



GREENHOUSE GASES FROM MAJOR INDUSTRIAL SOURCES – IV THE ALUMINIUM INDUSTRY

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Background to the Study

The IEA Greenhouse Gas R&D programme (IEA GHG) is systematically evaluating the cost and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels. The first phase of this Programme concentrated on emissions of carbon dioxide from power generation. In the second and third phase, attention has also been given to other greenhouse gases, notably methane, and a broader range of industrial processes.

Greenhouse gases are produced from a variety of industrial activities. The main industrial sources, other than power generation, are those energy intensive industries that chemically or physically transform materials from one state to another. During these processes many greenhouse gases (carbon dioxide, methane and nitrous oxide) are released. One notable example is the aluminium industry where considerable amounts of greenhouse gases including CO₂ and Perfluorocarbons (PFC's) are produced. This study is the fourth in a series to look at greenhouse gas abatement and mitigation options for the energy intensive industries.

The study was undertaken by ICF Consulting of the USA.

Industry overview

In nature, aluminium is never found in its metallic state but is a common constituent of many minerals where it is normally combined with silicon and oxygen. Bauxite is the main ore from which aluminium can be economically retrieved. Once the ore is mined, a chemical process is then used to extract aluminium oxide, or alumina, and an electrolytic process (the Hall-Héroult process) reduces the alumina to aluminium. This overall production process is referred to as primary aluminium production. All aluminium extraction is by electrolytic means, where the electrolyte used is cryolite (Na₃AlF₆). The principal gases emitted are carbon dioxide and carbon monoxide as well as a number of volatile fluorides (PFC's). The electrical energy required for the process is 13,000-18,000 kWh/tonne of metal. A large part of the fluorine consumed from the cryolite in the process is recovered (in the USA, 15kg of fluoride ion is produced per tonne of aluminium). Some 45 tonnes of bauxite are required to produce two tonnes of alumina, which yield one tonne of aluminium.

Aluminum is one of the most recyclable of all materials. Scrap metal can be recycled from both pre and post consumer sources, which in the later case normally requires some pretreatment¹. The scrap

¹ Recycling involves a number of stages that remove impurities, including primary pre-treatment (shredding and cleaning), remelting (which degasses the aluminium and removes magnesium as well as other impurities in the skimmed dross) and alloying in which the levels of other agents (zinc, copper, manganese) are adjusted to meet the specific product requirements. Secondary production is a common source of metal for castings and is often mixed with primary aluminium to obtain a desired product quality.

metal can be recycled into the same, or other, products with little deterioration in quality giving the process a high degree of product flexibility. The process is referred to as secondary aluminium production. Recycling aluminum only requires about 5% of the energy required to produce primary metal and in turn leads to much lower emissions of greenhouse gases. In addition to the environmental advantages of aluminum recycling, there are economic benefits. Aluminium's high scrap value is also a great incentive for collection. Over one-third of the aluminum used in the Western World is produced from recycled metal. More than 50% of recycled metal comes from facilities that remelt scrap from a wide range of other used aluminum products such as cookware, aircraft fuselages and automobile parts. Typically, these "secondary smelters" produce foundry alloys for use in shape castings. Greater usage of re-cycled material is expected to lead to a reduction in greenhouse gas emissions from aluminium production. .

Results and Discussion

The following areas are described in the report

- A profile of the Aluminium industry worldwide
- A discussion of energy use in the Aluminium industry
- The sources and emissions of greenhouse gases from the Aluminum Industry.
- The opportunities identified to reduce greenhouse gas emissions
- The costs of abatement of greenhouse gas emissions
- Projections of future greenhouse gas emissions from the Aluminium industry

Aluminium Industry Profile

The global primary aluminium industry is dominated by a small number of multinational firms that control over 40 percent of the primary aluminium production capacity and about 60 percent of the alumina refining capacity. The remainder of the smelter capacity is controlled by governments, traders, smaller companies with one or two plants and investors. The price of aluminium is determined by activities on the London Metal Exchange, where aluminium is a traded commodity.

In 1998, over 22 million tonnes of primary aluminium were produced in 46 producer countries, requiring approximately 44 million tonnes of alumina and 133 million tonnes of bauxite. North America was the largest primary aluminium producer with almost 30 percent of the world total, followed by Eastern Europe & the Former Soviet Union and Western Europe with 17 and 16 percent of the world total, respectively.

Secondary aluminium production in 1998 totalled 7.4 million tonnes with production concentrated in countries with developed economies that have a high historic rate of aluminium consumption (e.g., United States, Japan, United Kingdom). In the largest three end-use sectors for aluminium (transportation, packaging, and construction) the potential exists for using recycled aluminium in virtually every application. Recent years have seen major developments, especially in the recycling of aluminium beverage cans in some regions.

Energy Use in the Aluminium Industry

Primary aluminium production is an energy- intensive process. On a unit basis, producing a tonne of primary aluminium requires approximately 120 Gigajoules (GJ)². The primary production stage is the

² This estimate includes the energy (fuels and electricity) required for all process stages including, bauxite mining, alumina refining and aluminium smelting.

most energy intensive stage in the process requiring 95 GJ per tonne, whilst alumina refining uses 26 GJ/t. In contrast, secondary aluminium production requires only 6 GJ per tonne.

