the region (as result of Eq. 4) and is to be distributed among all the available technologies of the region. *SHAPE* is defined by: *ptype, ppriority, pwidth, pextra*. In the model, when assuming that the technology supply curve is a standard integral rectangle, i.e. *ptype* is 1. The *ppriority* specifies the midpoint of the rectangle, and it is determined by a relative preference of one technology in comparison to the others. The *pwidth* element determines the speed at which the curve goes from 0 to the specified quantity, which is estimated using the base year data. In this case, *pextra* is ignored.

Figure 21 The allocate function



4.4 Primary aluminium capacity planning

The current (2002) capacity of major smelters is reported by CRU international (*CRU, 2004*). Capacity planning is chiefly driven by production, and given the increasing demand of primary aluminium worldwide, it is expected that the growth of world primary aluminium capacity will follow the same trend. Upgrading and retrofitting are the core actions in capacity planning. Upgrading involves optimising the potline through, for example, increasing the electrical current, adjusting the temperature, modifying the anode, modernising the control system, etc. Retrofitting refers to converting one technology to another, usually resulting in improvements in efficiency and cost reduction. In the primary aluminium industry, both upgrading and retrofitting often increase the production capacity and since they are often accompanied by the addition of the potline, their final completion brings a considerable capacity expansion. Installation of a new smelter plant can also take place; however, it is more costly and in some region, the planning can take many years just to ensure a steady power supply. Given this analysis as the basis of capacity planning, the model distinguishes the capacity in four categories:

I. Remaining capacity, *REMCAPALUPRI*: each year a certain amount of capacity retires, *RETCAPALUPRI,* due to reaching its end of lifetime. The amount varies depending on the age of the capacity.

$$(6) \qquad REMCAPALUPRI_{t,\ region,tech} = CAPALUPRI_{t,region,tech} - RETCAPALUPRI_{t,region,tech}$$

II. Upgrading capacity, *UPGCAPALUPRI*: upgrading could be done to all the remaining capacity (excluding the capacity for retrofitting) periodically over the year. The model assumes that average upgrading brings an overall 0,5% efficiency improvement. In regions that the trend of decreasing production is observed, it is expected that no investment on upgrading capacity or retrofitting would take place.

III. Retrofitting capacity, *RTFCAPALUPRI*: although retrofitting does not occur every physical year, the model assumes that a certain amount of capacity is being retrofitted each year under the condition that the required production exceeds the capacity. There are no data available which can be used to estimate the amount of capacity for retrofitting; however, the model assumed, for each technology, a certain retrofitting factor, a parameter calibrated by the desirability of the region in the aluminium market and the preference of the technology in comparison to another. It is likely that a smelter evaluates their capacity and plans retrofitting every five years, and decides on the amount of capacity that should be retrofitted. However, in order not to disrupt production completely, it is assumed that only part of the potline will be retrofitted at any time. The model assumes that no more than 10% of the remaining capacity of any technology would be retrofitted each year, which means that the maximum retrofitting can only be 50% of the total capacity every five years.

$$(7) \qquad \begin{aligned} & IF(TONALUPRI_{t,region} > \sum_{tech} REMCAPALUPRI_{t-1,region,tech}), \\ & THEN(RTFCAPALUPRI_{t,region,tech} = REMCAPALUPRI_{t-1,region,tech} \\ & \times 10\% \times FACTOR_{region,tech}), \\ & ELSE(RTFCAPALUPRI_{t,region,tech} = 0) \end{aligned}$$

The retrofitting *FACTOR* determines how fast a technology should be retrofitted. In the model, the *FACTOR* is estimated according to the potential energy savings that can be achieved by retrofitting. In the case of aluminium, the existing information indicates that PFPB is currently considered to be the best available technology and is the only retrofitting option. Furthermore no information indicates that retrofitting option such as HSS to VSS or SWPB to CWPB are taking place. Therefore, if there is no new technology in the time horizon, all the retrofitting capacity will become PFPB.

IV. Installed capacity, $INSTLCAPALUPRI_{region,tech}$: after upgrading and retrofitting, if the required production is still higher than the total capacity, there will be new capacity installed. In the model, it is assumed that smelters will only install the most advanced technology, which means state of the art PFPB.

As discussed in the previous chapter, new technologies have been investigated for primary aluminium smelting, such as the reduced temperature and inert anode; however, they are not expected to be applicable during the simulations period of the model, and furthermore, there are very little information and data available to characterise theses technologies, therefore they are not integrated in the current model. However, for the purpose to illustrate an alternative perspective for the industry and the types of analysis that the model can provide, the new technologies are introduced in a simple manner with a very basic set of assumptions to construct an alternative scenario, and this is discussed in the next chapter.

At the end of each year, the final capacity would be the sum of the upgraded capacities, final retrofitting capacities and newly installed capacities.

4.5 Primary aluminium production costs and price

4.5.1 Production costs

The total primary production costs, $COSTPROALUPRI_{region,tech}$ (€/t of primary aluminium, the same unit for all the cost variables unless specified) in each region are the sum of the fixed and the variable costs, Eq. (8):

$$(8) \qquad COSTPROALUPRI_{region,tech} = CF_{region,tech} + CV_{region,tech}$$

The fixed cost of the different technologies, $CF_{region,tech,}$, is the sum of the fixed operation and maintenance costs, $CFOM_{region,tech}$ and the annualised investment cost, $CFIV_{region,tech.}$ $CFOM_{region,tech}$ is estimated as a fraction, 5%, of the annualised investment cost, and the annualised investment costs is the investment cost discounted through the economic lifetime of the technology, ELT_{tech} (year), to the discount rate, DR, assumed here to be 8%, Eq. (9):

$$(9) \qquad CF_{region,tech} = CFOM_{region,tech} + CFIV_{region,tech} * \frac{DR \cdot (1+DR)^{ELT_{tech}}}{(1+DR)^{ELT_{tech}} - 1}$$

The total variable production cost, $CV_{region,tech}$, is the sum of the variable operation and maintenance costs, the energy costs, and the raw material costs, Eq. (10):

$$(10) \qquad CV_{region,tech} = CVOM_{region,tech} + CVENG_{region,tech} + CVRM_{region,tech}$$

The raw material cost ($CVRM_{region,tech}$) is a sum of the cost of alumina, carbon, and other materials used in the primary production.

As already mentioned, the vast majority of alumina is sold under one-year or medium to long term contracts that are priced as a percentage of the prevailing LME 3-month metal price. Therefore, the model determines the alumina price (in other words, the cost of alumina to primary production) based on such a relationship with the adjustment of energy price and the efficiency of the alumina production. Since many smelters produce anodes onsite, the carbon cost is calculated in relation to its consumption which is in ratio, depending on the technology, to the aluminium production taking into account the change of the price of coal (in representing that of coke and pitch). The energy efficiency of the industry is simulated in the energy sub-module. The energy cost ($CVENG_{region,tech}$) comes from two parts: the cost of primary fuel, which is calculated with the fuel price from the POLES model; and the electricity price, which also comes from the POLES model. As discussed previously, for many primary producers the electricity price is also specified in contracts with power sector though data and information indicates that this relationship is not straightforward and furthermore, the issue is irrelevant to the producers with self-generated power (see Section 4.8). Therefore, to avoid any bias due to lack of data, the model calculates both grid and self-generated electricity costs using industrial electricity tariff from the POLES model taking into account the past record of electricity tariff under specially contracts between aluminium industry and power producers. The variable operation and maintenance cost ($CVOM_{region,tech}$) covers the labour costs and overhead costs. They are estimated in accordance with general economic trends ($GD_{,region}$) and as a function of the production process.

The investment costs of each technology, $CFIV_{region,tech}$ are represented by a learning curve, depending on the previous value of the investment cost, the cumulative capacity, $CUMCAP_{region,tech}$ (Mt), and the elasticity, $CFIVE_{tech}$:

$$
(11)\qquad
\begin{array}{lll}
CFIV_{t,region,tech} = & & \\
& If & INSTLCAPALUPRI_{t,region,tech} > 0 \\
& Then & CFIV_{t-1,region,tech} \cdot \left(\dfrac{CUMCAP_{t,tech}}{CUMCAP_{t-1,tech}} \right)^{CFIVE_{tech}} \\
& Else & CFIV_{t-1,region,tech}
\end{array}
$$

The accumulative capacity refers to the entire capacity of a given technology being built from the moment when the first one was installed. Clearly it is difficult to estimate with limited data. To accommodate the limitation of data, it is assumed in the model that *CUMCAP* is the world sum of the apparent capacity of a technology. In the case of today's aluminium industry, Søderberg technology is gradually being replaced by PFPB and the Preback technologies are also being upgraded to PFPB, and the installed capacity can only be observed for PFPB, i.e. $INSTLCAPALUPRI_{region, PFPB} > 0$. Thus, the model calculates the investment cost of PFPB using Eq. 11, and the annualised investment cost of all the other technologies will stay constant till its end of life.

The average national production cost, $COSTALUPRI_{region}$, is the weighted sum of the production costs by technology. The weights are the shares of the technologies in the national production, $SHPROALUPRI_{region, tech}$:

$$
(12)\qquad COSTALUPRI_{region} = \sum_{tech} SHPROALUPRI_{rgion,tech} * COSTPROALUPRI_{region,tech}
$$

$$
(13)\qquad SHPROALUPRI_{region,tech} = \frac{PROALUPRI_{region,tech}}{\sum_{tech} PROALUPRI_{region,tech}}
$$

4.5.2 Price of primary and secondary aluminium

As discussed, since many smelters have power and alumina supply contracts that relate electricity and alumina costs to aluminium prices, the aluminium price determines the input cost and not the other way round. The aluminium price, especially in the short term, is reflected by the correlation of the monthly fluctuation of aluminium prices of the world stock as reported by LMT. One study by Figuerola-Ferretti shows that the aluminium price responds to changes in consumption, production and capacity (*Figuerola-Ferretti, 2003*). A decrease in capacity and lower production levels lead to price increases and upward consumption trends also raise the price. In fact, these changes can be seen as notions of the change in stock quantity. Historically, the real price of primary aluminium in the US has decreased at an average rate of 1,5% yearly during the period 1970 to 2004, as shown in Figure 15, and this decrease reflects the overall trend of decreased production costs mainly due to energy savings brought by significant technology improvements, such as the realisation of PFPB and the implementation of computer controlled processes. Taking into account that most of the existing technologies are being retrofitted and the lack of further technology breakthroughs, the decrease in production costs is not expected to be much slower in the next 20-30 years (*personal communication with EEA and Alcan inc., 2006*). To reflect the above factors, the model assumes that the long term price of primary aluminium can be expressed as a function of the production of primary aluminium and its production cost, i.e. the price inversely correlating to growing production and positively relating to production costs:

$$\begin{aligned} &ALUPRIPRICE_t = (TOTTONALUPRI_{t-1} / TOTTONALUPRI_{t-2})^a \\ &*[(COSTAVERAGE_{t-1}) * PROFITALUPRI] \end{aligned} \tag{14}$$

Where, *ALUPRIPRICE_t* is the primary aluminium market price which is assumed to be the same for all regions; $TOTTONALUPRI_t$ is the world total aluminium production; $COSTAVERAGE_t$ is the world average primary production cost, and it is adjusted with *PROFITALUPRI*, the average factor of the profit margins and transportation costs.

A similar approach is discussed for the simulation of the price formation of secondary aluminium (aluminium alloy). There is very little information available on both the supply and demand side; however, past studies show that the price of secondary aluminium seems to be driven mainly by the demand which largely comes from the automobile industry (Blomberg, etc. 2003). It can be reasonably assumed that, since production in the automobile industry is on the increase and the climax is yet to come with development in countries like India and China and the fact that the use of aluminium per vehicle is continuously increasing, the demand for secondary aluminium is on the inclining side of the curve. Furthermore, there are no technical constraints for the production of secondary aluminium from scrap. Therefore, the key question is whether the supply of scrap can satisfy the demand. The estimation of scrap supply is discussed in Section 4.6.

$$\begin{aligned} &ALUSECPRICE_t = (TOTSCRAPSUPPLY_{t-1} / TOTSCRAPSUPPLY_{t-2})^k \\ &*[(COSTAVEREG_{t-1}) * PROFITALUSEC] \end{aligned} \tag{15}$$

Where $ALUSECPRICE_t$ is the secondary aluminium market price which is assumed to be the same for all regions; $TOTSCRAPSUPPLY_t$ is the world total potential scrap supply; here due to the lack of information on secondary production costs, $COSTAVERAGE_t$ from primary aluminium is used, and it is adjusted with *PROFITALUSEC*, the average factor of the profit margins and transportation costs. The difference between *PROFITALUPRI* and *PROFITALUSEC* is the fact that primary production consumes much more energy and is much more concentrated in a number of countries.

4.6 Scrap recycling and supply

There is little information on scrap generation and collection at regional/country level, and also for many countries little is known regarding sectoral consumption as well as the rate of recycling. This makes it impossible to make estimations at regional level. Although scrap trading is more on a continental scale, imports and exports across different parts of world are widely known and are increasing, for example, between China and North America or Europe. Therefore, it can be assumed that scrap supply is global and, in the present model, the global supply influences the market price.

In order to estimate the amount of old scrap collected at world level, there is the need to investigate the potential scrap sources by sector and their respective collection rates. Furthermore, since different products have distinct life times, the generation of scrap from that product is thus more relevant to the amount of aluminium that is stored in such products over the years than the immediate consumption. The accumulation of aluminium products in use can be estimated as:

$$\begin{aligned} ALUPOOL_{t,sector} &= ALUPOOL_{t\text{-}1,sector} + TOTCONALU_{t,sector} \\ &- TOTSCRAPGEN_{t,sector} - TOTSCRAPLOSS_{t,sector} \end{aligned} \tag{16}$$

$$TOTCONALU_{t,sector} = (TOTCONALU_{t}) * SHARESECTOR_{t,sector} \tag{17}$$

$$TOTSCRAPGEN_{t,sector} = (TOTCONALU_{t,sector}) * SCRAPRATE_{t,sector} \tag{18}$$

Where, $ALUPOOL_{t,sector}$ is the total accumulated aluminium in a given sector since the beginning of the industrial use of aluminium. $TOTCONALU_{scetor}$ is the world's total aluminium consumption by sector. The share of aluminium consumption by sector, $SHARESECTOR_{scetor}$ is estimated based on expert judgement. $TOTSCRAPGEN_{scetor}$ is the total scrap generated by sector. The rate of scrap generation, $SCRAPRATE_{scetor}$ is extrapolated from the past trend at world level. The total loss of scrap, $TOTSCRAPLOSS_{scetor}$, is partially due to the loss to irreversible applications of aluminium, and the amount that is deemed unrecoverable due to economic reasons, which is estimated as a percentage of the scrap generated.

4.7 Alumina consumption and production

Alumina is mainly used for the production of primary aluminium, therefore the world demand for alumina in this model takes into account only the need of the primary aluminium industry.

On average 1,98 tonnes of alumina are needed for the production of one tonne of primary aluminium. In the model, this is the principle assumption used to estimate the demand for alumina by region, $CONALA_{t,region}$ and their sum is the world's total demand, $TOTCONALA_{t}$:

$$CONALA_{t,region} = TONALUPRI_{t,region} * 1.98 \tag{19}$$

Alumina is traded worldwide and production is concentrated in several countries due to their availability of and accessibility to bauxite. Furthermore, because transportation of bauxite is not favoured economically, most alumina is produced near the bauxite mines. Thus the model assumes that the world demand for alumina is shared by the alumina production regions and such sharing should reflect the competitiveness of a producer being compared with others in terms of capacity, production costs, and availability of low priced bauxite. This is again simulated using the *ALLOCATE BY PRIORITY* function in the VENSIM, as explained in Section 4.3.

$$\begin{aligned} TONALA_{t,region} = \text{ALLOCATE BY PRIORITY} \, (\, & CAPALA_{t,region}, \\ & PRIORITYALA_{t,region}, \\ & SIZEALA, \\ & WIDTHALA_{t,region}, \\ & TOTCONALA_{t} \,) \end{aligned} \tag{20}$$

Similarly, $TONALA_{t,region}$ and $CAPALA_{t,region}$ are the regions' total alumina production and production capacities respectively.

As already noted, the technology employed for alumina production is mature and the variation depends highly on the type of bauxite to be processed. The share of production between the technologies thus depends on the share of bauxite sources. Among all the production regions, only Russia and China have two different technologies both for accommodating different raw materials mined in the country. For many refineries, bauxite is supplied internally, i.e. in-situ.

Many European and North American alumina refineries import bauxite from mines outside the region, for instance from Australia. The advantage of the in-situ bauxite is clearly the average cost. In other words, the cheaper the bauxite, the more it is favoured for alumina production and, consequently, the bigger share of the corresponded technology for the process of the bauxite. In the next decades, for all the main leading producers, it is assumed that their source of bauxite will not change and no new technologies and breakthroughs will take place. Therefore, any change in the technology share is modelled as a direct result of the change in bauxite source/cost.

$$
\begin{aligned}
&SHALATECH_{t,region,tech,source} = SHALATECH_{t-1,region,tech,source} * \\
&(AVCOSTBAU_{t-1,region,source} / AVCOSTBAU_{t,regionsource})
\end{aligned}
\tag{21}
$$

$$
\begin{aligned}
&SHALATECH_{t,region,tech} = (\sum_{source} SHALATECH_{t-1,region,tech,source}) / \\
&(\sum_{tech} \sum_{source} SHALATECH_{t-1,region,tech,source})
\end{aligned}
\tag{22}
$$

Here $SHALATECH_{t,region,tech,source}$ is the share of the source of bauxite per technology in each region, and $AVCOSTBAU_{t,region,source}$ is the average cost of bauxite by source in each region.

As a basic commodity, the price of bauxite (USD/t) can be estimated using its price and demand elasticity, *PREBAU,* which is fairly small and can be assumed to range between 0,05 and 0,1. The cost of bauxite for each producer is distinguished by its source, i.e. in-situ or non-situ, which also determines the technology used for alumina refining. The cost of bauxite (USD/t alumina) in alumina production is the sum of the bauxite price and transportation costs and multiplied by a conversion ratio, $BAURATIO_{source}$. The transportation costs only apply to non-situ source and it is assumed that it will have an average increase of 2% when CO_2 emission costs on fuel apply from 2008.

$$
\begin{aligned}
&BAUPRICE_{t,region,source} = (BAUPRICE)_{t-1,region,source} * (1 + ((DEMBAU_{t,region} \\
&-DEMBAU_{t,region}) / DEMBAU_{t-1,region}) * PREBAU)
\end{aligned}
\tag{23}
$$

$$
\begin{aligned}
&AVCOSTBAU_{t,source} = (BAUPRICE_{t,source} + AVTRANSBAU_{t,source}) \\
&*BAURATIO_{source}
\end{aligned}
\tag{24}
$$

Where $BAUPRICE_{t,region,source}$ is the price of bauxite by source and $DEMBAU_{t,region}$ is the demand for bauxite per region.