Electricity required for the reduction of alumina to aluminium is the major fuel type consumed in the primary production process, accounting for over 80 percent of total per unit energy use at the primary production stage. Energy accounts for about one-third of the cost of primary aluminium production, the majority of which is spent on electricity.

Over the past 50 years, the energy required to produce one tonne of primary aluminium has decreased by 40 percent as a result of improvements in the electrolytic process. The recent trend toward increased recycling has also reduced overall industry energy intensity. Efficiency gains in the last three decades were achieved by installing improved cell technologies that operate at higher amperages, installing computer control systems, instituting better operating practices in new and existing smelters, and increasing recycling.

The Sources and Emissions of Greenhouse Gases

Greenhouse Gas emissions from the aluminium production process result from three sources:

- Carbon dioxide emissions generated from combustion of fossil fuels during alumina refining and for electricity generation for use at all stages of the production process;
- Process-related CO₂ emissions from consumption of the carbon anode in the electrolytic cell;
- Process-related PFC emissions generated during operational disturbances in the electrolytic cell known as “anode effects”.

Total greenhouse gas emissions from the aluminium industry were estimated to be 364 million tonnes CO₂-E³ in 1995 (16.5 tonnes CO₂-E per tonne of aluminium produced). The aluminium industry, therefore, contributed 1 percent of total anthropogenic greenhouse gas emissions in 1995⁴. The largest source of CO₂ and overall greenhouse gas emissions from the aluminium industry is fossil fuel combustion, which accounted for 68 percent of total emissions in 1995. Of the fossil fuel related CO₂ emissions, which are equivalent to 11.3 tonnes of CO₂ per tonne of aluminium produced, electricity production is the main source. Electricity use in primary aluminium production results in some 9 tonnes of CO₂ emitted per tonne of aluminium produced compared to only some 2 tonnes of CO₂ emitted during fossil fuel combustion in alumina refining. The process related emissions of PFC's and CO₂ from primary aluminium production accounted for only 17 and 15 percent (2.8 t CO₂-E/tonne of product and 2.5 t CO₂/tonne of product, respectively) of the total 1995 emissions, respectively.

North America was the largest emitter in 1995, accounting for 27 percent of the industry's greenhouse gas emissions. Eastern Europe & Former Soviet Union and Western Europe were the next largest, accounting for 25 and 14 percent of total emissions, respectively.

The Opportunities Identified To Reduce Greenhouse Gas Emissions

³ Emission estimates are presented as CO₂ equivalents (CO₂-E) - these weight each gas by its global warming potential (GWP).) which indicates how much these gases enhance greenhouse radiation, as well as taking account of their different lifetimes in the atmosphere. Carbon dioxide has a GWP of 1 and the main emitted PFC's, CF₄ and C₂F₆ are 6,500 and 9,200 respectively, taken over 100 years. For calculation purposes a mass ratio of C₂F₆:CF₄ of 0.08 was used. This figure was based on industry emission data from the International Primary Aluminium Industries IPCC submission in 1999.

⁴ It was estimated by Massachusetts Institute of Technology that total anthropogenic emissions of greenhouse gases were about 35 000 million tonnes CO₂-E in 1995. Reference: Harnisch et al "Primary Aluminium Production: Climate Policy, Emissions and Costs" Massachusetts Institute of Technology, 1998.

The primary aluminium production process consists of a diverse set of emission sources and the number of potential mitigation options is very large. The study focused on those sources that are significant in terms of emissions and options that have significant potential for reducing emissions.

The principle options identified by the study are discussed below.

Options to Improve the Hall-Héroult Process

The basic technology used by the aluminium industry has remained essentially unchanged since the Hall-Héroult process for electrolytic reduction was invented in 1888. To improve the Hall-Héroult process the study identified a number of options that included:

- (1) retrofit existing cells, which involves capital investment that reduces energy use and emissions within a given technology-type;
- (2) convert existing cell technologies to state-of-the-art cell technologies (the capital investment shifts existing production to a more efficient type of technology);
- (3) implement advanced technologies that are expected to become commercially available by 2020.

Of these options conversion to the state-of-the-art point cell technology was considered to be the most reliable route to increasing operational and production efficiency. However, the capital outlay for this option can be significant. The inert anode and wettable cathode are two advanced technologies that are being pursued aggressively by the industry. The development of inert, dimensionally stable, non-carbon anodes that are not consumed in the electrolytic process represents the major potential advancement in the aluminium production process. The non-carbon anodes would remove the source of carbon for process-related CO₂ and PFC generation, thereby eliminating these emissions altogether.

Options to Improve the Alumina Refining Process

The two main options for improving the alumina refining process are to replace rotary kilns with fluidised bed kilns and increase the use of cogeneration. The fuel demand of a fluidised bed kiln is about one third the fuel demand of the rotary kiln. Cogeneration, or combined heat and power (CHP), produces both electricity and process steam for use at different stages in the refining process. The current economics of the process warrants that all alumina refining facilities have to be CHP integrated in order to compete in the world market.

Increased Recycling

Increased recycling may play a major role in meeting the rising demand for aluminum products globally. The increased market share of secondary aluminium will have a significant impact on industry energy use and emissions. On a per tonne basis, recycling aluminium uses about five to eight percent of the energy required to produce primary aluminium and releases less than four percent of the greenhouse released when producing primary aluminium (including all stages). Growth in the secondary aluminum industry will depend on an increase in recycling rates (i.e., quantity recovered/quantity consumed) and increase in metal recovery efficiency.