However, while production technology remains the same, its capacity and overall efficiency is expected to increase due to the increasing demand for aluminium production. Since there are no indications of any constraints on the applicability of the current alumina technology and no limitations on industrial capacity, the model assumes that the alumina demand in each region would be met by capacities expanding, and new capacities, *NEWCAPALA*. Here, *PROALA* is the production of alumina by technology and *REMCAPALA* is the remaining alumina capacity taking into account that a small amount of capacity retires each year due to ageing.

$$
NEWCAPALA_{t,region,tech} = PROALA_{t,region,tech} - REMCAPALA_{t,region,tech}
\tag{25}
$$

4.8 Energy consumption

4.8.1 Electricity demand

As already mentioned, the primary aluminium industry is electricity intensive. Although improved technology certainly results in better efficiency, it is not always straightforward as shown by the data. This is mainly because most of the capacities are being retrofitted from installation of various age and, depending on the electricity current that is available in the smelter, the electricity efficiency varies from site to site for the same technology. Therefore, in the model the electricity consumption is region specific rather than technology specific. Furthermore, information indicates that for the same technology, the efficiency also depends on the age of the capacity, the older the capacity the lower the efficiency. Since there are no data series available on electricity efficiency, it is not possible to give any detailed evaluation on the evolution of energy efficiency. However, as discussed in Section 4.4, upgrading is often accompanied by a small capacity increase and as a consequence a gradual improvement of the overall efficiency can be expected. Taking all this into account, the model estimates the average electricity efficiency factor per technology, $EELEALUPRI_{tech}$, by comparing the age of the capacity and their average efficiencies that have been reported in the past, and through this the total electricity demand by region, *SELEDALAPRI* can be estimated as:

$$(26) \qquad SELEDALUPRI_{t,region} = \sum_{tech} (ROALUPRI_{t,region,tech} \cdot EELEALUPRI_{t,region,tech})$$

In primary production, self generated electricity accounts for a significant share of the total electricity supply. Self-generation is an important issue, since it influences the energy demand pattern and meanwhile affects the production cost, and as consequence the production allocation. Thus, in the model, electricity demand is distinguished by source, i.e. from the grid or self-generation. Given the limited data and information available, it is not possible to foresee the impact of energy demand and price on the choice that a smelter will make regarding electricity source. However, considering that the installation of a new electricity generator and abandoning the existing generator is a more cautious decision to make, the model could assume that the current self-generation capacities remain the same for the smelters and when a certain amount of capacity is retrofitted, $RTFCAPALUPRI_{i,j}$, the share of self-generation, i.e. $SHSELF_{t-1,i}$, in that capacity will apply to the retrofitted capacity, note that here the subscript *i* and *j* representing to different technologies. Therefore, the new share of self-generation will become:

$$(27) \qquad \begin{aligned} SHSELF_{t,j} = {} & (\sum_{1}^{i} (RTFCAPALUPRI_{(t,i,j)} * SHSELF_{(t-1,i)}) \\ & + (UPGCAPALUPRI_{(t,j)} * SHSELF_{(t-1,j)}) + INSTLCAPALUPRI_{(t,j)} * SHSELF_{t-1}) \\ & / CAPLALUPRI_{(t,j)} \end{aligned}$$

As shown in Eq. (27), the upgraded capacity keeps the same share of self-generation, $SHSELF_{t-1,j}$, and the newly installed capacity could apply the average share of self-generation of the region, the weighted average in total production $SHSELF_{t-1}$. Since it can be expected if primary production from self-generation has the advantage of a lower and stable electricity price, this part of the capacity would be favoured and as a consequence would drive up demand. However, this does not necessarily mean that smelters would increase the self-generation capacity accordingly. The above estimation of self-generation serves to limit any radical change in electricity demand even when the cost of self-generation is lower than the grid price. The breakdown of the share of primary fuel for self-generation is assumed to be constant without any change of the fuel type, and in terms of energy consumption, fossil fuel used in self-generated electricity is reported as part of the demand for primary fuel of the industry, discussed in Section 4.8.2 below.

4.8.2 Primary fuel demand

Heat is used mainly for anode production and casting, as well as alumina production. For the primary production process, it is not possible to cross compare thermal energy efficiency since not all smelters produce anode at the plant site and there is no distinction of energy consumption by different technology in the data. Since this part of the energy consumption is much less significant compared to electricity, the model assumes a stable improvement of the efficiency through the modelling period. Primary fuel is used in the alumina production process for digestion and calcination, as already discussed in Chapter 3. Clearly, technology improvements will bring benefit to energy efficiency and any increase in fuel cost would stimulate such improvements. Due to a lack of data, it is not possible to give rational arguments to calibrate this trend in the given time frame, therefore an expert estimate is made which assumes an overall efficiency improvement in alumina production at an annual average rate of 0,4%.

The aggregated region/country demand for this type of primary fuel is expected to change depending on the fixed user costs of the fuels, which are a function of the investment cost related to the use of the fuel, the fuel price, and the average efficiency. While assuming that the existing production capacity has very limited possibilities for fuel substitution, the model expects that the "new" demand for primary fuel, *NWPRFDALU*, due to new installations has greater flexibility in choosing the type of fuel to satisfy this demand. This is calculated as the balance between the total demand of non-electricity fuel in two consecutive years, *FCNELALU.*

$$(28) \qquad NWPRFDALU_{t,region} = FCNELALU_{t,region} - FCNELALU_{t-1,region}$$

This implies that the share of different types of primary fuel in $FCNELALU_{t-1}$ remains the same, and the "new" demand, $NWPRFDALU_t$, is being simulated in the model according to the factors stated above and this "new" share of primary fuel, *PRFSHNWDALU*, here is calculated as:

$$(29) \qquad PRFSHNWDALU_{t,region,fuel} = \frac{CU_{t,region,fuel}^{\;-EH}}{\sum_{fuel} CU_{t,region,fuel}^{\;-EH}}$$

Here, *EH* is a substitution factor between primary fuels, and the fixed user costs of the fuels, CU_{fuel} (EUR/toe) are given by:

$$(30) \qquad CU_{t,region,fuel} = RESCU_{t,region,fuel} + FIC_{t,region,fuel} + \frac{CPFUEL_{t,region,fuel}}{AFE_{t,region,fuel}}$$

where $RESCU_{fuel}$ is the fixed user cost for the energy in a non-electrical process, FIC_{fuel} is the investment cost related to the use of the fuel, $CPFUEL_{fuel}$ is the fuel price, and AFE_{fuel} is the average efficiency, all expressed in EUR/toe.

Thus, the final primary fuel demand in a given year can be calculated as:

$$(31) \qquad \begin{aligned} &NELPRFDEMALU_{t,region,fuel} = \\ &\quad If \qquad NWPRFDALU_{t,region} \geq 0 \\ &\quad Then \qquad FCNELALU_{t-1,region} * PRFSHALU_{t,region,fuel} + NWPRFDALU_{t,region} * \\ &\quad PRFSHNWDALU_{t,region,fuel} \\ &\quad Else \qquad FCNELALU_{t,region} * PRFSHALU_{t,rehion,fuel} \end{aligned}$$

$$(32) \qquad PRFSHALU_{t,region,fuel} = NELPRFDEMALU_{t-1,region,fuel} / \sum_{fuel} NELPRFDEMALU_{t-1,region,fuel}$$

Where, *PRFSHALU* and *PRFSHNWDALU* represent the old and new share of primary fuel respectively. *NELPRFDEMALU* is the final non-electricity fuel demand by the type of primary fuel.

Primary fuel is also consumed for the production of self-generated electricity in the primary aluminium smelters. As discussed in the Section 4.8.2, given the limited data on the development of self-generation, the type of primary fuel in demand is assumed to remain unchanged. Electricity generation efficiency varies significantly from technology to technology, and it is not possible to simulate power generation in detail in this model. This model takes the average power generating efficiency data for all three types of primary fuel, i.e. coal, gas and oil, from the POLES model where electricity generation is modelled in great detail. Therefore, the fuel demand for self-generated electricity, *NATSELFDEMALU*, can be estimated as:

(33) $$NATSELFDEMALU_{t,region,fuel} = ELESELFDEMAND_{t,region,fuel} / ELEefficiency_{fuel} / 41.868$$

(34) $$ELESELFDEMAND_{t,region,fuel} = SHSELF_{t,region} * SELEDALUPRI_{t,region} * SHSELFFUEL_{t,region,fuel}$$

Where, *ELESELFDEMAND* is the demand of fuel for self-generation; and the relative share of type of fuel in the self-generation, *SHSELFFUEL*, is assumed to be the unchanged.

The total primary fuel demand, *NATFUELDEM*, is the sum of *NELPRFDEMALU* and *NATSELFDEMALU*.

4.8.3 GHG emissions

As discussed in Section 2.4, GHG emissions are considered to be one of the most important environmental issues of the industry and have been a key driving force in the evolution of technologies in the last few decades. In the model, GHG emissions are distinguished as process-induced and energy-related.

Process generated emissions depend on the technologies used in the primary aluminium smelters. The emission factors (kg/tonne Al) of the PFC gases are clearly in relation to the anode effect; therefore vary greatly depending on the technology, and with the improvement of technologies these emission factors are expected to continuously decrease. Due to a lack of data, the model tries to analyse the emission factors of the currently installed technology in relation to the age of the technology, and extrapolate this trend to the simulation years of the model. On the one hand, technology improvements at a smelter will result in decreased emissions, on the other hand, when an installed capacity gets old, its overall performance declines. These trends cannot be fully captured with limited information for a detailed simulation. Nevertheless, in the model, the emission factors of a facility, disregarding its location, can be estimated by its current emission factor, $EMIFACTOR_{tech,t}$, (data at the starting year of the simulation), which follows a dynamic trend, $TREND_{tech}$, calibrated based on the relationship between the emission of an installed capacity and the age of the capacity for each of the technology:

(35) $$EMIFACTOR_{tech,t} = (EMIFACTOR_{tech,t-1})^{TREND_{tech}}$$

The current emission factors per technology mainly comes from IAI report on the Results of the Anode Survey, which is carried yearly since 1990 (the latest data available to this report is from 2004 published in June 2006), though several other source are also take into account for comparison as shown in Table 6. The default emission factor published in the 2006 Guideline by International Penal on Climate change (IPCC) is also based on IAI's survey; however the data is from 1990. In this study, the lasted IAI data are used.

Process induced carbon emissions are the necessary result of the reaction of the carbon anode with the oxygen released from alumina, so its emission factor varies little among different technologies and can be assumed as constant for the current technologies. Available data indicate that because Prebake technology employs dry carbon anodes, it generates slightly less process CO_2 emissions than that of the Søderberg technology. However, fuel related carbon emissions are higher in the case of Prebake due to the separate baking process of the anode. The region/country process emissions, *GHGPROEMISSION*, can thus be calculated as:

$$(36)\qquad GHGPROEMISSION_{region,gas} = \sum_{tech} EMIFACTOR_{tech,gas} * PROALUPRI_{region,tech}$$

Total GHG emissions in the model are expressed as CO_2 equivalent emissions calculated using the 100-year Greenhouse Warming Potentials (GWP) as defined in the Third Assessment Report (TAR) of the IPCC. The GWP of $CF_4 = 5700$ and $C_2F_6 = 11900$. Thus the total GHG emissions in carbon equivalent, *CPROEMISSION*, by region are:

$$(37)\qquad CPROEMISSION_{region} = \sum_{gas} GHGPROEMISSION_{region,gas} * GWP_{gas}$$

Fuel combustion is responsible for the bigger share of the carbon emission in the aluminium industry. The emissions can be calculated based on the consumption of fuel, $NATFUEL_{region,fuel}$, and the specific carbon content of the fuel, $KGCFUEL_{fuel}$. Although no combustion reaches 100% efficiency, the model assumes that all carbon is converted into CO_2 during combustion. Thus, the fuel related carbon emissions, *CFUELEMISSION*, are shown as:

$$(38)\qquad CFUELEMISSION_{region} = \sum_{fuel} (NATFUEL_{region,fuel} * KGCFUEL_{fuel})$$

The grand total of regional CO_2 emissions from the aluminium industry can be then calculated as, in CO_2 equivalent:

$$(39)\qquad CO2EMISSION_{region} = (CPROEMISSION_{region} + CFUELEMISSION_{region}) * 44/12$$

Currently the aluminium industry is not covered by the Emissions Trading Directive of the EU, although the discussion on the second period of emissions trading has proposed to include the aluminium industry, along with several others. The inclusion of PFC gases is also under debate and to be decided. Depending on the carbon value, the industries in the EU would then incur expenses based on their GHG emissions:

$$(40)\qquad COSTEMISSION_{region} = CARBONEMISSION_{region,gas} * CARBONVALUE_{region}$$

Where $COSTEMISSION_{region}$ is the cost of emission, $CARBONEMISSION_{region,gas}$ is the emissions in carbon equivalent and $CARBONVALUE_{region}$ is the market value of carbon.

In the simulation results illustrated in the Chapter 5, scenarios of alternative technology, emissions trading, and carbon prices are discussed together with their implications on the evolution of the industry as whole and its environmental performance.

5 MODEL SIMULATION AND RESULTS

5.1 Coverage and set-up

As already mentioned, the aluminium model is a world model and it divides the world into 47 regions with some countries being grouped as one region while others are regions on their own. For geographical reasons and the in-depth analysis of key players in the industry, the results of the model are often reported in larger groups. All the divisions and groups are presented in the following Table 5 for clarification and for a better understanding of the model results.

Table 5 Regions and country in the model

	47 country-regions	
N. America	CAN	Canada
	USA	United States
Europe	FRA	France
	GBR	United Kingdom
	ITA	Italy
	RFA	Germany
	AUT	Austria
	BLX	Belgium, Luxembourg
	DNK	Denmark
	FIN	Finland
	IRL	Ireland
	NLD	Netherlands
	SWE	Sweden
	ESP	Spain
	GRC	Greece
	PRT	Portugal
	HUN	Hungary
	POL	Poland
	RCZ	Czech Republic
	RSL	Slovak Republic
	BLT	Estonia, Latvia, Lithuania
	SMC	Slovenia, Malta, Cyprus
	BGR	Bulgaria
	ROM	Romania
	ROWE	Gibraltar, Iceland, Norway, Switzerland
	TUR	Turkey
	RCEU	Albania, Bosnia-Herzegovina, Croatia, Macedonia, Serbia & Montenegro
Oceania	RJAN	Australia, Fiji, Kiribati, Vanuatu, New Zealand, Papua New Guinea, Solomon Islands, Tonga, Western Samoa
CIS	RUS	Russia
	UKR	Ukraine
	RIS	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyz Rep., Moldova, Tajikistan, Turkmenistan, Uzbekistan
S. America	MEX	Mexico
	RCAM	Bahamas, Belize, Bermuda, Barbados, Costa Rica, Cuba, Dominican Rep., Grenada, Guatemala, Honduras, Haiti, Netherlands Antilles & Aruba, Jamaica, St. Lucia, Nicaragua, Panama, El Salvador, Trinidad, St Vincent & the Grenadines
	BRA	Brazil
	RSAM	Argentina, Bolivia, Chile, Colombia, Ecuador, Surinam, Guyana, Peru, Paraguay, Uruguay, Venezuela

Asia	JPN	Japan
	NDE	India
	RSAS	Pakistan, Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal
	COR	South Korea
	RSEA	Brunei, Myanmar, Indonesia, Cambodia, Lao, Malaysia, Mongolia, Philippines, North Korea, Singapore, Thailand, Taiwan, Vietnam
	CHN	China
AFMI	EGY	Egypt
	NOAP	Algeria, Libya
	NOAN	Tunisia, Morocco, Western Sahara
	MEME	Israel, Jordan, Lebanon, Syria
	GOLF	United Arab Emirates, Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, Yemen
	SSAF	All the other African countries

5.2 Data and reference scenario

5.2.1 Data source

Data used in the model come from various industrial reports and studies by consulting companies, and they are, in general, limited in many regions. Data and forecasts of the GDP and population for all regions are based on published UN statistics. In many cases they have been evaluated and re-estimated for the consistency of data and aggregated or disaggregated in order to be suitable to the model structure and definition. The following table (Table 6) intends to provide a transparent list of key source of data for the model. The details of these sources are listed in the Reference.

Table 6 Model and data overview

	Source of data
Consumption and production	EAA, 2000-2006 IAI, 1990-2005 Roskill, 2003 UNCTAD, 1996-2001 USGS, 1970-2005
Capacity, technology, cost and energy use	CRU, 2002-2003 USGS, 1998 EAA, 2006 IAI, 1995-2000 ENERGETICS, 1997 RIVM, the Netherlands, 2000 IPPC, 2000
Scrap and recycling	EAA, 2006 Roskill, 2003 Hydro, 2001
Price and trade	Riskill, 2003 LME website, 2006
Emission estimation	ICF Consulting, 1990-2000 IAI, 1990-2006 EAA, 2000-2005 ENERGETICS, 1997
Population	UN, 2004
GDP	IPTS POLES model, 2007

5.2.2 Scenario and assumptions

The basic reference scenario is the so-called 'business as usual' (BAU). In order to construct this scenario, assumptions have been made, and while some of them are described in the previous chapter in order to describe the estimations made in the model, the overall outlook of the economy and aluminium industry, based on which the results of the simulation and their limitations should be understood, are discussed here.

The aluminium industry, like all other industries, is part of the economy and influenced by the overall economic growth and is interrelated with several other industries, either in terms of market competition or demand and supply relationship. In principle, under business as usual, the current economic development and the trends in resource use continues. The often applied indicator for the level of economic activity and trend is the growth in GDP per capita.

Economic trend: GDP and population

- The rate of economic growth in industrialised regions converges to under 2%/yr in the very long run. Growth in Asian emerging economies will fall significantly after 2010, while it will be almost constant in Africa and the Middle East. As a result, global economic growth is expected to progressively slow down from 3,5%/yr during the 1990 - 2010 period to 2,9%/yr between 2010 and 2030. Economic growth in Europe is expected to stabilise at 2,1% during this period.

- World population will grow to 8 billion by 2030, with a growth rate of 1,3% between 1990 - 2010 and of less than 1% after 2010.

The use of aluminium in industrial applications

- The overall the consumption of aluminium will increase at an annual rate of 3,2% between 2005 and 2030.

- The transportation sector is and will remain the most important market for aluminium and the use of aluminium is expected to follow the growth rate of the sector at 4% during the period.

- The global growth rate of the construction and building sector is driven by Asia’s development at 2%. The same is expected for packaging applications, at 3%.

- Engineering, electronics, and cable will grow at a rate of 2,6% and the growth rate of all other sectors is expected at 3%.

Other scenarios, such as a high recycling rate, and alternative technologies in the long term including extending the model simulation to 2050, will be considered in the next step of the development of the model. However, as already mentioned, an alternative scenario assuming two advanced primary production technologies has been constructed for illustration purpose. This scenario is largely based on the futuristic assumptions from literature, ALT TECH, and is described in Section 5.3.3.

5.3 Simulation results

Under the assumptions of the above described business as usual scenario, the simulation results are discussed in the following section.

5.3.1 Demand and consumption

Total consumption

At global level, the absolute amount of total aluminium consumption is expected to be more than doubled from 36 Mt in 2003 to over 87 Mt by the year 2030. Averagely, the annual rate of increment of the aluminium consumption will be about 3,3% in the next 30 years, which is lower than the 5% high growth in recent years. The estimate shows that this high rate of increase of the recent phenomenon will continue at between 3,5 - 4% per annum until 2010 and then decline to 2,4% by around 2030.