Alternatives to the Hall-Héroult Process

Alternative, less energy and emissions intensive methods of producing aluminium would be desirable. However, currently, no alternative production processes exist that could displace the existing Hall-Héroult process. One process, direct carbothermic reduction, has shown potential, and if successfully developed to operate on a commercial scale, would save approximately 25 percent of the energy used in Hall-Héroult cells. However, industry interest is limited because of the high retrofit costs involved.

In addition, to the abatement options identified the potential for CO₂ capture and recycling was considered as means of making deep reduction in greenhouse gas emissions. As stated earlier the largest sources of CO₂ emissions is from the combustion of fossil fuels used for electricity generation. It was considered that these CO₂ emissions would not be effectively recycled within the aluminium

process because of the likely remoteness of the electricity plant from the aluminium production plant in most (possibly except for a few isolated cases) cases. Alternative applications such as capture and storage of the CO₂ in geological reservoirs would be appropriate to deal with these emissions.

Within the aluminium production process itself CO₂ is generated as a result of combustion of carbon anode during electrolysis. The emissions of process CO₂ are generated in the pot room, where large quantities of air are used to maintain the climatic conditions in the room and reduce fumes to acceptable working levels. The extracted gas, therefore, only has very low concentrations of CO₂, as well as other contaminants present. It was considered that the very low concentrations in the pot room exhaust gas make CO₂ capture uneconomically unattractive. A radical overhaul of the pot room and conventional extraction processes would be required to make this option attractive. However, with the development of inert anode technology, which will abate this emission source of CO₂, further consideration to this option was not given by the contractors.

Projections Of Future Greenhouse Gas Emissions

Estimates of energy use and emissions until the year 2020 were developed by the consultant for three scenarios:

- *Business-as-usual*: This case represents a continuation of recent industry trends in energy and emissions through incremental improvements in the current state of technology.
- *State-of-the-art*: This case represents the potential for aggressive adoption of cost-effective, state-of-the-art technologies to reduce energy use and emissions.
- *Advanced*: This case represents the potential for breakthrough technologies and practices expected in the next 15 to 20 years to reduce energy use and emissions.

For all scenarios, world primary aluminium production is projected to increase from 23 million tonnes to 38 million tonnes from 2000 to 2020, an average annual growth rate of 2 percent.

Under the business-as-usual scenario, emissions are expected to increase at a rate of approximately 1.4% per year (see Figure 1 below). Under the state-of-the-art scenario, emissions increase at a somewhat slower rate, 1 % per year. The most dramatic decrease in emissions growth occurs under the advanced scenario where industry-wide greenhouse emissions remain almost constant at the year 2000 levels. In the advanced scenario, the introduction of the inert anode and the wetttable cathode contribute in part to the overall decline in the emissions growth rate.

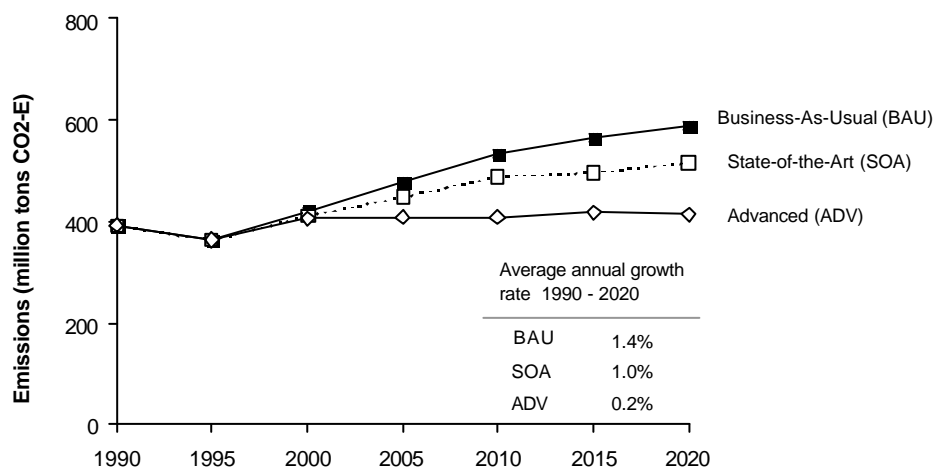


Figure 1 Projected Emission Scenarios for the Aluminium Industry

It was noted that the estimates of future emissions levels are highly sensitive to the fuel or resources used to generate electricity supplied to the aluminium industry. Emission levels in 2020, under the business-as-usual scenario decrease by 56 percent when fossil-fuel generated electricity used in aluminium production is replaced by hydroelectricity. Energy-sector options aimed at reducing the carbon-intensity of electricity supply will, therefore, have a significant impact on global emissions.

The Costs Of Abatement Of Greenhouse Gas Emissions

The costs of abatement of greenhouse gas emissions for the aluminium industry for 2000, 2010, and 2020 are shown in Figure 2 below.