By region and country, the consumption of aluminium varies significantly. Asia, including Japan and China, will remain the largest consumer and keep a high growth rate. The highest growth rate in total consumption is observed in Asia and the Africa - Middle East regions and is approximately 5% and 4% annually respectively, followed by CIS at 3,4%, Oceania and South America at 3%, Europe at about 2% and North America at the lowest of 1,4%, as shown in Figure 22. Figure 23 shows the share of each region in the world aluminium market, and as consequences of the growth rate, the share of Asia, which is the largest, will continuously increase to more than 50% by 2030. To a much lesser extent, slight increase of the market share (2 - 3%) can be seen in the CIS and Africa - Middle East regions. Both the shares of Europe and North America will decline from 28% and 30% in 2000 to 19% and 15% by 2030 respectively. As is being expected the strong increasing trend in Asia is attributed to the continuous growth in consumption in China, which is expected to double its consumption from nearly 8 Mt in 2005 to over 16 Mt in 2030 overtaking America and becoming the largest consumer of aluminium. However, the result indicates the growth in China will not be as strong as that observed between 2000 and 2004, when the consumption doubled in just 5 years.

Figure 22 Total aluminium consumption by region

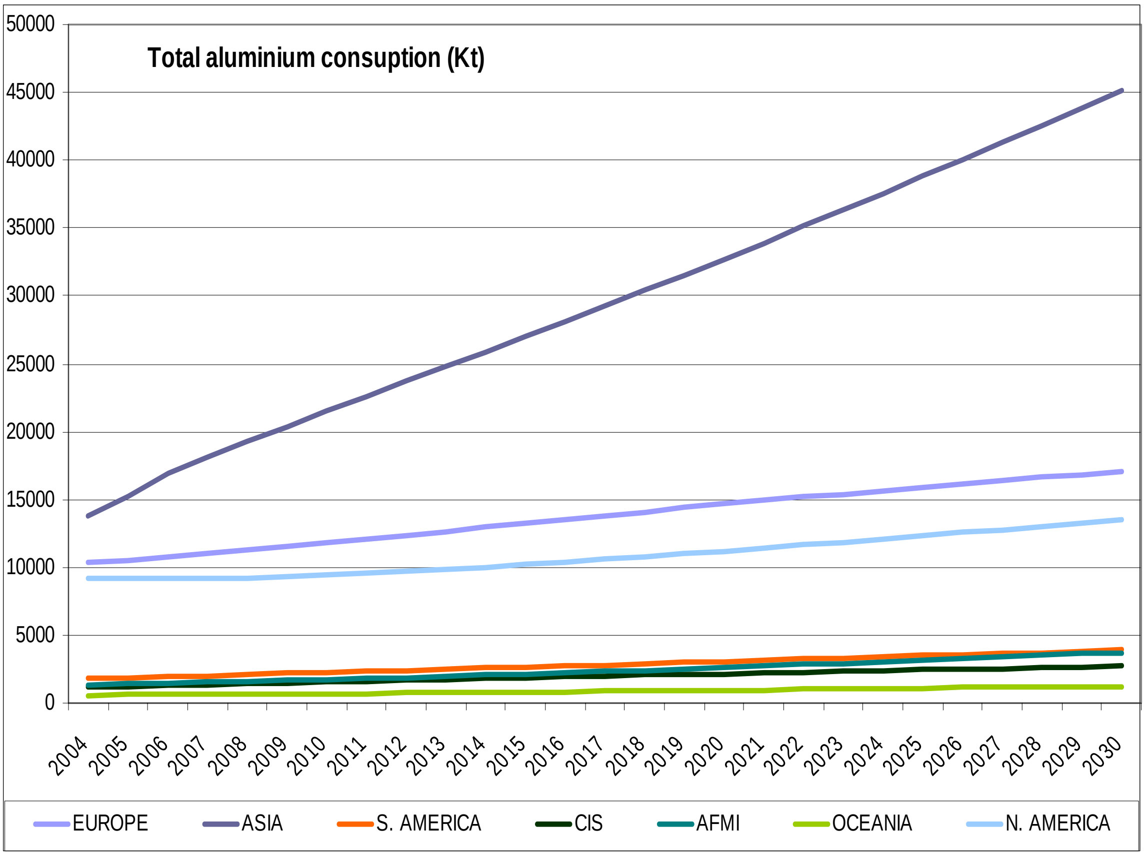
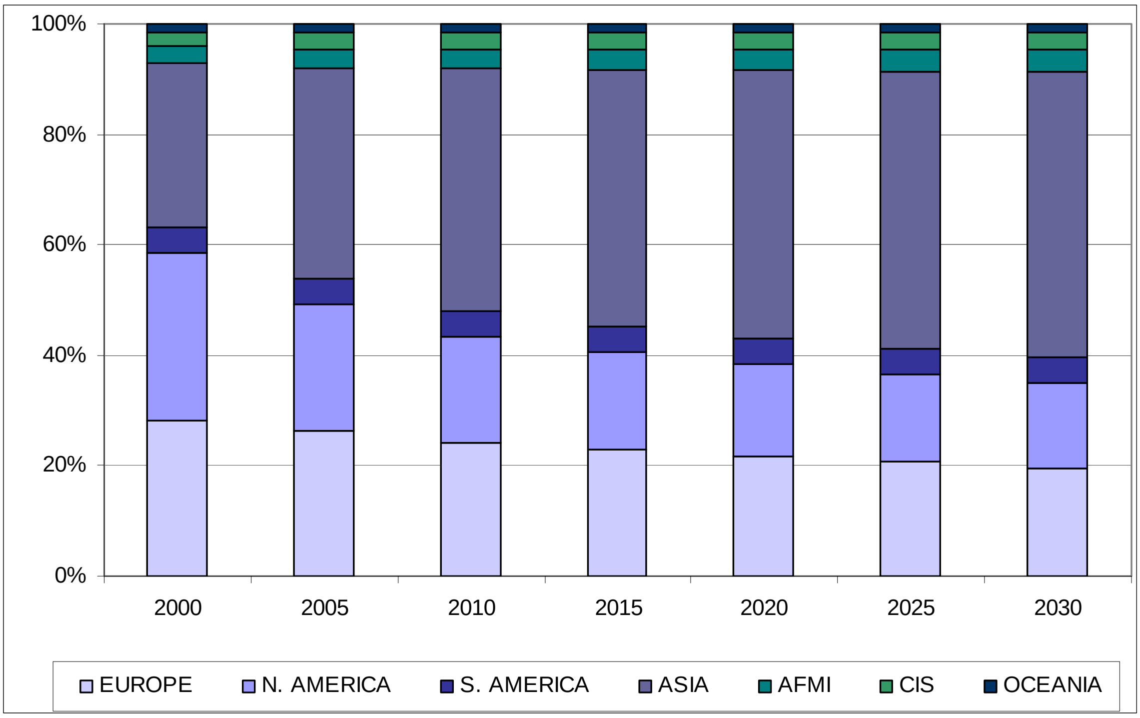
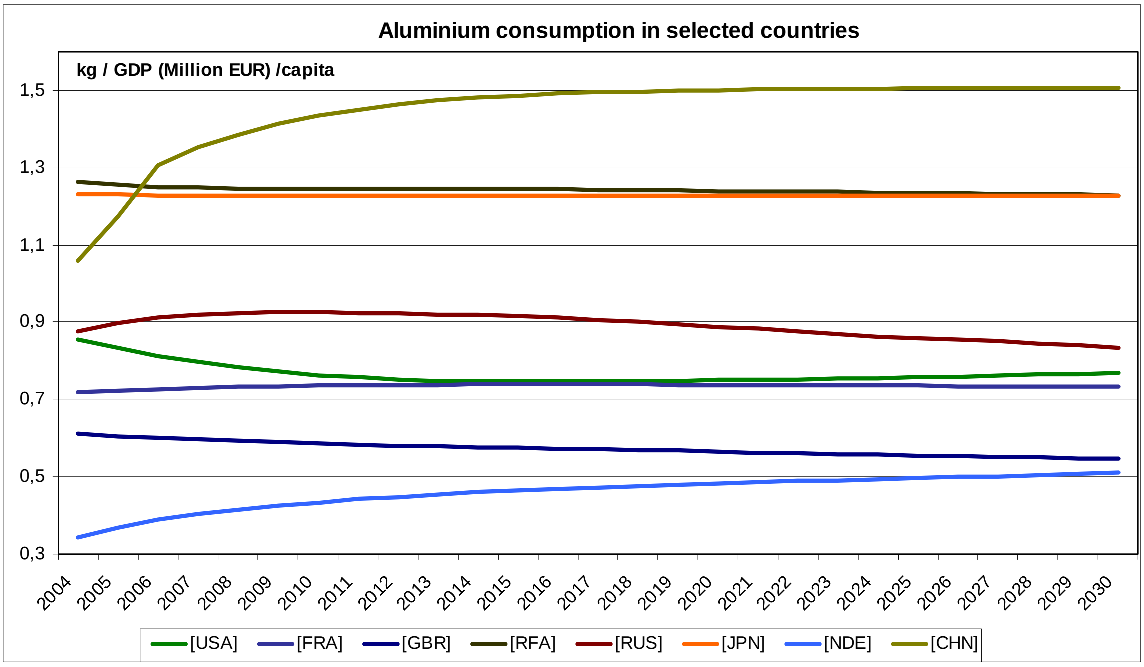


Figure 23 Total market share of aluminium consumption by region



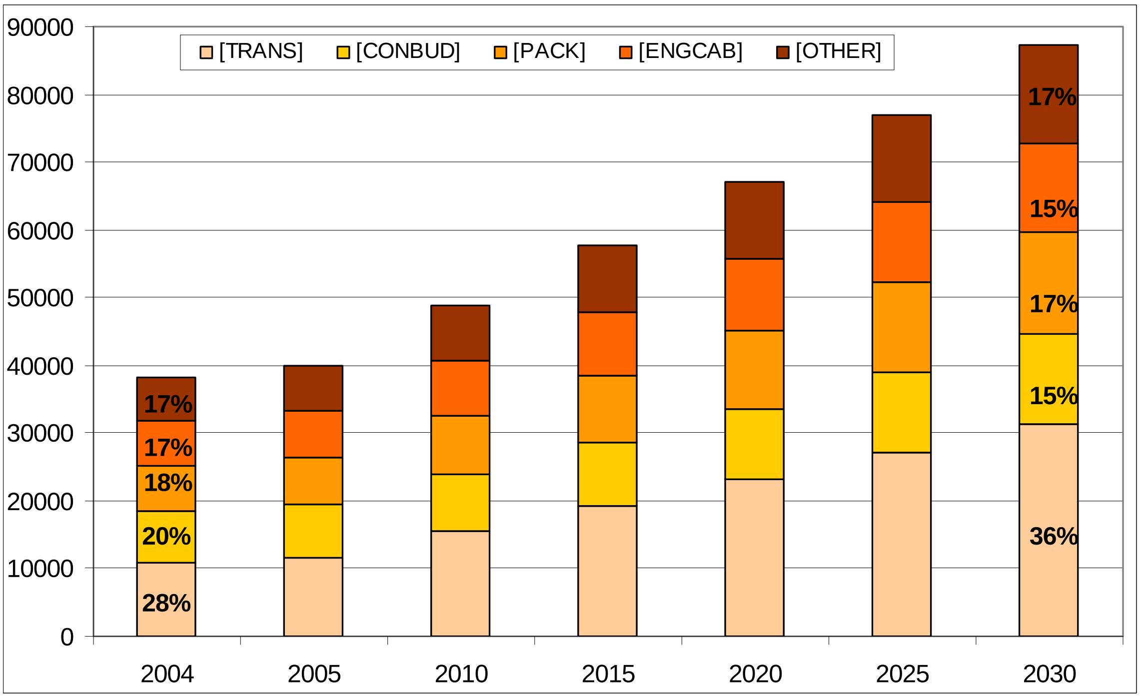
In general, aluminium consumption per GDP and population (aluminium intensity) is relatively high in developed countries, especially the ones with large automobile industries such as Japan and Germany, compared to that in the developing countries, and remains to be high as shown in the result of the simulation, shown in Figure 24. For the developing countries, a clear increasing trend of intensity can be observed; however in most countries, the rate of this change is much less than 1% per annum.

Figure 24 Aluminium intensity



Due to lack of data, it is difficult to translate the demand which is based on overall economic evolution into the sectoral demand. Nevertheless, the growth of aluminium consumption in all sectors is estimated as discussed in the previous section. The economic analysis shows that the strongest increase is in the transportation sector and the trend will continue into the medium to long term. Such an increase is not only due to the productivity of the industry, with a sharp inclining trend in China and to a lesser extent in other developing countries, but also because of the increasing application of aluminium, in particular, in light vehicles. For example, the aluminium content per light vehicle has been increasing at a rate of nearly 9% per year in North America for the last 30 years. Compared to other sectors, these factors will result in a stronger increase in aluminium consumption in transportation. Consumption in the construction and building sector is expected to see little change, with the increase in Asia off-setting the decrease in developed countries. The increase of aluminium consumption in the packaging and electricity/electronic sector is expected to be slightly higher then overall economic growth in developing Asia and Central European countries; therefore contributing slightly to the intensity increase. Based on this outlook of each sector, the model estimates the demand of aluminium in a number of key sectors. As expected, both the absolute amount and the share of transportation sector show highest increase, accounting to 36% of the world aluminium market in 2030 from the current 28%. While the aluminium consumption will increase in absolute terms in all the sectors, the share of theses sectors will decrease, as shown in Figure 25.

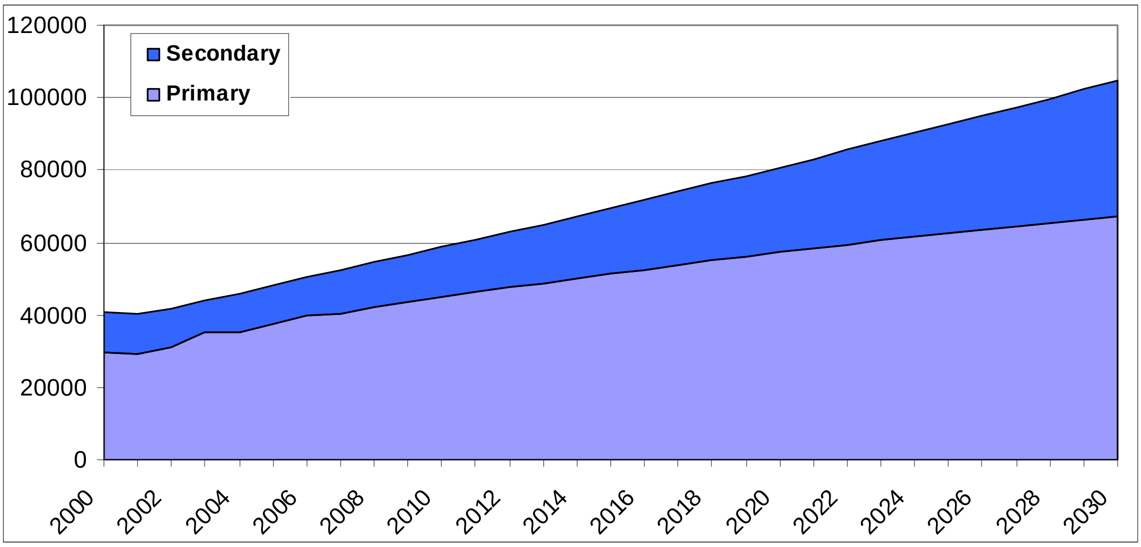
Figure 25 Aluminium consumption by sector



Primary and secondary demand

At world level, the demand (i.e. the amount of aluminium that is needed to meet the consumption, see Section 1.3)) for both primary and secondary will increase with secondary at an annual rate of 5%, about twice of that of primary, at 2,4%, as shown in Figure 26. The growing demand of primary will slow down after 2010 and its annual growth rate will become less than that of the total aluminium consumption.

Figure 26 Growth of primary and secondary demand



As a consequence, the share of secondary aluminium in the total demand is increasing at world level as well as regional level, as shown in Figure 27. On average, the share of secondary aluminium is expected to reach around 36% by 2030, with the highest being observed in South America at close to 60%. The share in Europe will continuously stay higher than the world average and reach 47% by 2030, while North America will increase from around 25% in 2004 to nearly 40% by 2030, remaining slightly above world average. In absolute terms, as presented in Figure 28, while already being the largest market of primary aluminium, Asia's secondary demand will overtake Europe after 2010 becoming the largest secondary consumer. The rate of growth in secondary demand is, on a yearly average, higher in developing countries than that in developed countries. The highest can be observed in the CIS region at close to 14% per year in the next 25 years followed by Asia and the Africa - Middle East regions at between 6 and 8%. The annual growth rate of secondary market in both America and Europe is observed at around 3% in the same period of time.

Figure 27 Share of secondary demand by region

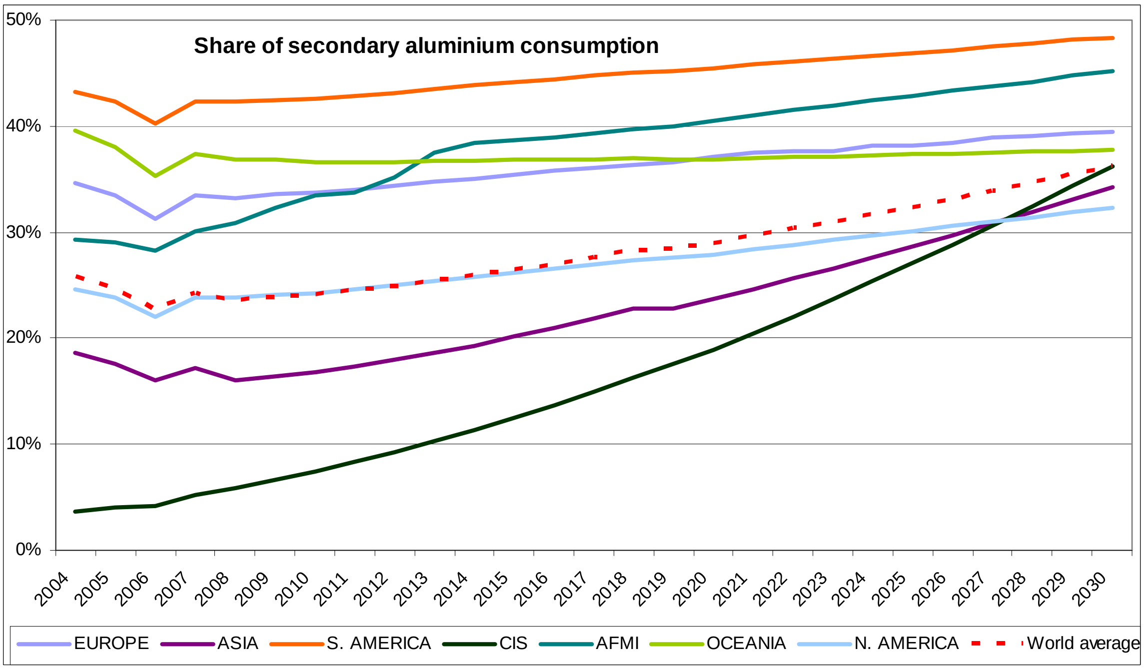
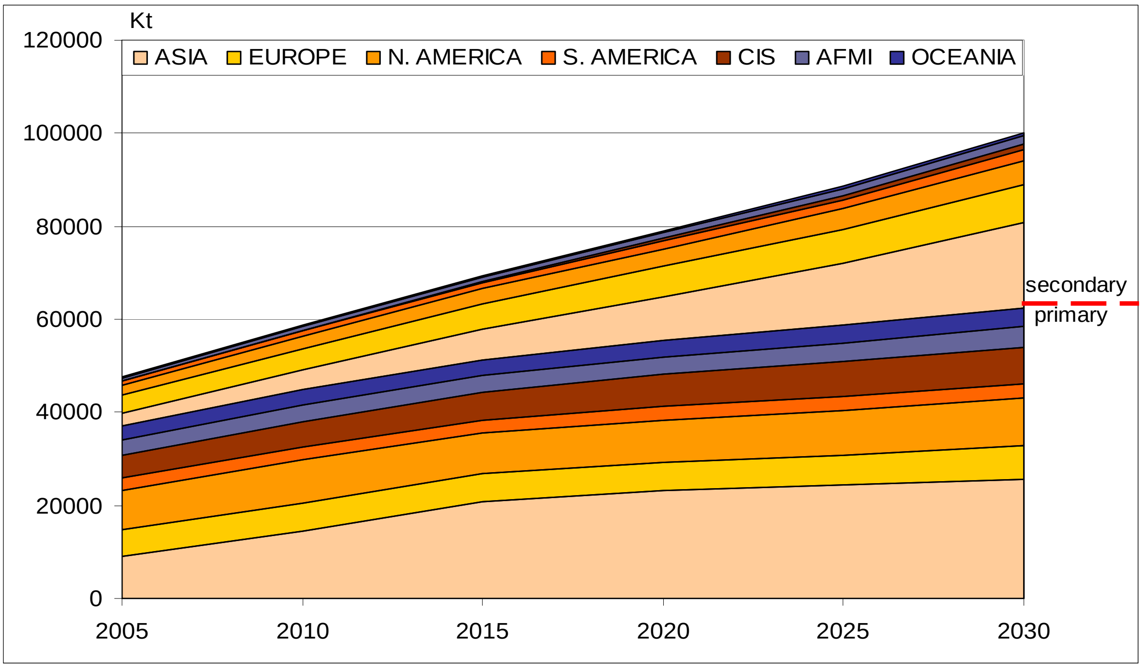


Figure 28 Demand by region



5.3.2 Primary production and capacity

While fulfilling the primary demand, global primary production follows the same trend of growth. Global production is expected to double in the modelling period reaching more than 60 Mt in 2030 (Figure 29). Production in North America and Europe is expected to increase at around 70% and 55% respectively of its total production during the entire simulation period and to stabilise at an annual growth rate of 1 - 2% from around 2015 onwards. However, in comparison to 2004 both regions will significantly loose their world share, 6% for North America and 5% for Europe. The growth in Asia is shown not only in absolute quantity, which will more than double when compared with 2004, but will also increase in its share of the world total, from 23 to 41% becoming the largest of all regions as shown in Figure 30. Oceania, lead by Australia, the largest alumina producer, will also gain 4% of the world share from 2004 to 2030 with a steady growth rate of 4% yearly. Growth in world share (2%) can also be observed in the Africa - Middle East region where production output will double.