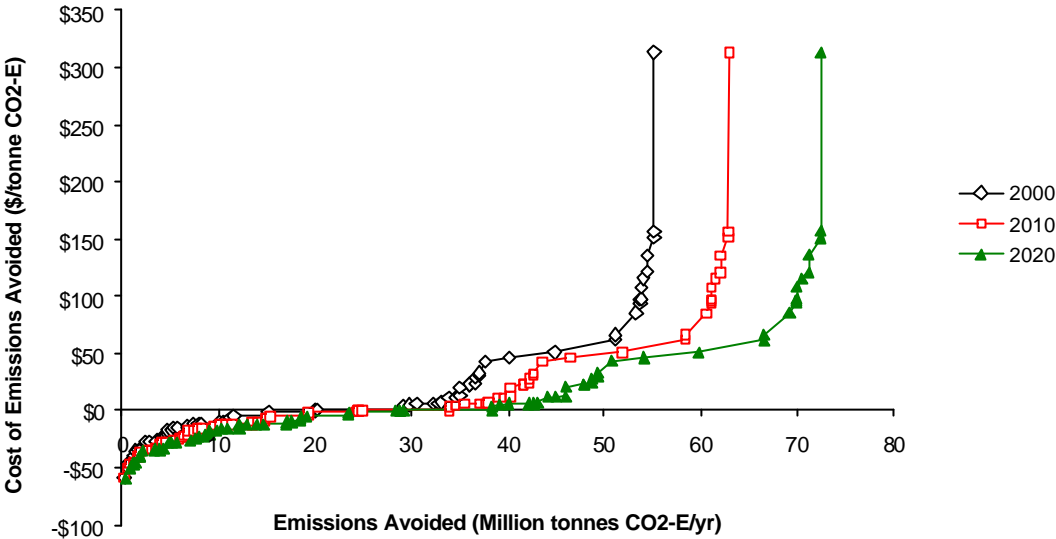


Figure 1 Greenhouse Gas Abatement Cost Curve for The Aluminium Industry

Figure 2 Costs of Greenhouse Gas Abatement for the Aluminium Industry

In 2000 the study has shown that emission reductions amounting to approximately 30 million tonnes CO₂-E are achievable at net cost. This figure increases to 35 million tonnes CO₂-E by 2020. In 2000 a further 20 million tonnes of CO₂-E can be avoided at a cost of less than \$75/t; by 2020 this figure rises to 33 million tonnes.

The greatest potential for cost-effective mitigation lies in Asia (China) and Eastern Europe and the Former Soviet Union (Russia). These regions rely on older technology, which produce greater greenhouse gas emissions than more modern technology

Expert Group Comments

Two sets of expert reviewers assisted in the review of this study. The first group comprised reviewers selected by the Programme and a number recommended by the Programme’s members. In addition, a second group of reviewers drawn from the aluminium industry were asked to assess the study report findings, as it was considered important to have a strong aluminium industry input to the review.

The comments drawn from both sets of expert groups were generally complimentary of the study. From the Programme’s reviewers, most of the comments received were editorial. A number of the reviewers questioned the cost data given for certain technologies and the energy mixes for two of the regions studied. All the points made have been reconciled and corrected.

The Aluminium industry's reviewers commented on three specific areas of the study: industry emissions, recycling and use of aluminium in transport. Their main point related to the issue of industry emissions, which the reviewers considered were over-estimated by the contractor. The main difference related to the fact that they felt that the industry currently uses a greater proportion of hydro-power than was shown in the study data, which will lower process related CO₂ emissions. The industry provided further data on fuel mix to allow these differences to be reconciled in the final report

Major Conclusions

The aluminium industry contributed 1 percent (about 364 million tonnes CO₂-E) of total anthropogenic greenhouse gas emissions in 1995. North America and Eastern Europe and the Former Soviet Union were the largest sources of greenhouse gas emissions in 1995. These regions have the largest share of primary aluminium production and tend to have older technologies.

The majority of greenhouse gas emissions are a result of fossil fuel combustion used to provide energy for the mining and processing of raw materials, power electrolytic reduction of alumina to aluminium, and cast metal. Primary aluminium production is the most energy and emissions-intensive stage in the process of aluminium production. Secondary aluminium production only requires about 5% of the energy required to produce primary metal.

Technologies for reducing greenhouse gas emissions are well demonstrated and readily available. Approximately 35 million tonnes of CO₂-E reductions can be achieved at a negative cost in 2010 and are available in each of the eight world regions of this study. Increased recycling will have a significant impact on industry energy use and emissions.

World primary aluminium production is projected to increase from 23 million tonnes to 38 million tonnes from 2000 to 2020, an average annual growth rate of 2 percent. Growth in greenhouse gas emissions is expected to be lower than the growth in production due to the implementation of cost-effective technologies that improve operational and production efficiency.

Recommendations

The study has highlighted the potential for reduction in greenhouse gas emissions from the aluminium industry through the transfer of more energy efficient technology from western countries to countries such as the former Soviet Union. Technology transfer could be achieved through mechanisms such as Joint Implementation and the Clean Development Mechanism.

Increased scrap use, particularly in developing countries, will assist in reducing the greenhouse gas emissions from the aluminium industry globally. Governmental action is needed to stimulate recovery/recycling systems and markets in the developing countries.

Incentives, such as international emissions trading, may be required to promote the take up of the most energy efficient technology in the aluminium industry.

Greenhouse Gas Emissions from the Aluminium Industry

Final Report

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Mention of any trade names or commercial products does in this report not constitute endorsement or recommendation for use.

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Executive Summary

This study evaluates the scope of technical options and costs for mitigating greenhouse gas (GHG) emissions from the life cycle of the aluminium production process. In 1995, GHG emissions from the aluminium industry accounted for 1 percent of global anthropogenic GHG emissions. The majority of these emissions are a result of fossil fuel combustion used to provide energy for the mining and processing of raw materials, power for electrolytic reduction of alumina to aluminium, and cast metal. GHG emissions also result from consumption of the carbon anode and operational disturbances known as “anode effects”, which occur during the electrolytic reduction process. Reducing GHG emissions intensity is consistent with improving the operational and production efficiency. Increasing the market share of recycled aluminium can play a significant role in reducing overall GHG emissions from the aluminium industry. Future technological breakthroughs, such as the inert anode and wettable cathode, will increase emission reduction potential. Policy options should focus on promoting research and development into GHG emission reduction measures, providing industry with incentives to reduce GHG emissions, and reducing regulatory uncertainty by providing credit to producers who voluntarily reduce emissions.

Objective

The objective of this study is to evaluate the scope of technical options and costs for the mitigation of greenhouse gas emissions from the life cycle of the aluminium production process. By focusing on the options and costs to reduce greenhouse gas emissions, this study complements the IEA Greenhouse Gas R&D programme's (IEA GHG) objectives to evaluate technologies for mitigation of greenhouse gas emissions and develop targets for research, development, and demonstration.

Industry Profile

The aluminium industry is characterised by four stages: (1) the mining of bauxite ore, (2) the refining of bauxite to alumina, (3) the production of aluminium from alumina (primary production) or recycled scrap (secondary production), and (4) the casting of molten aluminium.

Primary aluminium is produced in smelters using the Hall-Héroult process. In this process, alumina is dissolved in a molten cryolite bath in an electrolytic cell to produce aluminium. A direct current is passed through the bath (between the suspended carbon anode and the carbon cathode at the bottom of the cell) to reduce the alumina to aluminium. Aluminium is also produced from new and used scrap aluminium by the secondary aluminium industry.

Current resources of bauxite total approximately 20 billion tonnes¹ with the bulk of the economic deposits in Australia and the tropics. Alumina refineries are concentrated in these regions because bauxite is costly to transport. Alumina is then transported to primary aluminium producing countries world-wide (ICF, 1999).

¹ 1 tonne = 10³ kilograms = 10⁶ grams

The global primary aluminium industry is dominated by a small number of vertically integrated multinational firms that control over 40 percent of the primary aluminium production capacity and about 60 percent of the alumina refining capacity. The remainder of the smelter capacity is controlled by governments, traders, smaller companies with one or two plants and investors. Aluminium producers are price-takers. The price of aluminium is determined by activities on the London Metal Exchange, where aluminium is a traded commodity. Therefore, in order to remain competitive, aluminium producers must reduce production costs, of which energy accounts for a significant portion.²

In 1998, over 22 million tonnes of primary aluminium were produced in 46 producer countries, requiring approximately 44 million tonnes of alumina and 133 million tonnes of bauxite. North America was the largest primary aluminium producer with almost 30 percent of the world total, followed by Eastern Europe & the Former Soviet Union and Western Europe with 17 and 16 percent of the world total, respectively (ICF, 1999).

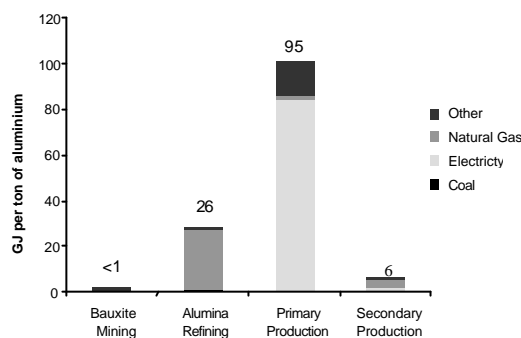
Secondary aluminium production in 1998 totalled 7.4 million tonnes with production concentrated in countries with developed economies that have a high historic rate of aluminium consumption (e.g., United States, Japan, United Kingdom) (AA, 1997). In the largest three end-use sectors for aluminium – transportation, packaging, and construction – the potential for using recycled aluminium in virtually every application exists. Recent years have seen major developments, especially in the recycling of aluminium beverage cans in some regions.

² Recent developments with mergers of major industry players (e.g., Alcoa and Reynolds, Alcan, Pechiney, and Alusuisse) have led to the creation of mega-companies. These companies may have sufficient market power to influence the price at which aluminium is sold.

Energy Use and Emissions

Primary aluminium production is an energy-intensive process. On a unit basis, producing a tonne of primary aluminium requires approximately 120 gigajoules (GJ).³ This estimate includes the energy required for bauxite mining, alumina refining and primary production.⁴ Primary production is the most energy-intensive stage, requiring approximately 95 GJ per tonne. In contrast, secondary production requires 6 GJ per tonne (see Exhibit ES-1) (AA, 1998a; USDOE,/OIT, 1997).

Exhibit ES-1. Per Unit Energy Use by Fuel-Type for Each Stage of the Process



Note: Primary and secondary energy intensity estimates include energy for casting.

Electricity required for the reduction of alumina to aluminium is the major fuel type consumed in the primary production process, accounting for over 80 percent of total per unit energy use at the primary production stage.