Figure 29 Primary production by region

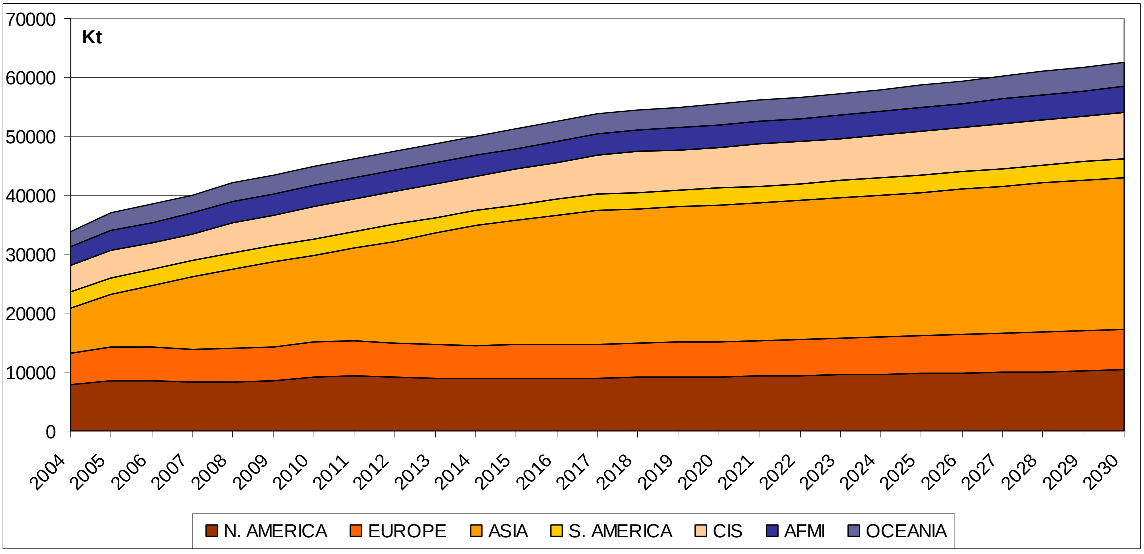
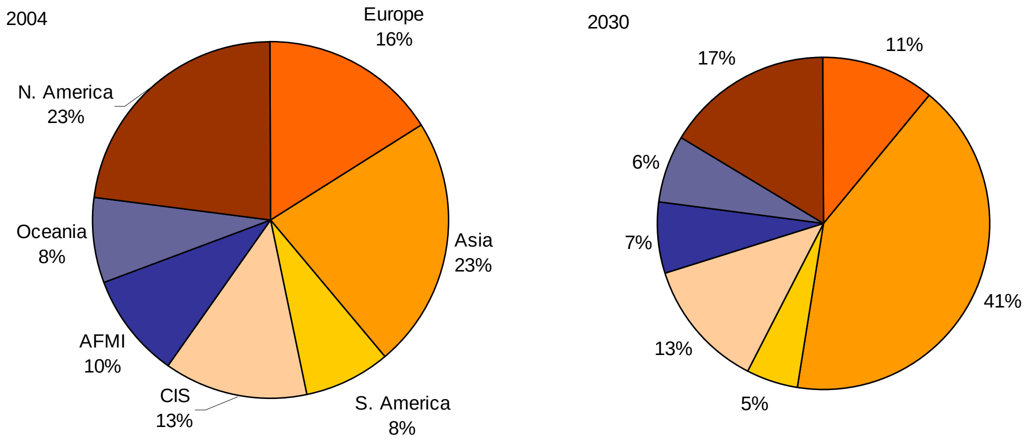
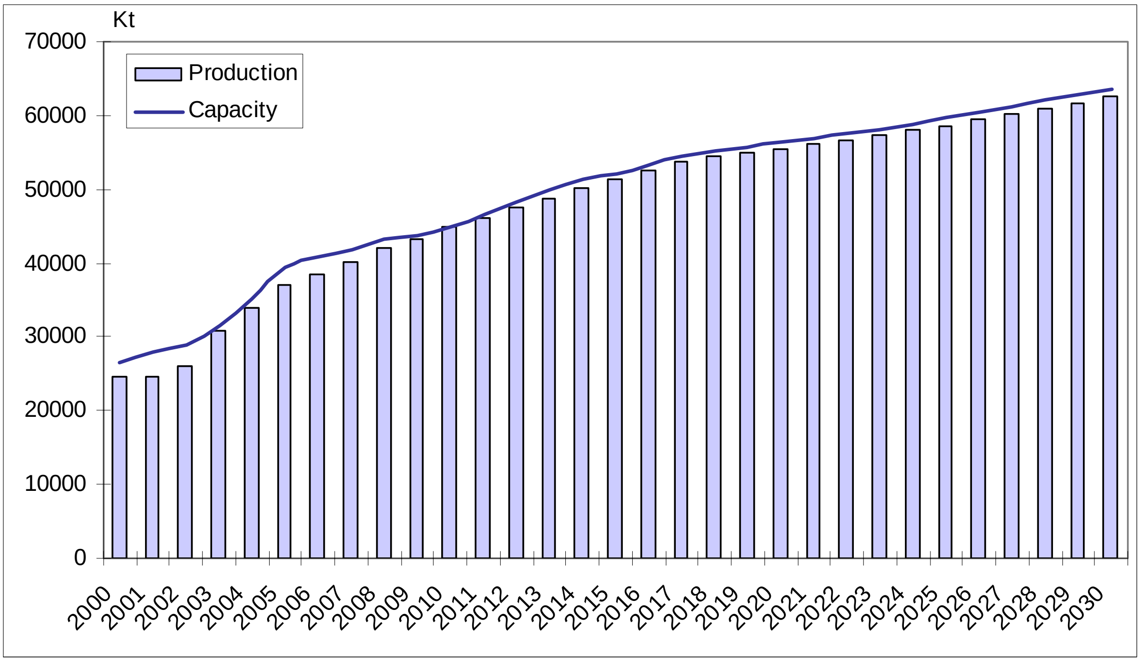


Figure 30 Change of share in production by region



Clearly, capacity will increase to sustain the growing production. For the simulation period, world capacity, assuming a high utilisation rate of smelters due to high investment costs, is expected to increase about 25 Mt in total between 2004 and 2030, at an average of 2,7% per year and installed new capacity will account for 2 - 4% of the yearly total capacity. Closely resembling the pattern of production, capacity increases are mainly concentrated in Asia, Oceania and the Africa - Middle East. In the next 25 years, more than 40 Mt of new capacity is to be installed, which will account for more than 60% of the total capacity in 2030.

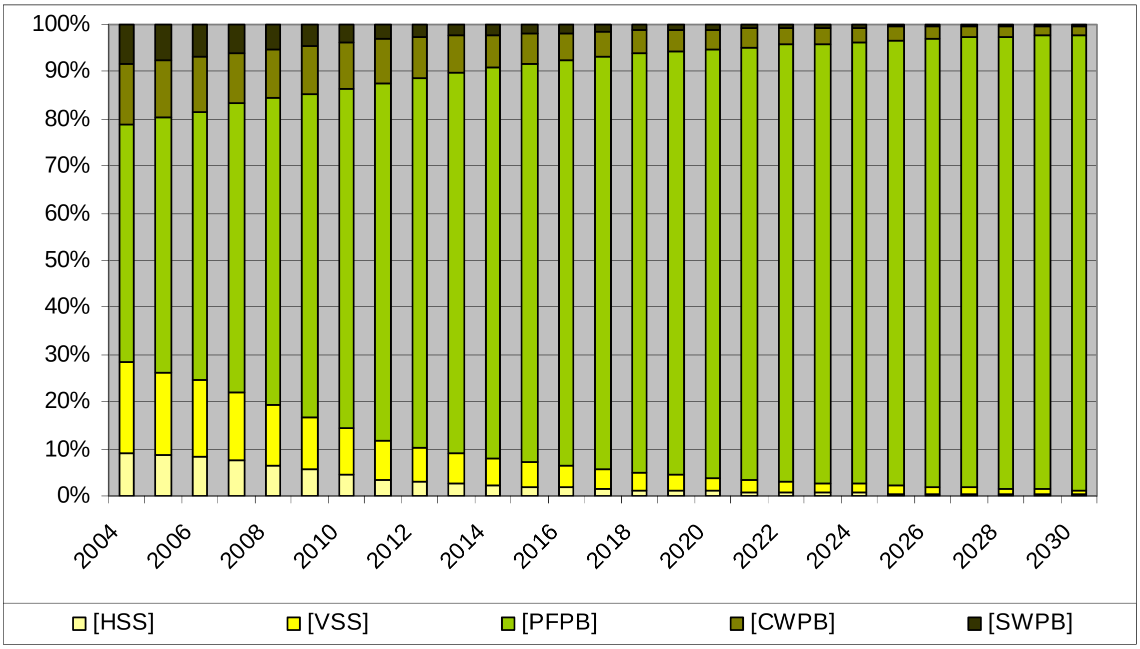
Figure 31 World production and capacity of primary aluminium



5.3.3 Technology in primary production

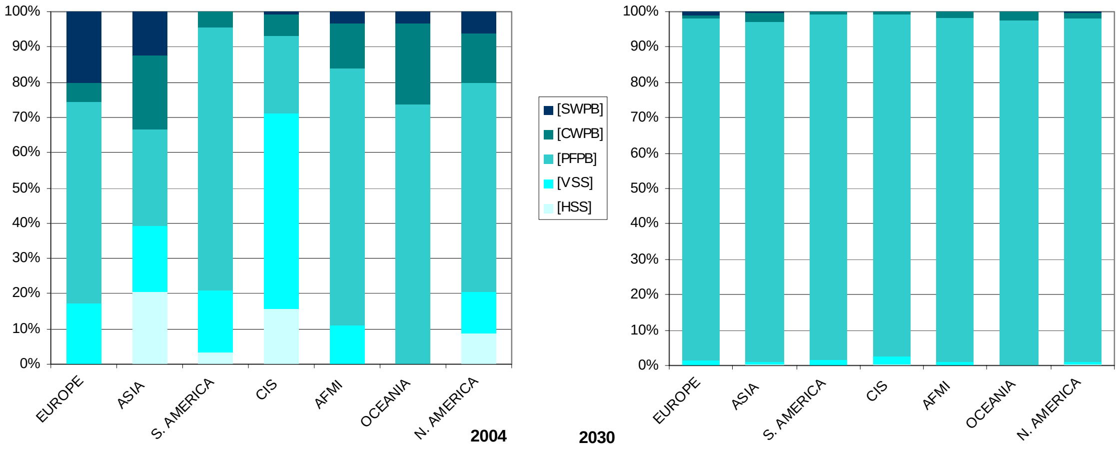
The technological evolution in the primary aluminium industry, as expected, shows a clear preference for Prebake technology, especially PFPB. Since retrofitting and new installations are expected to be based on PFPB, all the other technologies are gradually being replaced by PFPB, as shown in Figure 32.

Figure 32 Share of technology



Comparing to the technology mix across the regions, large differences currently exist, from only Prebake technology in Australia to Sødergerg which dominates in the CIS region. However, with retrofitting now geared towards PFPB, it is expected such that variations will gradually disappear, as shown in Figure 33.

Figure 33 Technology mix by region



Alternative scenario on technology (ADV TECH)

As noted in Section 3.5, two further technologies for primary aluminium production, PBRTE and PBANOD, may be expected to emerge by the end of the model's simulation period. Little information is available so far on these two technologies. From their technical descriptions, the following are assumed in the model:

- Since both PBRTE and PBANOD are Prebake based technologies, any of the three existing Prebake technologies can be retrofitted to either, while this is much more costly in the case of Søderberg cells. Furthermore, as there will be only very small fraction of Søderberg technology left after 2020, retrofitting from Søderberg to future Prebake technology can be neglected. Although the SWPB and CWPB can be retrofitted to advanced technologies, the model assumes that since the retrofitting cost may be rather high and given the fact that they will be largely converted to PFPB, the only technology that is to be retrofitted to the advanced technology is PFPB.

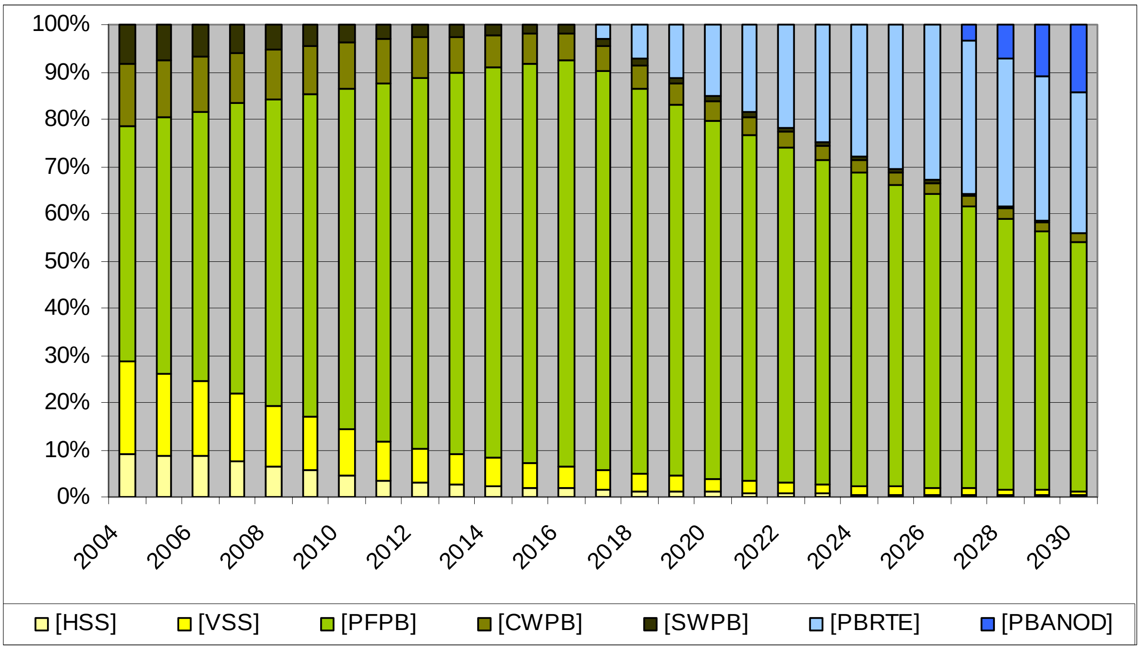
- In the BAU case, the model assumes that whenever a technology is retrofitted, its alternative can only be PFPB. In this alternative scenario, the model has to assume an earlier appearance of the new technologies on the market in order to observe the possible changes. Therefore, the assumption is that after 2015, PBRTE will be the end technology of retrofitting until 2025, and then PBANOD will be the subsequent successor, as in Table 7. A new installation is assumed to be always the most advanced technologies.

Table 7 Retrofitting options

	Current - 2030					2015-2025	2025-2030
	HSS	VSS	CWPB	SWPB	PFPB	PBRTE	PBANOD
HSS	-	-	-	-	√	-	-
VSS	-	-	-	-	√	-	-
CWPB	-	-	-	-	√	-	-
SWPB	-	-	-	-	√	-	-
PFPB	-	-	-	-	-	√	√
PBRTE	-	-	-	-	-	-	√
PBANOD	-	-	-	-	-	-	-

As a result, the technology mix will be altered. Without data and information to estimate the rate of penetration of the new technologies, the speed of the introduction of these technologies can only be illustrative. By 2030 more than 40% of the world's production could be using the new technologies, which will have significant impact on the energy use and emissions (see Section 5.3.9), as shown in Figure 34,

Figure 34 Share of technology: ADV TECH

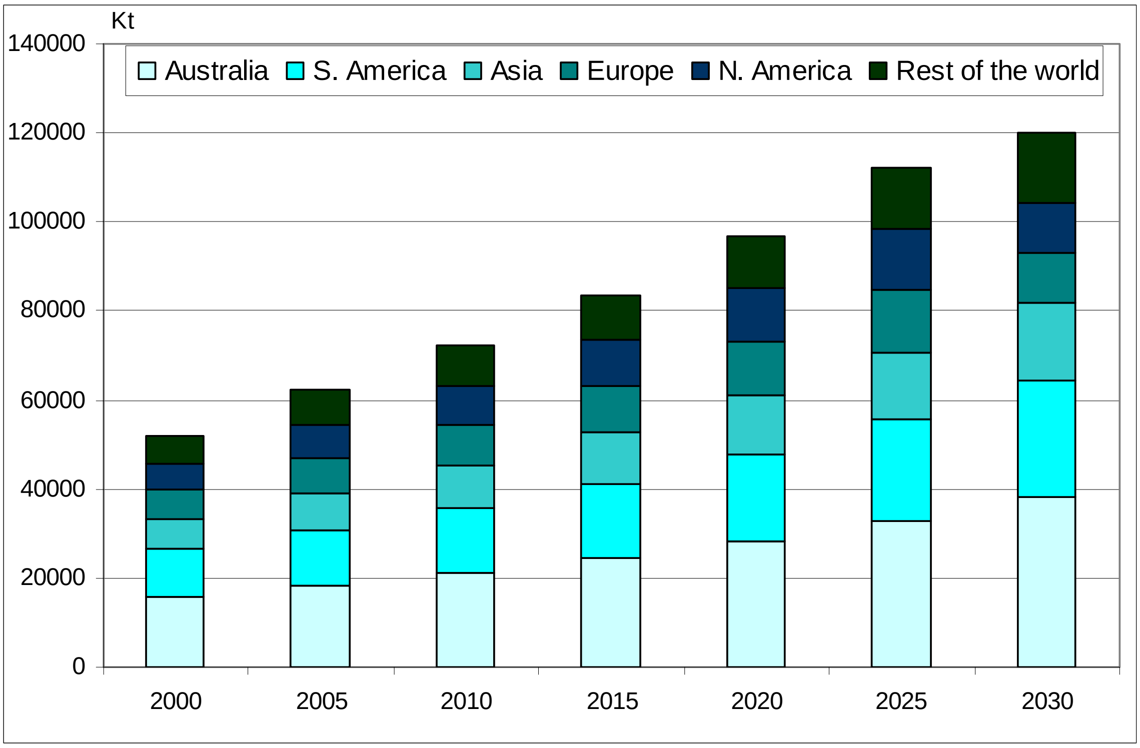


In comparing the two scenarios, it is noted that without any alternative technology the world primary aluminium industry will be "locked into" one single technology, i.e. the PFPB. The advanced technologies, i.e. PBRTE and PBANOD, though providing technology substitution, are future variations of the PFPB technology. This implies that any future technology based on processes other than electrolysis could face a strong lock-in affect of the current technology development.

5.3.4 Alumina production

Following the growth in primary production, alumina production will increase by some 100% by 2030 from its 2004 level (see Figure 35). The key producing regions, i.e. Australia, S. America and Asia, are expected to increase their production by more than 140% during the simulation period, while the increase in Europe and N. America is expected to be much less, around 70%, and a decreasing production trend will be observed after 2025. In terms of world market, the share most of the regions will slightly increase, except North America and Europe, where their share will decline. Australia alone will continuously supply one third of the total alumina demand. The bauxite price is expected to change little in the coming years. However, due to production increase in China and Russia, where different types of bauxite are used, alternative production technologies, especially Bayer-Sinter, and, to a lesser extent, the Nepheline process show a slight increase of share in total production. By 2030, they will together account for 17,5% compared to 16% in 2004.

Figure 35 Alumina production by key region



5.3.5 Secondary aluminium and scrap supply

As discussed in Section 5.3.1, since the consumption of aluminium in all sectors is expected to increase, the accumulated aluminium products in use as well as the end-of-life products containing aluminium are expected to increase. The total amount of aluminium products in use will more than double in the next 25 years reaching more than 1,2 billion tonnes in 2030, as show in Figure 36. Assuming the current trend of scrap generation and collection continues, 3 - 4% of the total amount of aluminium products in use will turn into old scrap each year, and 50 - 60% of the scrap will be collected and used again in secondary production. As a result, collection of old scrap will increase from about 7 Mt currently to 30 Mt by 2030. In 2030, transportation, being the largest scrap source, will generate close to 45% of the total scrap (Figure 37). Packaging will still be the second source though its share shows a decreasing trend and a similar tendency can be observed for the engineering/cable sectors. On the other hand, the share of scrap from building and construction sector is expected to increase from 7% to some 10% in 2030.

Figure 36 Aluminium production in use by main sectors

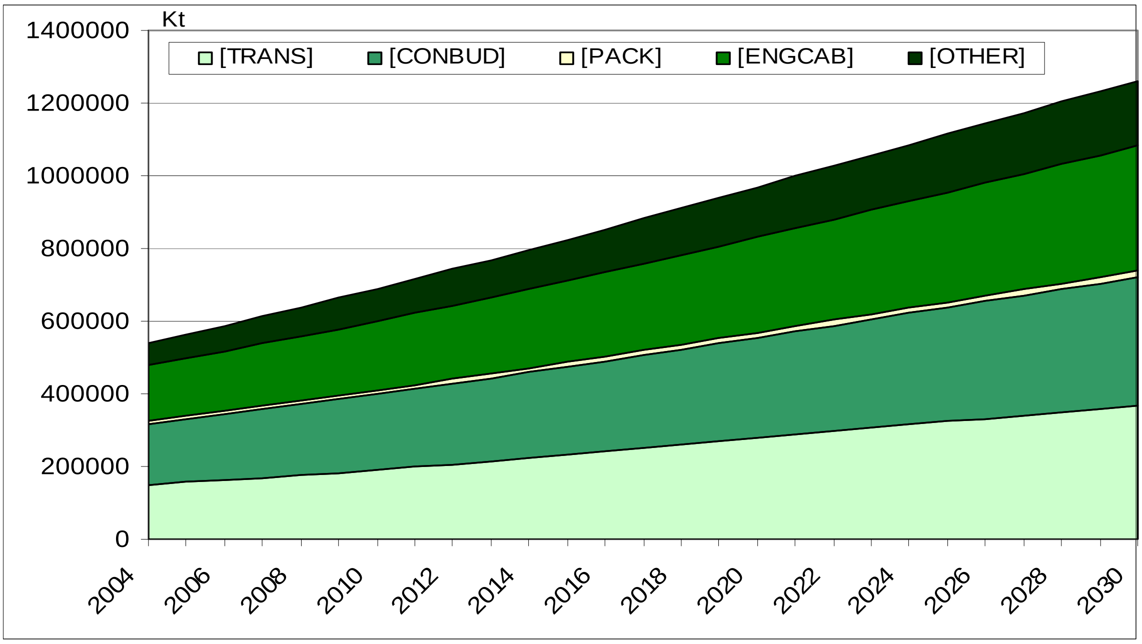
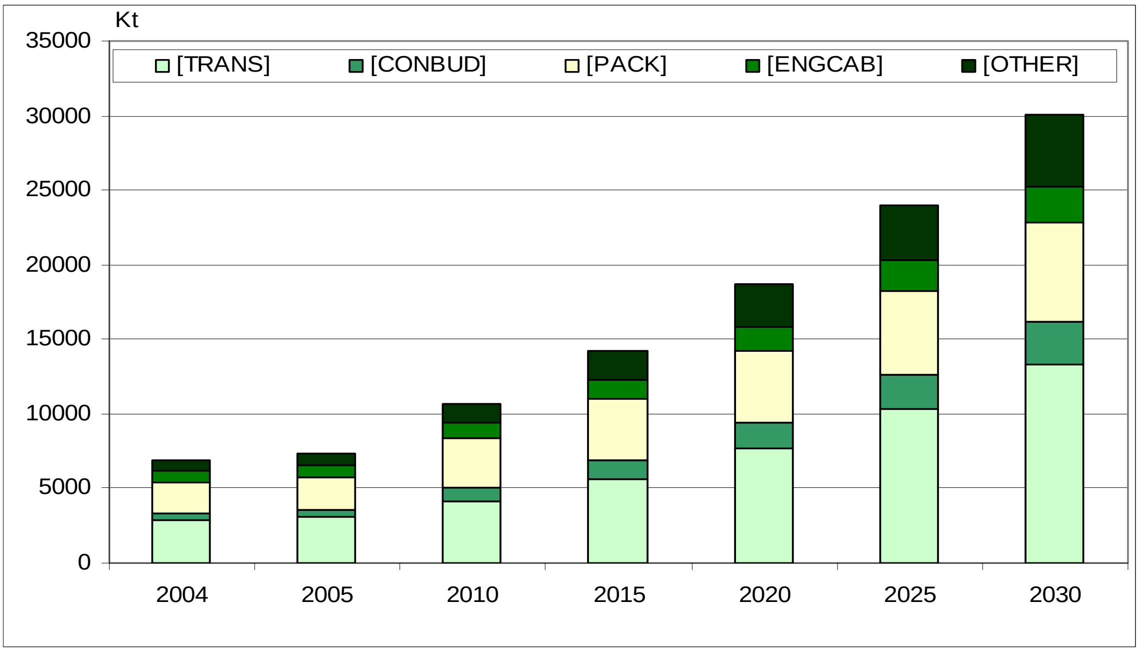


Figure 37 Scrap generation and collection by source

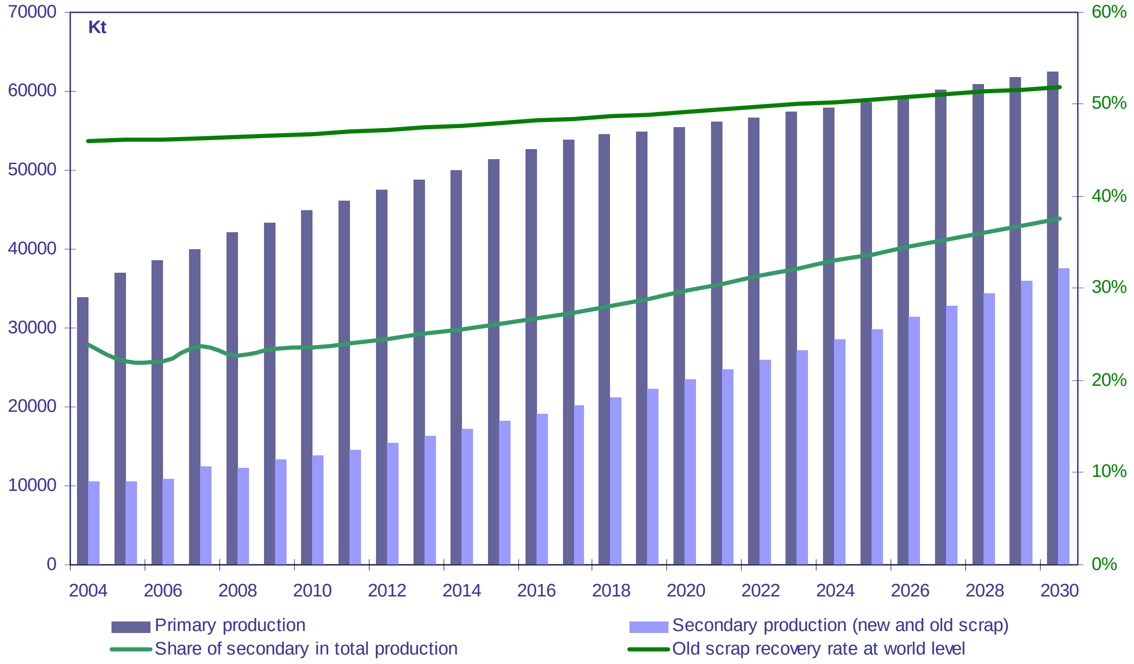


New scrap generated from production processes is partially traded on the scrap market, which will impact the market demand and supply equilibrium and price. With the limited data, a simple estimation can be made on the amount of new scrap based on primary aluminium production. Therefore, in total the scrap traded on the world market is expected to reach close to 46 Mt in 2030, an average increase rate of 4,5% per year.

In summarising the world aluminium supply, as shown in Figure 38, total aluminium production is expected to increase by 230% from 44 Mt in 2004 to 100Mt in 2030. The share of secondary (both from new and old scrap) in total aluminium production is expected to increase from 25% to nearly 40% in the same period and will amount to half of the primary aluminium production by

2030. The recycling rate of old scrap, expressed as old scrap recovered as a percentage of the total scrap generated, is estimated to grow little to over 50% at the world level.

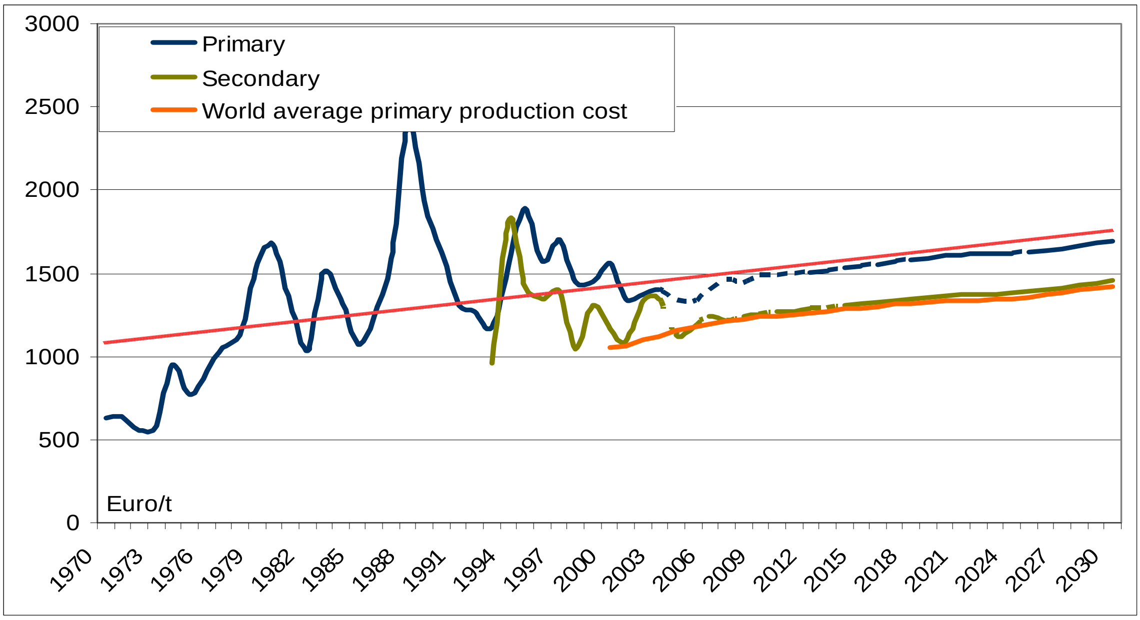
Figure 38 World total aluminium production



5.3.6 Aluminium production cost and prices

As shown from the data in the past (Figure 15), the price of aluminium has been increasing in the last 30 years. In general since the demand for aluminium is still on the inclining side of the curve, supply is the main constraint in the market equilibrium, depending on the evolution of both demand and supply. The simulation result, as exhibited in Figure 39 indicates the continuation of the increasing trend and indicates that the average production cost and price of primary aluminium will increase at a rate of 0,8 and 1% annually after 2004, and the rate of increase for secondary aluminium is expected to be closely following that of the primary, about 1%. However the real price of aluminium is expected to decrease, depending on the rate of inflation, at a rate of 1-2% per year.

Figure 39 Production cost and price of primary and secondary aluminium



As also discussed, the key cost factors in the primary production are the cost of alumina and energy. The model results indicate that while the share of alumina cost will averagely increase 0,3% per year, the share of energy cost is expected to decrease gradually at approximately 0,1% per year between 2004 and 2030, implying the fact that the improvement in energy efficiency is more pronounced than the increase of energy price.

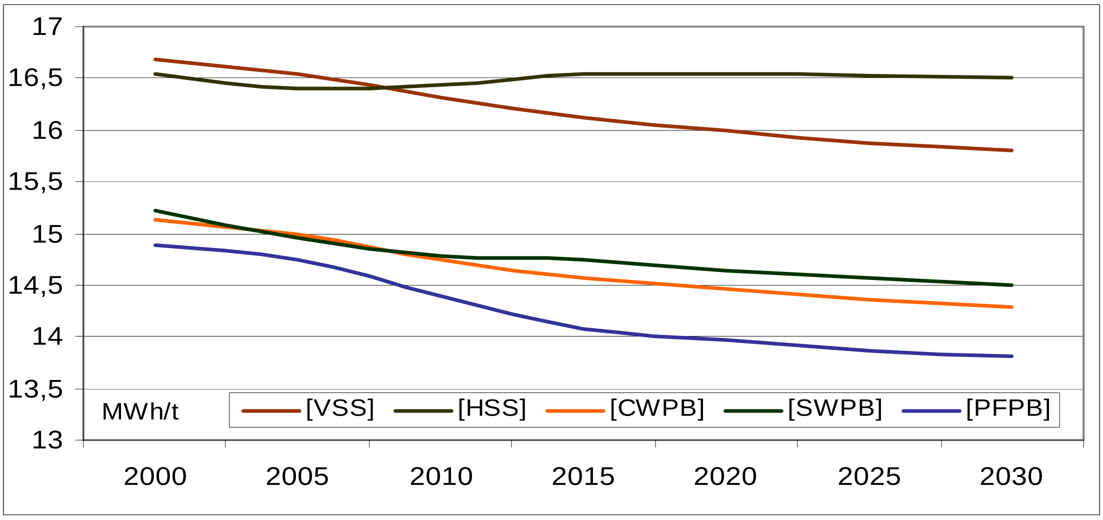
5.3.7 Energy consumption

Increased production determines that the demand for energy will also increase. The most important factor determines that the energy consumption of the industry is electricity consumption for primary production.

Electricity efficiency in primary production

In general, Prebake is more energy efficient than Søderberg, consuming 9 - 11% less electricity per unit production on average. The improvement in efficiency has been evident over the past years achieving around 13MWh/t as the state of the art performance of PFPB; however, without a further technology breakthrough, a significant further achievement is not likely to occur in the next 20 years.

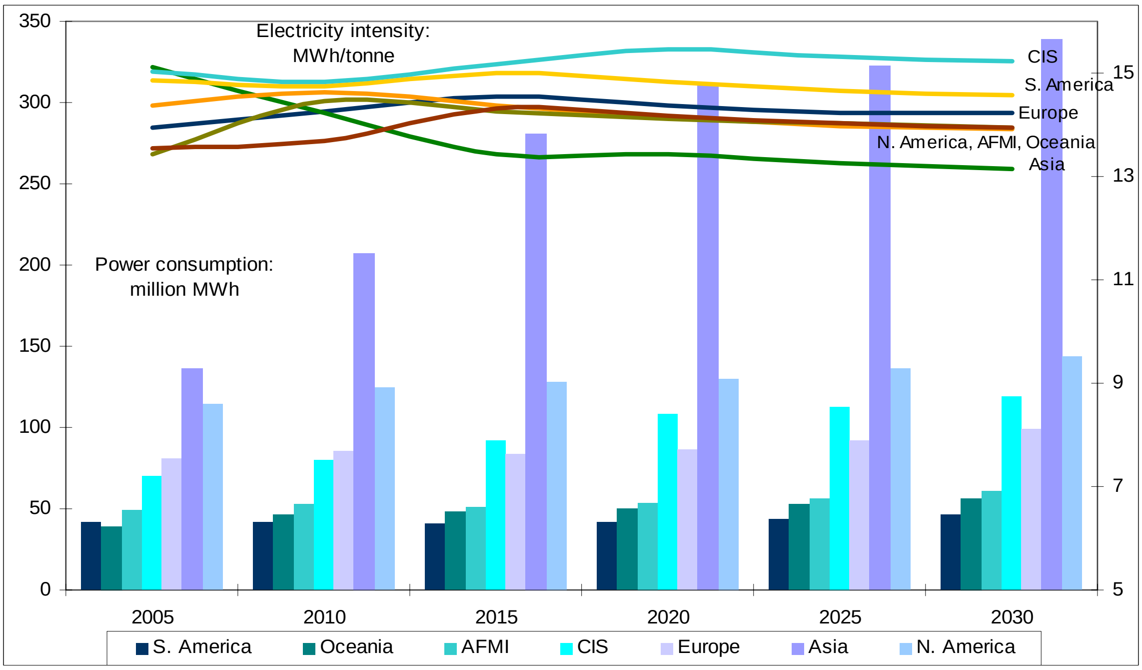
Figure 40 World average electricity efficiency by technology



Electricity consumption in primary production

The power demand of the main primary production regions is shown in Figure 41. The difference in electricity intensity of the production reflects the differences in the technology mix and age of capacity in each region.