Energy accounts for about one-third of the cost of primary aluminium production, majority of which is spent on electricity. A 200,000 tonne per year facility spends approximately \$60 million per year on electricity, assuming a smelting electricity requirement of 15 kilowatt-hours (kWh) per kilogram (kg) of aluminium and a cost of electricity of 2 cents per kWh. Therefore, the

³ 1GJ = 0.9478 Btu

⁴ Energy associated with transportation is not included.

industry can minimise production costs by increasing energy efficiency.

Over the past 50 years, the energy required to produce one tonne of primary aluminium has decreased by 40 percent as a result of improvements in the electrolytic process (Haupin, 1986). The recent trend toward increased recycling has also reduced overall industry energy intensity.

Efficiency gains in the last three decades were achieved by installing improved cell technologies that operate at higher amperages, installing computer control systems, instituting better operating practices in new and existing smelters, and increasing recycling (Haupin, 1986; Kvande, 1999).

GHG emissions from the aluminium production process result from three sources:

- Carbon dioxide (CO₂) emissions generated from combustion of fossil fuels at all stages of the production process;
- Process-related CO₂ emissions from consumption of the carbon anode in the electrolytic cell; and
- Process-related perfluorocarbon (PFC) emissions generated during operational disturbances in the electrolytic cell

known as “anode effects”.

GHG emissions estimates for a hypothetical plant for each stage of the process are shown Exhibit ES-2. Emissions estimates are presented in units of thousand tonnes of carbon dioxide equivalents (thousand tonnes CO₂-E), which weights each gas by its global warming potential (GWP). GWP is a measure that combines expected atmospheric lifetime and infrared absorption capacity and provides a common unit for comparing the relative impacts of gases on global warming (IPCC, 1996). As shown in the exhibit, the primary production stage has the highest energy related emissions per unit product and is the only source of significant process related GHGs.

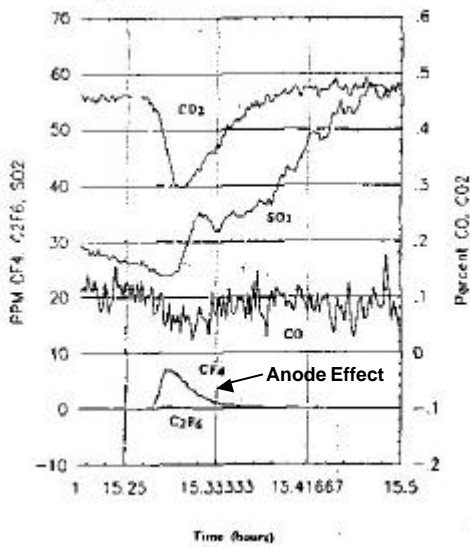
Exhibit ES-3 illustrates the composition of GHGs produced in the primary production (electrolytic) cell, both when the cell is on anode effect and under normal operating conditions. Under normal operating conditions, the exhaust gas from the electrolytic cell consists of about 50 percent CO₂ and 10 percent CO. During an anode effect, concentrations of CF₄ and C₂F₆ are detected and the concentrations of CO₂ and CO decrease. However, the CO concentrations decrease less rapidly than the CO₂ concentrations resulting in a relatively higher CO concentration during an anode effect than during normal operation (Roberts, R. and J. Marks, 1996).

Exhibit ES-2. GHG Emissions for a Hypothetical Plant by Stage of Process

Stage of Process	Production (tonnes of product/year)	Emissions ('000 tonnes of CO ₂ -E)				Total
		Energy -CO ₂	Process-CO ₂	Process-PFCs		
				CF ₄	C ₂ F ₆	
Bauxite Mine	1,000,000	9				9
Alumina Refinery ²	400,000	1,160				1,160
Primary Production Facility ³	200,000	2,200	300	780	110	3,390
Secondary Production Facility	70,000	45				45

1. See Chapter 3 for more detail on derivation of emissions factors by stage of process.
2. Alumina refinery is assumed to use fluidized bed technology.
3. The primary production facility is assumed to be a center worked prebake facility in North America. The specific electricity consumption of the plant is assumed to be 15 kWh/kg and the regional grid fuel mix for North America is used to estimate the electricity generation emissions factor. The estimate for energy related CO₂ includes natural gas, other fuels, anode consumption, and primary ingot casting. The process CO₂ emissions factor assumed is 1.5 kg CO₂/ton of aluminium. The emissions factors for CF₄ and C₂F₆ assumed are 0.6 and 0.06 kg/ton of aluminium, respectively. Global warming potentials (GWPs) used for CF₄ and C₂F₆ are 6,500 and 9,200, respectively.

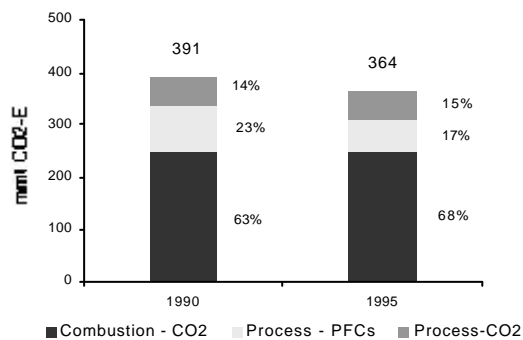
Exhibit ES-3. Gas Composition in Electrolytic Cells



Source: Roberts, R. and J. Marks, 1996

Total GHG emissions from the aluminium industry were estimated to be 391 million tonnes CO₂-E in 1990 and 364 million tonnes CO₂-E in 1995. It is estimated that total anthropogenic emissions of GHGs were about 35,000 million tonnes CO₂-E in 1995 (Harnisch et al, 1998). The aluminium industry, therefore, contributed 1 percent of total anthropogenic GHG emissions in 1995. Exhibit ES-4 shows the estimated emissions of the different sources of GHG emissions in 1990 and 1995.