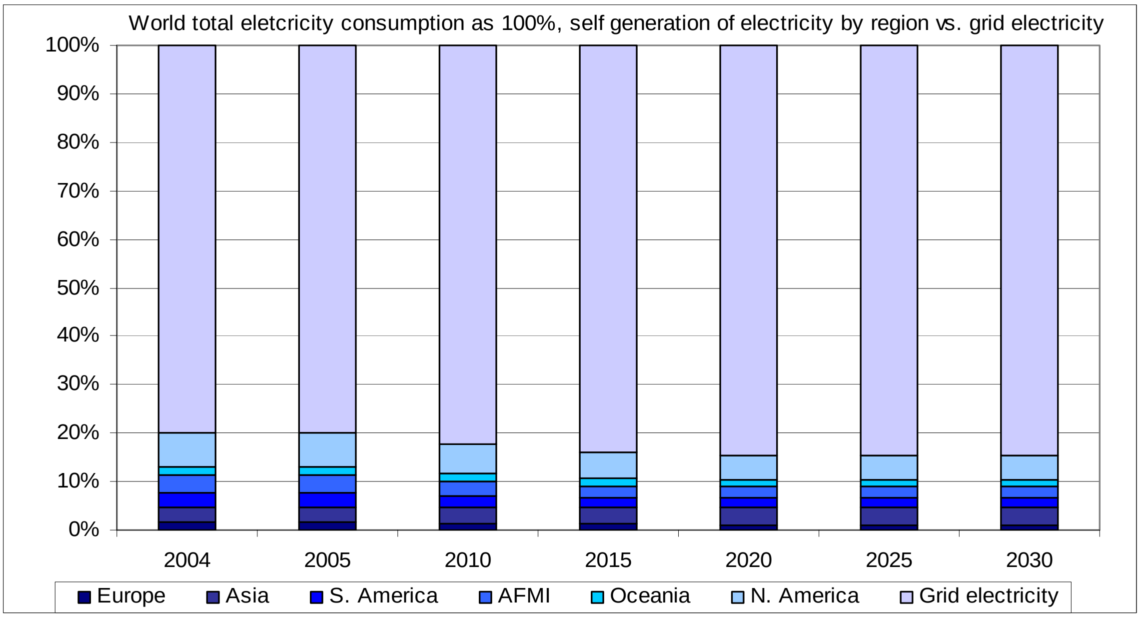
Figure 41 Power use in primary production



In total, the primary industry will consume around 860 million MWh of electricity in 2030, an increase of 80% from the consumption in 2004, while the production is to increase slightly more, 86%, in the same period of time.

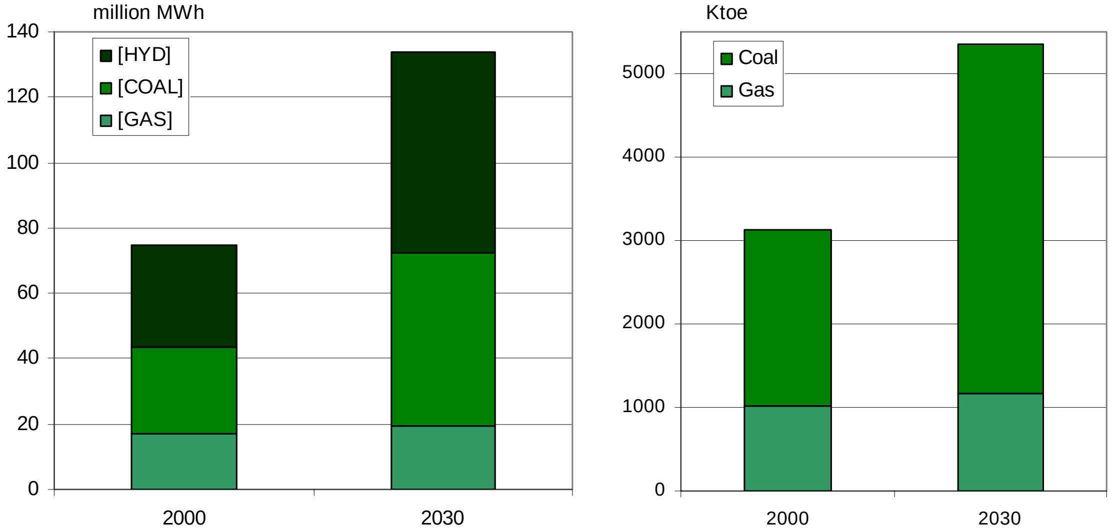
The model assumes that self generation of electricity is favoured in terms of securing a low electricity price; however, the choice is not flexible due to the high investment cost needed for power generation. Furthermore, due to the relatively high increase of production in regions with a low share of self generation, e.g. CIS and Asia, compared with that in the regions with a higher share of self generation, e.g. North and South of America, the simulation shows a decreased share of self generation at world level, as presented in Figure 42. The total share is expected to reduce to less than 16% in 2030, about 4% when compared with 2004.

Figure 42 Share of self generation of electricity



Primary fuel demand at the smelters for the self-generation of electricity is assumed to be inflexible, i.e. no change from the current type of fuel used. The primary fuel demanded for the self-generation of electricity is to increase more than 70% (in the same magnitude as total electricity demand) reaching more than 5 Mt of oil equivalent, as shown in Figure 43. Similarly, the change in power demand is underlined by the fact that a high increase of production in Asia where coal and hydro is the main source of self power generation.

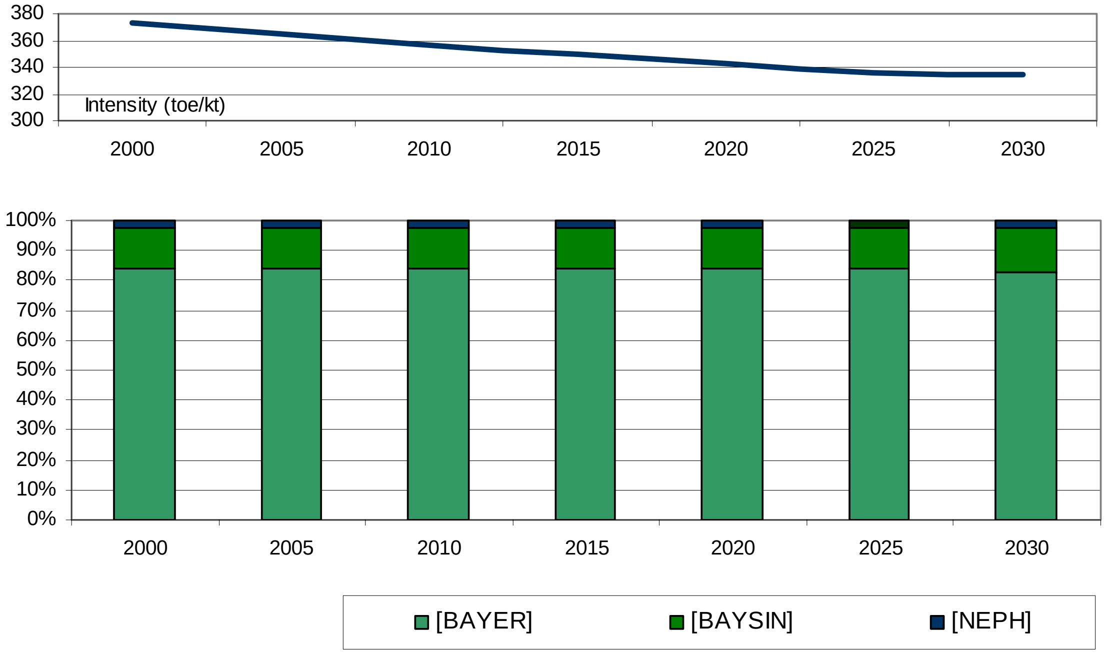
Figure 43 Self generation of electricity by fuel and the demand of primary fuel



Primary fuel consumption in alumina production

With a 100% increase in the world total production of alumina, an increase in energy demand will follow. As shown in Figure 44, energy intensity will decrease at an average rate of 0,4% annually during the simulation period, though the relatively higher growth of production in Asia and Russia, where different types of bauxite are used, will slightly slow down the improvement of overall energy efficiency. On average the saving of energy is about 40 toe/t of alumina production by 2030 when compared with 2000.

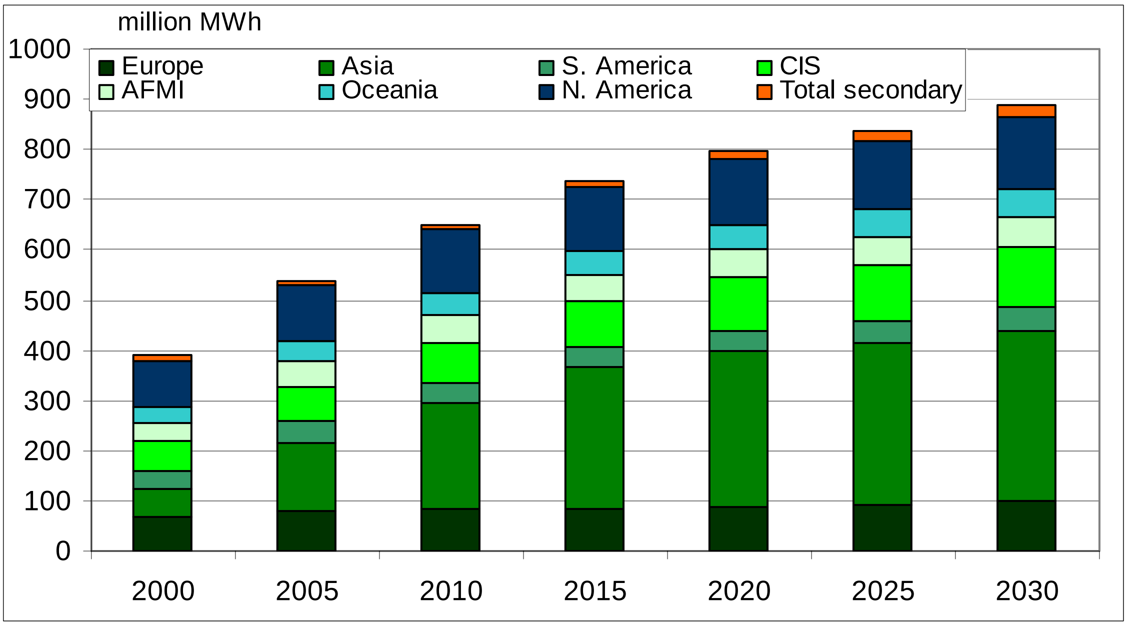
Figure 44 Energy intensity and alumina production



Total energy demand in aluminium industry

The total demand of energy for the aluminium industry covers alumina, primary aluminium production and the secondary production. Due to the lack of data, the energy consumption for secondary production, which is currently around 5% of the primary industry, can only be estimated and discussed here at world level.

Figure 45 Electricity demand of aluminium industry (primary by region and secondary in total)



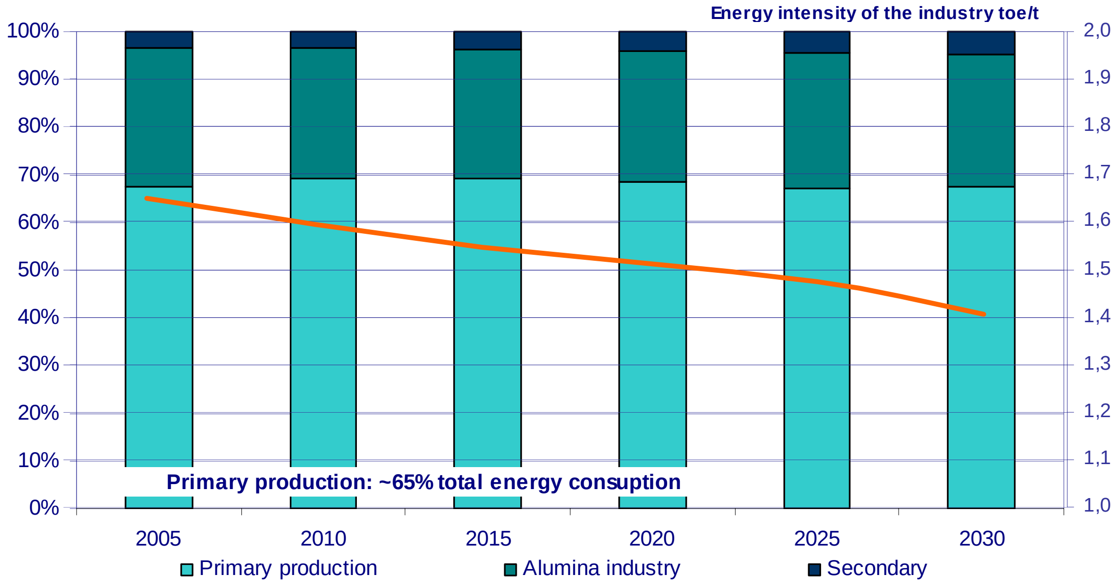
The world total electricity demand of the entire aluminium industry is to increase from 530 to around 900 million MWh from 2005 to 2030 (Figure 45, i.e. an increase of 170%, while total production of primary and secondary aluminium will grow by 230% in the same period. As is expected, the largest share of electricity demand will be from Asia accounting for one third of the world total in 2030, and a relatively high growth rate will also be observed in the CIS region. World total fuel demand for heat is to increase by 100% by 2030 when compared with 2005 reaching more than 64 million toe. Fuel demand for secondary production at world level will increase by 178% in the 25 years, which is more than twice of that for alumina production. The choice of primary fuel for the primary aluminium industry shows greater differences from region to region, as shown in Table 8. Sector demand for fuel in the Africa - Middle East region has the highest growth, followed by South America. This is due to the high growth of alumina production of the two regions. Overall, the demand for coal and gas is more prominent than that for oil. Since the model assumes that the choice of fuel is flexible the new demand of fuel (resulting from increased and new capacity), as discussed in Section 4.8.2, the simulation result shows the market preference for primary fuel without taking into account any other constraints.

Table 8 Total non-electricity energy and fuel demand (primary by region and secondary in total)

(ktoe)	2005	2010	2015	2020	2025	2030	Change in 25 years
Total primary (incl. alumina production)							
EUROPE	2979	3369	3767	4238	4788	3810	27,9%
[GAS]	1022	1147	1275	1433	1618	1258	23,1%
[OIL]	1749	1884	2021	2182	2371	1910	9,2%
[COAL]	208	338	471	623	800	642	209,1%
ASIA	4708	5736	6935	7907	8861	9946	111,3%
[GAS]	1310	1655	2056	2382	2701	3062	133,8%
[OIL]	1733	2081	2489	2821	3148	3521	103,2%
[COAL]	1665	2001	2389	2704	3013	3363	102,0%
S. AMERICA	3915	4439	5017	5683	6444	7308	86,7%
[GAS]	1063	1239	1432	1656	1913	2203	107,2%
[OIL]	2347	2526	2723	2951	3212	3509	49,5%
[COAL]	505	675	861	1075	1319	1596	216,3%
CIS	4935	5699	6533	7477	8468	9592	94,4%
[GAS]	1445	1699	1977	2294	2626	3004	107,9%
[OIL]	1874	2134	2420	2743	3083	3468	85,1%
[COAL]	1616	1865	2136	2441	2759	3119	93,0%
AFMI	611	702	752	834	932	1044	70,8%
[GAS]	261	291	308	335	368	406	55,5%
[OIL]	278	307	323	351	384	423	52,3%
[COAL]	73	104	122	148	180	216	196,5%
OCEANIA	5160	5877	6658	7545	8555	9702	88,0%
[GAS]	1728	1969	2232	2530	2869	3252	88,2%
[OIL]	1752	1996	2262	2565	2912	3307	88,8%
[COAL]	1681	1913	2164	2450	2775	3143	87,0%
N. AMERICA	2686	3072	3444	3838	4301	3642	35,6%
[GAS]	1192	1321	1445	1578	1734	1466	23,1%
[OIL]	1220	1352	1479	1614	1773	1499	22,9%
[COAL]	274	399	519	646	794	676	146,6%
Total secondary	6934	8682	10826	13356	16106	19278	178,0%
World total	31928	37576	43930	50878	58456	64323	101,5%

Therefore, as shown in Figure 46, there is little overall change in the share of energy demand by different sections of the industry, and primary production remains to be the largest consumer of energy. However, the energy intensity will improve gradually from 1,65 to 1,4 toe/t, i.e. 15% less energy is needed to produce one tonne of aluminium.

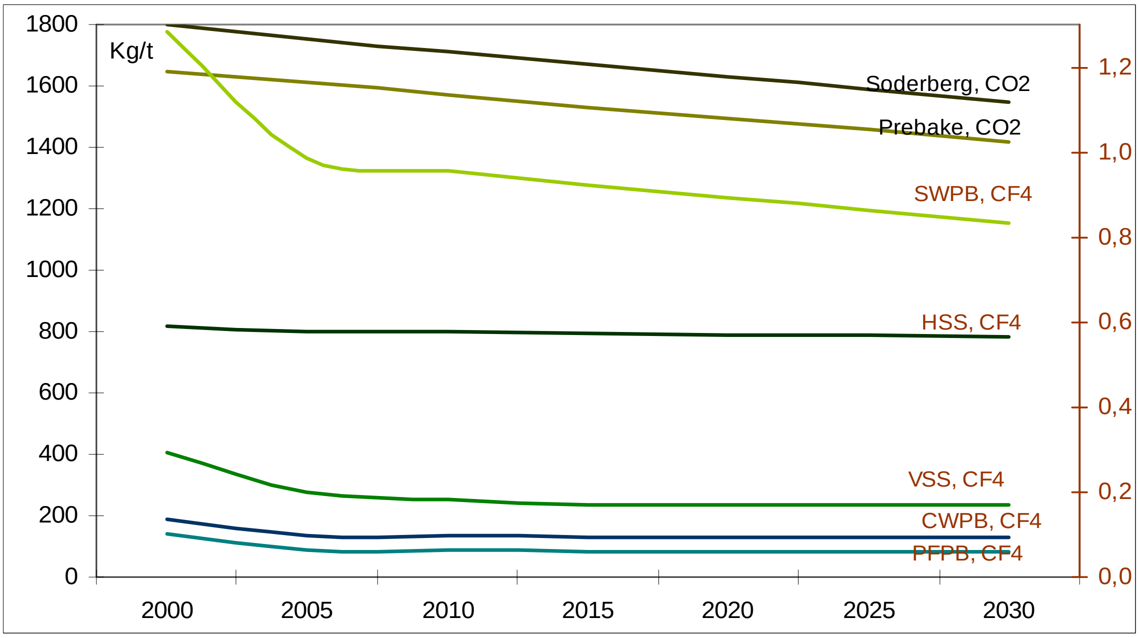
Figure 46 Share of energy demand and energy intensity of the aluminium industry



5.3.8 GHG emissions

As already discussed, direct GHG emissions come from both the process of primary production and fuel combustion during alumina and anode production (in the case of Prebake). Very little information is available on the evolution of the emission factors by different primary production technologies. The model assumes a continuation of the past trend taking into account the limitations of each technology to be further improved, and as shown in Figure 47, CO_2 emissions induced by the consumption of anodes are expected to continuously decline some 14% by 2030. The PFC emissions by each technology will also decrease; however, given the fact that most of the feasible measures have already been identified and implemented, the improvement is expected to be limited.

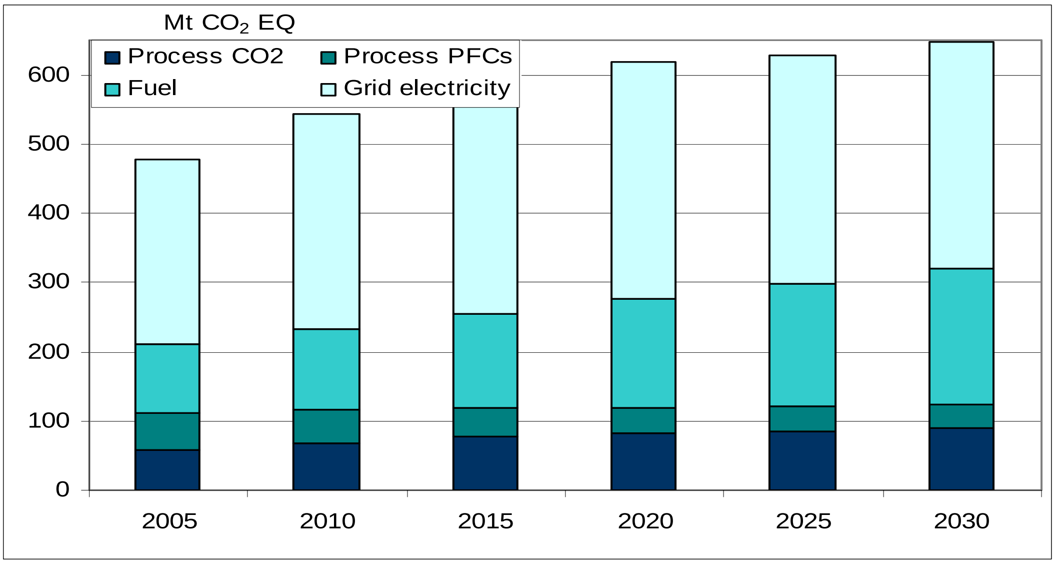
Figure 47 Process emission factor in primary aluminium production



As a result, the total direct GHG emissions (process and fuel related emissions) at the world level are expected to rise by 50% reaching 320 million tonnes (in CO_2 EQ) in the next 25 years.

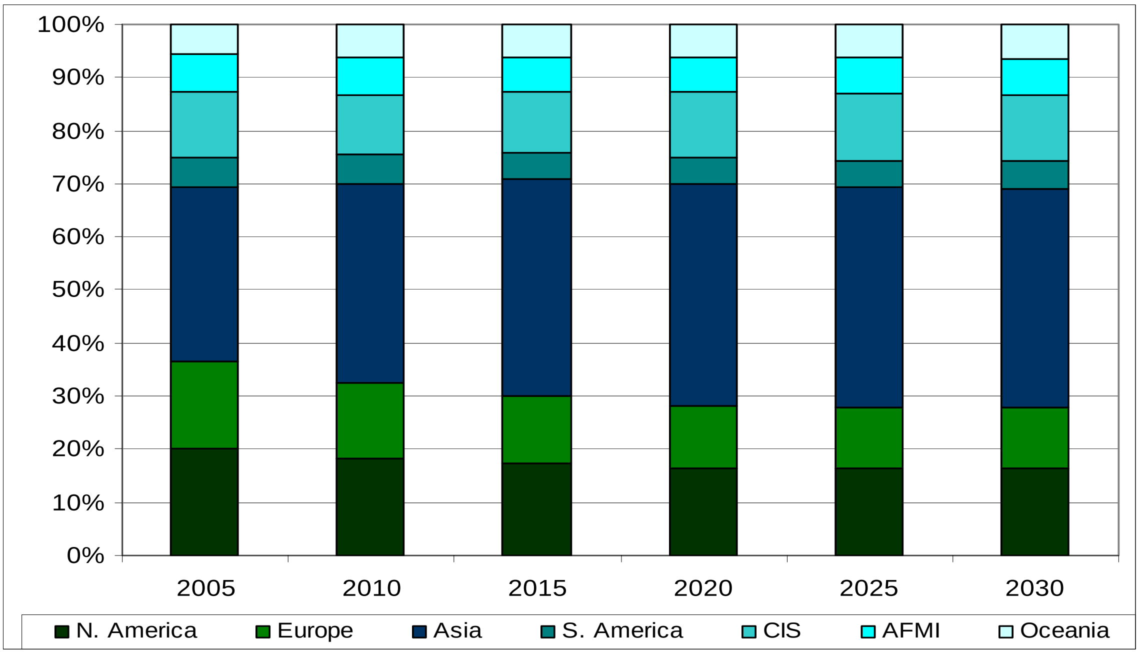
However, a closer look at the emissions by source, as in Figure 48, shows that PFC emissions will decrease by 26% while CO_2 emission from both process and fuel are expected to increase more than 110% and 145% respectively. Indirect GHG emissions from grid electricity remain much higher than the total of direct emissions, and will increase by about 80% from 2005 to 2030.

Figure 48 World total GHG emission of the aluminium industry



Asia will experience the highest increase of direct emissions from 134 to 188 Mt CO_2 EQ in the next 25 years, while the amount of emissions from North America and Europe will decrease 9 and 24% respectively. The strong production growth of primary aluminium as well as alumina in Oceania and the Africa - Middle East regions is expected to result in a 10 - 25% increase in the direct GHG emission of these regions by 2030. Shown in Figure 48, Asia has been and will continuously be the largest source of direct emission of the industry, accounting for 40% of the world total in 2030, increasing 10% from its share in 2005. The share of direct GHG emissions from Europe and North America are expected to decrease by more than 10% in total while the other regions are expected to change little.

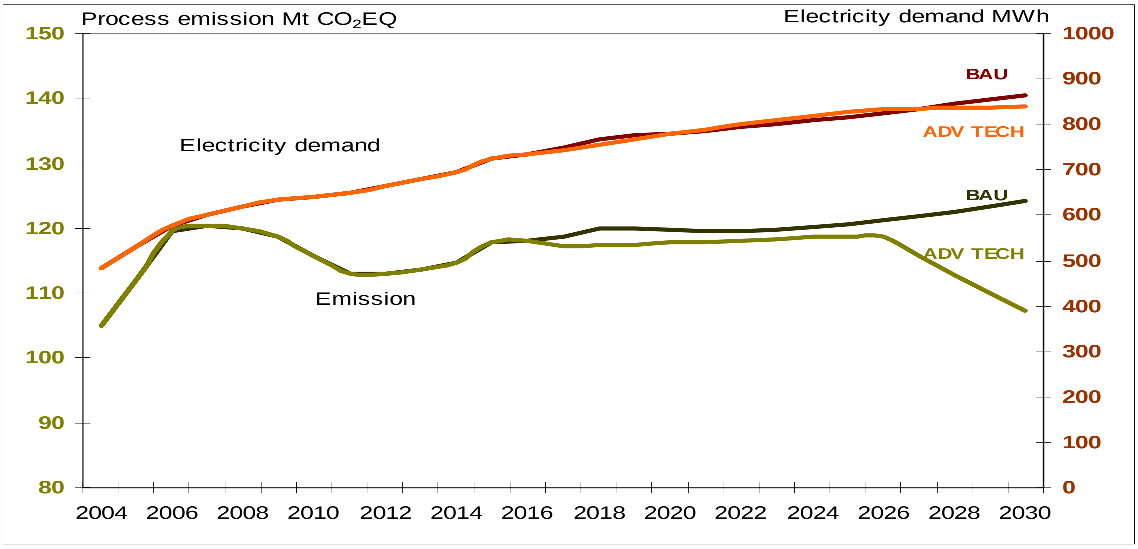
Figure 49 Share of total GHG emissions by region



5.3.9 Potential emission reduction

The alternative technologies scenario, discussed in Section 5.3.3, the ADV Tech scenario, is the only emission reduction option for the primary producers under the current knowledge. Given the current high uncertainty of the implementation of these technologies, a reliable estimate of their potential and marginal emission abatement curves is not possible. However, with limited data, the model can illustrate the potential of emission reduction if these technologies would be able to penetrate the market as assumed in Section 5.3.3.

Figure 50 World level scenario comparison: BAU vs. ADV tech



The introduction of the alternative technologies after 2015 will result in about a 14% reduction of process emissions and 3% less electricity will be required in 2030 when compared with the basic scenario (i.e. the difference in 2030 between ADV tech and BAU). Thus, under the ADV tech Scenario, the total process GHG emissions will be around 107 Mt (CO_2 EQ) in 2030, an avoided emission of 14 Mt of CO_2. As is observed in Figure 50, process emissions, though decreasing in the near future, are expected to rise again due to the projected increase of primary production and the possibility of a technology breakthrough may result in more stabilised emissions in the medium to long term.

5.3.10 Aluminium industry in the EU-25

Although the model covers all the regions in the world, the model is intended to provide a relatively more detailed analysis of the EU countries. In the future, the model will provide several scenario analysis taking into account various policy development that is relevant to the aluminium industry of Europe, such as the EU's emissions trading scheme, recycling policy, etc.

Industry evolution

For EU-25 as a whole, the total aluminium demand is to increase 75% by 2030, which is 36% for primary and more than 100% for secondary, respectively, using 2005 as the base year. As a result, the share of secondary on total consumption will increase from 30% currently to around 41% in 2030. The primary aluminium industry is expected to experience moderate growth in comparison to regions such as Asia, and little after the year 2020. As a result, it will gradually lose its share in the world market. With the 20% growth in production reaching 4 Mt by 2030, the import of primary aluminium is expected to increase to nearly 6 Mt, as exhibited in Figure 51. At country level, Germany and Spain are to experience the highest growth in demand, while France's demand is expected to stabilise after 2020 and the other countries will have moderate increases at lower rates, as in Figure 52.

Figure 51 Consumption and production in the EU-25

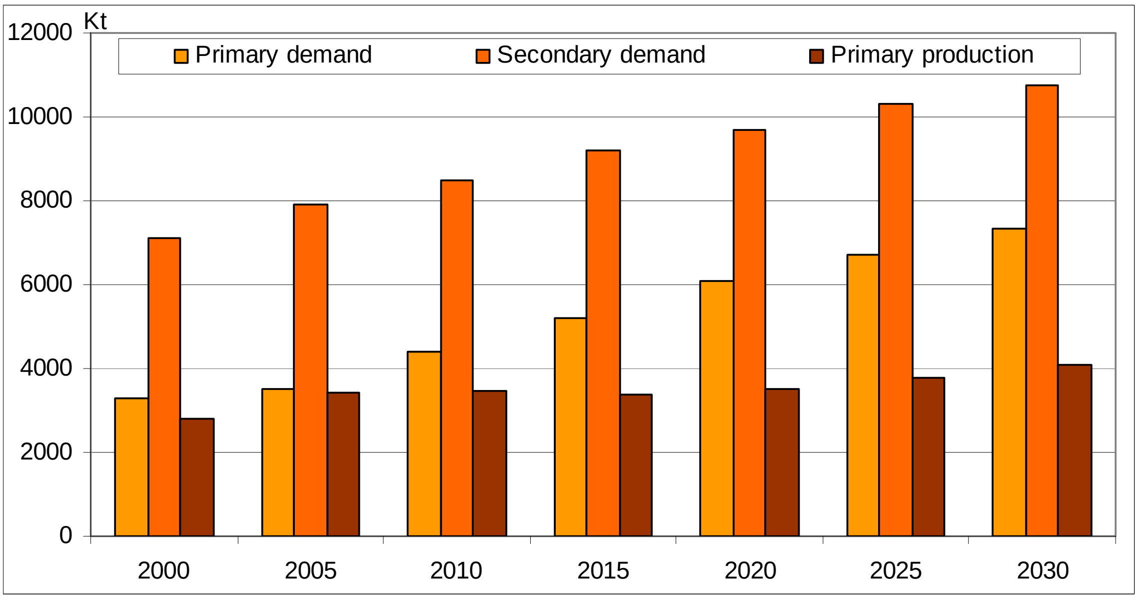
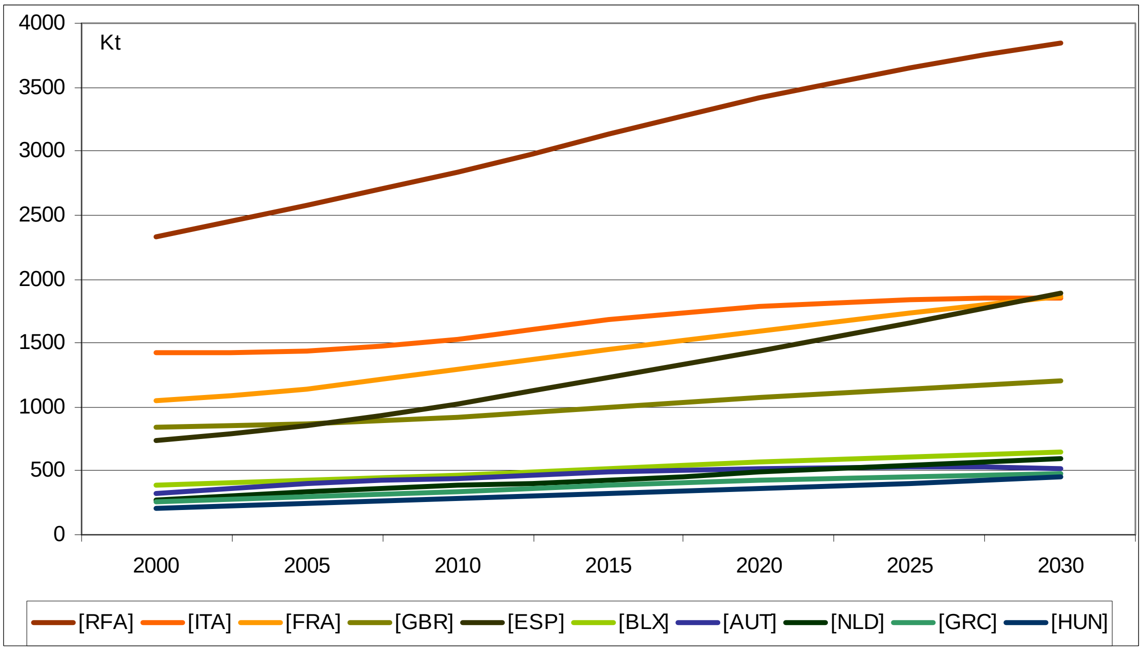
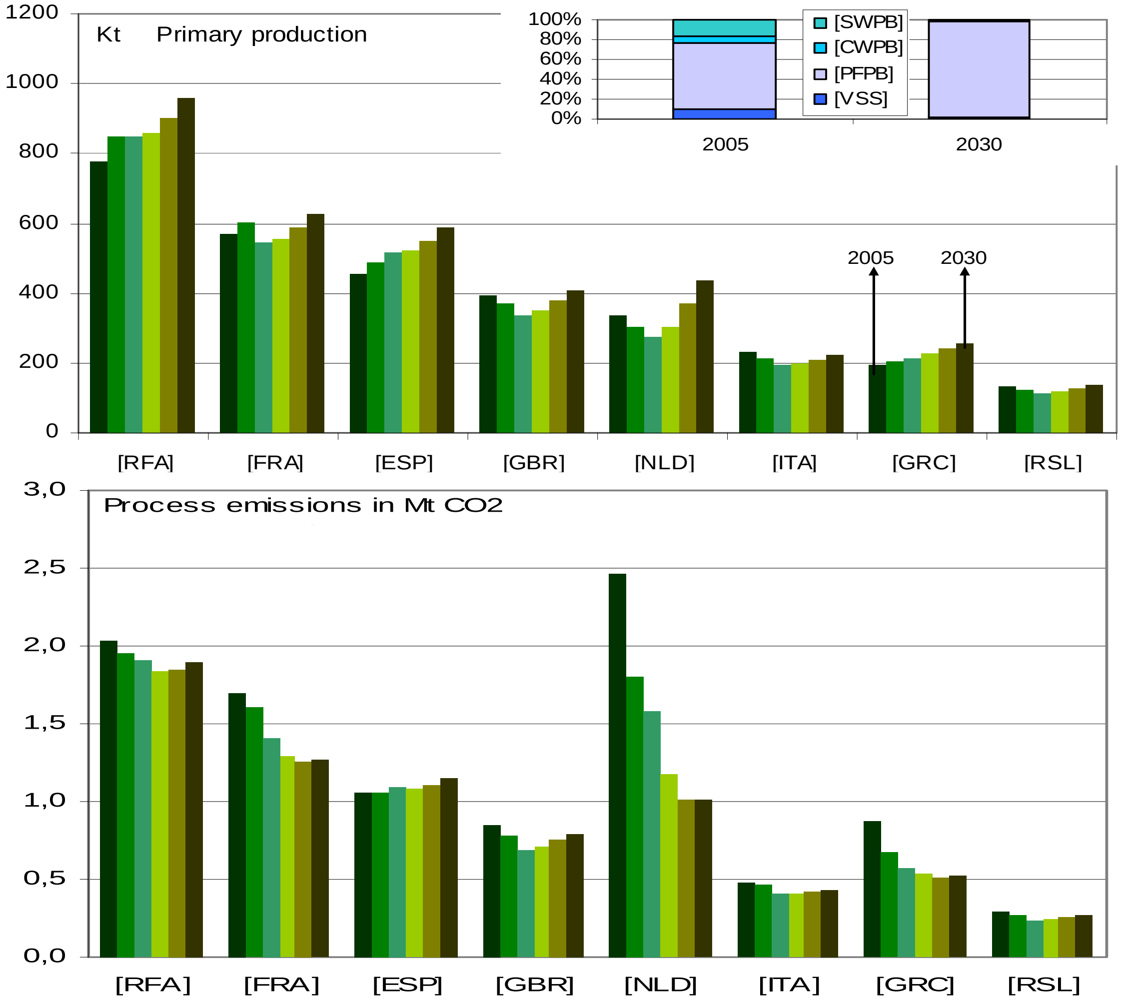


Figure 52 Total aluminium demand by main countries



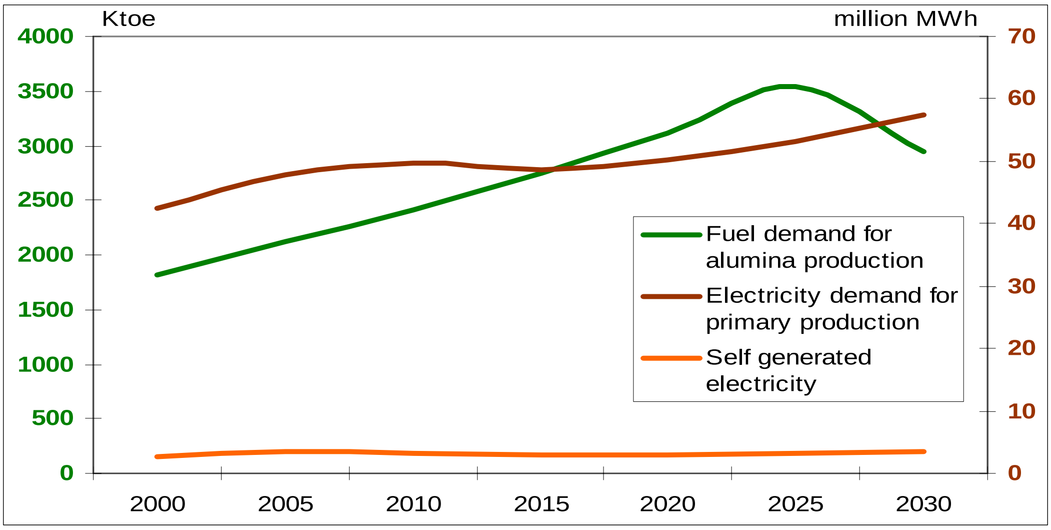
Looking into the details of primary production and its process GHG emissions, as shown in Figure 53, while production in all main producing countries experiences an increase in the next 25 years, the GHG emissions vary considerably among these countries. The Netherlands, with mainly SWPB capacity in 2000 will have the greatest benefit from technology retrofitting and a significant reduction of emissions. Greece, to a lesser extent, will have a similar experience, while emissions in Spain will continue to rise slightly. Total process emissions from primary production will decrease a little from the current 11 Mt to 8 Mt CO_2 EQ by 2030, while almost all capacity will be retrofitted to PFPB technology. Emissions from fuel combustion in mainly alumina and secondary production will add another 10 to 15 Mt of CO_2 per year in the simulation period. Thus in total, the aluminium industry is expected to emit 20 to 25 Mt CO_2 per year, and a decreasing trend is observed after 2025, when both production of alumina and primary aluminium gradually decline.