Exhibit ES-4. GHG Emissions from the Aluminium Industry: 1990 and 1995



The largest source of CO₂ and overall GHG emissions from the aluminium industry was

fossil fuel combustion, which accounted for 68 percent of total emissions in 1995. The majority of these emissions were a result of generating electricity required for smelting.⁵ Emissions of PFCs and CO₂ from the primary production process accounted for 17 and 15 percent of 1995 emissions, respectively.

Emissions by region are shown in Exhibit ES-5. North America was the largest emitter in 1995, accounting for 27 percent of industry GHG emissions. Eastern Europe & Former Soviet Union and Western Europe were the next largest, accounting for 25 and 14 percent of total emissions, respectively.

Exhibit ES-5. GHG Emissions by Region
(Data are in million tonnes CO₂-E)

Region	1990	1995
Asia	25	30
Australasia	47	48
Central and South America	30	32
Eastern Europe & FSU*	86	92
North Africa & Middle East	6	5
North America	117	100
Sub-Saharan Africa	7	7
Western Europe	75	51
Total	391	364

* FSU = Former Soviet Union

Between 1990 and 1995, Eastern Europe & Former Soviet Union's contribution to total emissions increased from 22 to 25 percent of total emissions. This trend is largely due to the shift in the geographic distribution of production between 1990 and 1995. Production declined in North America and Western Europe, relative to the Eastern Europe & the Former Soviet Union. This regional shift in production is an outcome of the adjustments the world aluminium industry underwent in the early 1990s to integrate Russia into the world market.⁶

⁵ Emission estimates were developed using the regional average fuel-mix for electricity supply. These estimates are based on IEA's regional average electricity emission factors. These estimates are about 10 percent higher than the aluminium industry estimates which are based on the industry-average fuel mix (IPAL, 1999).

⁶ The collapse of the Soviet Union in 1989–1990 and subsequent decline in metal demand, particularly in the

Overall industry emissions intensity was 16 tonnes CO₂-E per tonne of aluminium in 1990. In 1995, the industry emissions intensity fell by 17 percent from 1990 levels to 13 tonnes CO₂-E per tonne of aluminium. In this period, the share of secondary production of total aluminium supply (primary plus secondary production) increased by 3 percent.

Options for Reducing GHG Emissions

At any given time, the mix of technologies and practices used by industry ranges from older technologies and practices to state-of-the-art. State-of-the-art refers to existing best available technologies and practices with demonstrated technical feasibility in actual production environments. Energy efficiency (and GHG emissions intensity) improves as older facilities are upgraded partially or wholly to state-of-the-art ones.⁷ Energy efficiency and GHG emissions also improve as advanced technologies are developed to become the state-of-the-art tomorrow.

The aluminium life-cycle consists of a diverse set of emission sources and the number of potential mitigation options is very large. This study focuses on those sources that are significant in terms of emissions and options that have significant potential for reducing emissions.

Options to Improve the Hall-Héroult Process

The activities included in this area are: (1) retrofit existing cells, which involves capital investment that reduces energy use and emissions within a given technology-type; (2) convert existing cell technologies to state-of-the-art cell technologies (the capital

investment shifts existing production to a more efficient type of technology); and (3) implement advanced technologies that are expected to become commercially available by 2020.

Retrofit Existing Cells

Smelters typically evaluate retrofit options for improving the Hall-Héroult process in terms of their ability to increase cell amperage or current efficiency.

Smelter retrofit options include:

- point-feed systems that allow more precise alumina feeding;
- process computer control systems that control the repositioning of anodes as they are consumed and provide greater control over alumina feeding;
- improvements to bath chemistry;
- design changes in carbon anodes;
- busbar system modification to improve the magnetic balance of the cell; and
- design or material changes in the cathode shell.

Point-feed prebake systems operating at high amperages are the state-of-the-art technology in aluminium production. Conversion to the state-of-the-art point-feed prebake technology is the most reliable route to increasing operational and production efficiency. Increases in energy efficiency, production, and pot life can be expected with conversion to point-feed prebake technology. The capital outlay for this option can be quite significant. Retrofit options are usually implemented after extensive computer modelling and large scale development work is conducted on test cells.

Implement Advanced Technologies

Advanced technologies refer to those that are currently under development or have been seriously considered in concept and are expected to have an impact on the industry

military and aerospace sectors, led to excess metal from Russia and the Commonwealth of Independent States (CIS) flooding the world market.

⁷ Some of the older smelters in the industry may be “swing” plants that are brought on-line solely to exploit fluctuations in the price of aluminium. Efficiency improvements are typically not considered at such plants.

over the next 10 to 20 years. The inert anode and wettable cathode are two advanced technologies that are being pursued aggressively by industry.

The development of inert, dimensionally stable, non-carbon anodes that are not consumed in the electrolytic process represents the major potential advancement in the aluminium production process. The non-carbon anodes would remove the source of carbon for process-related CO₂ and PFC generation, thereby eliminating these emissions. Energy efficiency increases ranging from 10 to 30 percent are expected, with the higher efficiencies being achieved when the inert anode is coupled with a stable, wetted cathode (AA, 1998b).