Figure 53 Primary production, technology share and process emission



Total energy demand, electricity and fuel, all follow a similar path and by 2030, the demand for electricity will be around 60 million MWh and primary fuel to be 2900 ktoe, with the latter declining after 2025. Self generated electricity, from coal and hydro (78% and 22% respectively), shows a slight increase and will double by 2030 to 5 million MWh, as shown in Figure 54.

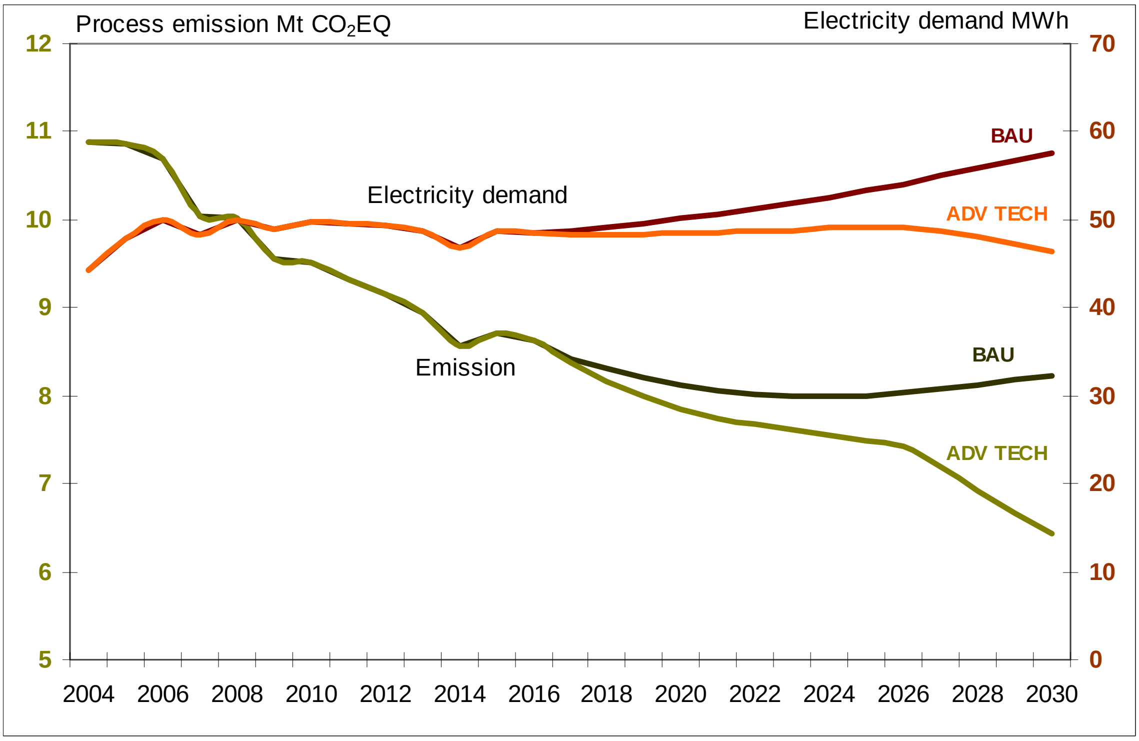
Figure 54 Total energy demand



Alternative technologies and emissions reduction

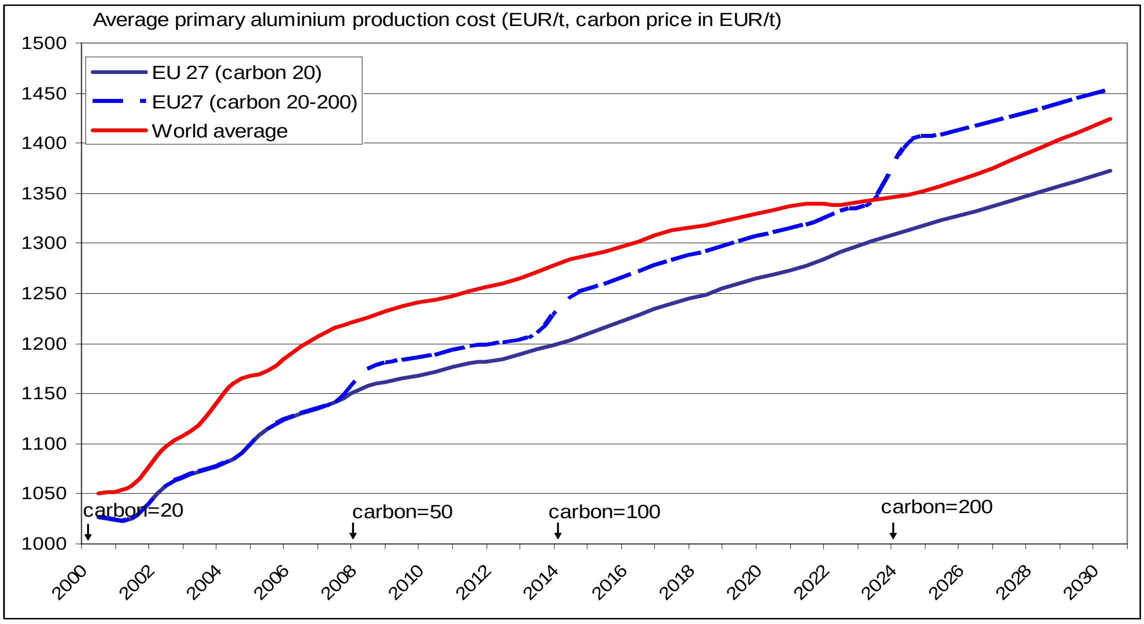
In the alternative scenario, as discussed in the Section 5.3.9, similar effect of the assumed new technologies can be observed for the EU aluminium industry. The introduction of the new technologies in the EU after 2015 will result in about a 22% reduction of process emissions and 19% less electricity being required at 2030 when compared with the basic scenario (differences in 2030 between ADV tech and BAU).

Figure 55 EU-25 scenario comparison: BAU vs. ADV tech



5.3.11 The cost of carbon emission

Figure 56 Carbon price and the primary aluminium production in the EU



Currently, the aluminium sector is not covered by the European Emission Trading Directive, even though installations of self generation with a thermal input exceed 20 MW is covered by the Directive. Therefore the significant impact of carbon price on the sector is not direct, but rather is received via the electricity tariff integrating with carbon price. Assuming that the market carbon price is being fully past down from the electricity producers to smelters in the EU countries, and the carbon price increase from 20 EUR/t before 2008 to 200 EUR in 2030, Figure 56 illustrate the relative changes in the average production cost of primary aluminium in the EU. A carbon price of 50, 100 and 200 EUR/t will result in an increase of production cost of 1%, 3% and 6% respectively when compared to a carbon price of 20 EUR/t. The high carbon value of 200 EUR/t most likely will result in production cost in the EU-27 exceeding the world average; however, the cost is not expected to be higher than that in the Asia and CIS region.

5.4 Results of the sensitivity analysis

In order to understand the robustness of the model, two sensitivity analyses are conducted to assess the sensibility of the baseline scenario.

5.4.1 Probabilistic distribution of aluminium consumption

As already discussed, GDP is a key exogenous input to the model and the relationship between aluminium consumption and GDP, which is determined by the parameters (α and β), is shown in the Eq 1. Assuming normal distribution for both α and β and each region with its own set of statistic data to determining the shape of the normal distribution, the probabilistic distribution of world total aluminium consumption is obtained in VESIM, as shown in Figure 57. The statistics show that more than 50% of the runs are in the range of 65 Mt to 70Mt and the standards deviation is approximately 20%.

Figure 57 Probabilistic distribution: world total aluminium consumption (500 simulations)

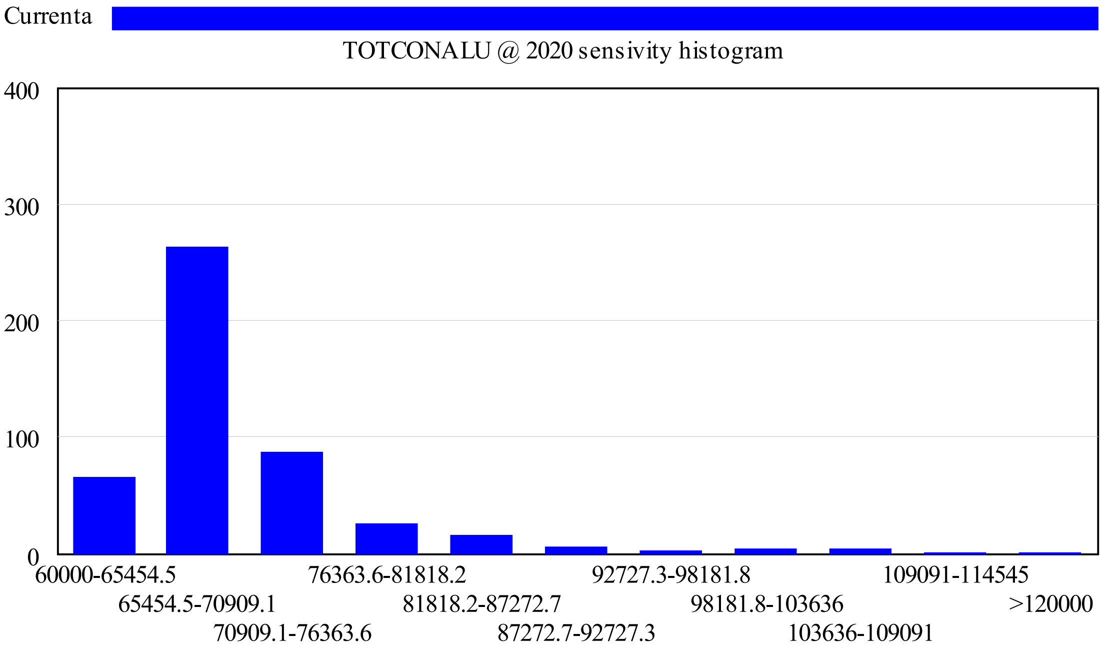


Table 9 Sensitivity results at time 2020 Runs: total aluminium consumption by region

	Count	Min	Max	Mean	Median	StDev	(Norm)
EU27	500	11762	18965	13927	13766	1091	7,8%
ASIA	500	28161	150374	37808	33687	14271	37,7%
SAMERICA	500	2385	3812	3053	3058	216	7,1%
CIS	500	2029	2305	2160	2162	61	2,8%
AFMI	500	1183	13102	3289	2466	2069	62,9%
OCEANIA	500	861	1043	948	946	36	3,8%
NAMERICA	500	8510	13127	11134	11174	910	8,2%
world	500	62218	188751	73846	69904	14461	19,6%

The Table 9 give the key statistics of the distribution by region with the same sensitivity runs as in Figure 57. The reason for the high deviation in the ASIA and the AFMI regions is the uncertainty and fluctuation of data shown in the past years. In the case of the ASIA region, apart from the uncertainty of data particularly in the South Asian countries, the economic crisis at around 2000 had strong affect on the consumption of all sectors and as a result a higher uncertainty is shown in the sensitivity analysis. In the case of Russia, the main country in the CIS region, the data series shows sharp decline of consumption in the late 80s and beginning of 90s and afterwards a steady growth in consumption, of which only the second part of the data is used in the model simulation. As a result, the CIS region has fairly small standards deviation, as shown in the Table 9. In the case of many countries in the AFMI region, data on GDP growth per population did not indicate a clear trend. This together with the uncertainty of data of aluminium consumption in the past 15 years affect strongly the confidence of the coefficien parameters (α and β).

5.4.2 Probabilistic distribution of primary aluminium demand

Another important assumption in the model is the substitution between primary aluminium and secondary aluminium as discussed in the Eq 2. By assuming a normal distribution of the substitution elasticity, sigma, the probabilistic distribution of the world primary demand of aluminium is obtained, as shown in Figure 58. It shows that around 50% of the runs are in the range of between 55-65 Mt, and the standard deviation is 16%.

Figure 58 Probabilistic distribution: world total primary aluminium demand (500 simulations)

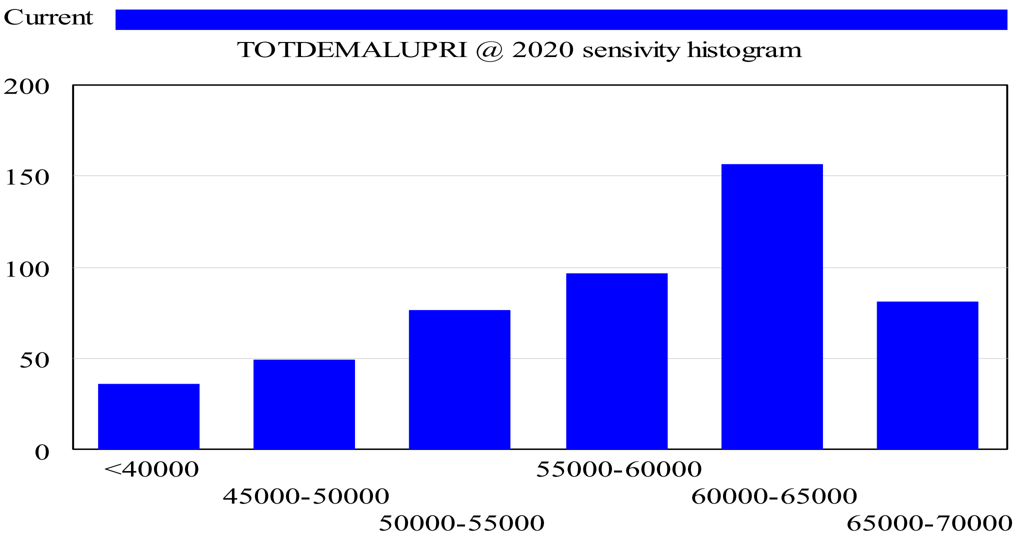
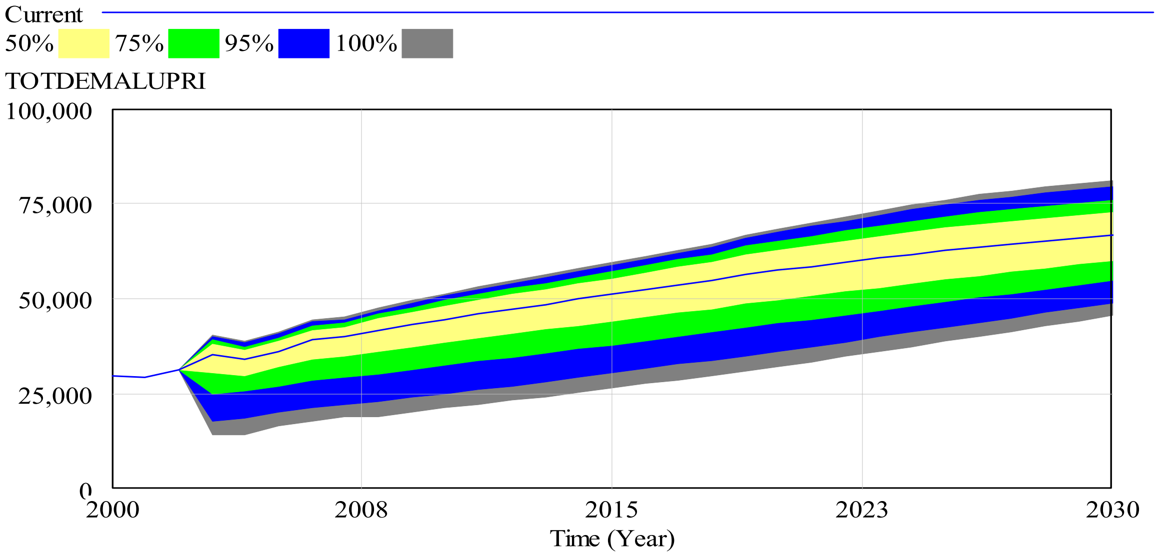


Table 10 Sensitivity results at time 2020 Runs: primary aluminium demand by region

	Count	Min	Max	Mean	Median	StDev	(Norm)
EU27	500	7070	11644	9754	9921	1090	11,2%
ASIA	500	14530	35817	28704	30052	5263	18,3%
SAMERICA	500	1766	2184	1992	2003	99	5,0%
CIS	500	897	2526	2000	2109	405	20,2%
AFMI	500	1377	1874	1786	1829	111	6,2%
OCEANIA	500	503	899	712	719	94	13,2%
NAMERICA	500	5351	12264	9462	9718	1688	17,8%

Data on primary demand and production are generally more reliable with clear trends and less oscillatory. Comparing among the regions, the differences in probabilistic distribution of the primary demand is the result of the certainty in recycling. Recycling rate in both South Africa and Mexico are among the highest in the past years, and as a result, the certainty of both primary and secondary demand is high, low value of standard deviation, as shown in Table 10.

Figure 59 Distribution and simulation time: world total demand for primary aluminium (500 runs)



The Figure 59 shows the probabilistic distribution in the entire simulation period. As anticipated, the range of distribution widens along the timeline, implying increasing uncertainty.

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Abstract

A series of Industrial models have been developed by the Institute for Prospective Technological Studies (IPTS) aiming at studying in detail the technological perspective of several energy intensive industries. This paper discusses one of such a simulation model for the aluminium industry at global, regional as well as national levels.

Aluminium is the third abundant element in the earth's crust and the most abundant metallic element. It never occurs as a free element in nature. Aluminium is a material with 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.

The aluminium model simulates the technology evolution of the industry from 2000 to 2030, exploring the alternative development trends in energy consumption, emissions, technology, retrofitting options and trade. Several future technologies foreseen in the primary aluminium production are considered and projected in the model allowing different scenarios to illustrate the technology dynamics of the sector's future. Scrap recycling is one of the key components of the aluminium industry and is crucial to the sustainable development of the sector. The model, thus, also explores the possible perspective of scrap availability and recycling potentials. Furthermore, based on the demand and supply trend of aluminium, the model also analyses the evolution of bauxite mining and the alumina refining industry.

The model is designed to be a flexible tool in accommodating policies to address different environmental issues such as GHG emissions, material use, and waste recycling. The aluminium industry of the European Union is given more detailed analysis to address the main environmental issues such as the GHG emissions.

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