The wettable cathode comprised of an inert titanium diboride and graphite (TiB₂-G) cathode is expected to increase the cell's stability and increase current efficiency. Field testing of the inert anode and wettable cathode are underway (AA, 1998b).

Options to Improve the Alumina Refining Process

The two main options for improving the alumina refining process are to replace rotary kilns with fluidised bed kilns and increase cogeneration. The fuel demand of a fluidised bed kiln is about one third the fuel demand of the rotary kiln (Nunn, 1999). As a result, rotary kilns are being replaced with the much more efficient fluidised bed kiln. Cogeneration, or combined heat and power (CHP), produces both electricity and process steam for use at different stages in the refining process. The current economics of the process warrants that all alumina refining facilities have to be CHP integrated in order to compete in the world market.

Increased Recycling

Increased recycling may play a major role in meeting the rising demand for aluminum products globally. The increased market share of secondary aluminium will have a significant impact on industry energy use

and emissions. On a per tonne basis, recycling aluminium uses about five to eight percent of the energy required to produce primary aluminium and releases less than four percent of the GHGs released when producing primary aluminium (including all stages). Growth in the secondary aluminum industry will depend on an increase in recycling rates (i.e., quantity recovered/quantity consumed) and increase in metal recovery efficiency.

Recycling Rates

Recycling rates can be increased by implementing or enhancing programs for used beverage can (UBC) recycling and where non-existent, developing an infrastructure for scrap collection. The UBC recycling rate is over 60 percent in the United States and Japan, and is still increasing. In Europe, the recycling of UBC's increased from 30 percent in 1995 to 40 percent in 1997 (AA, 1999; ICF, 1999).

The recycling rates for non-UBC scrap (e.g., automobile parts, aluminium siding and construction material) are high in North America, Western Europe and Japan. For non-UBC scrap, recycling rates as well as the proportion that is recoverable varies greatly among end-uses. Metal available in large chunks or where collection infrastructure is well developed have the highest recovery.

Developing or enhancing the infrastructure for UBC and non-UBC collection in several countries offers significant potential to increase secondary production. Costs for this option are difficult to quantify, as they will vary significantly by region and end-use.

Metal Recovery Efficiency

During recycling, some aluminium is lost (approximately 2 percent) during remelting and the concentration of alloyed metals must be adjusted by adding primary metal depending on end-user specification. Promising options to increase metal recovery efficiency and reduce energy intensity per unit of secondary aluminium produced

include: enhanced dross metal recovery; use of innovative scrap decoating equipment; and improved furnace efficiency.

Alternatives to the Hall-Hèroult Process

Alternative, less energy and emissions intensive methods of producing aluminium would be desirable. However, currently, no alternative production processes exist that could displace the existing Hall-Hèroult process. This process has been used to produce primary aluminium for over 100 years.

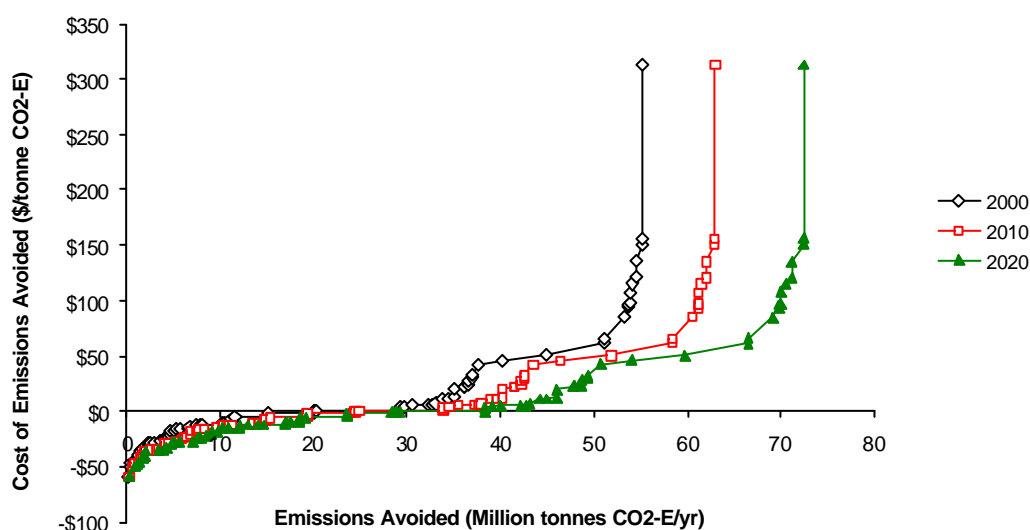
One process, direct carbothermic reduction, has shown potential, and if successfully developed to operate on a commercial scale, would save approximately 25 percent of the energy used in Hall-Hèroult cells (Richards, 1997). However, there is not much interest in this process because of the familiarity with the existing process, the enormous cost of demonstrating the direct carbothermic process (\$250 million), and the uncertainty that it would be adopted over the Hall-Hèroult process.

Marginal Abatement Costs

Cost-effective technologies and practices exist that can reduce GHG emissions from the aluminium industry. Exhibit ES-6 shows the global marginal abatement curve (MAC) for the industry for 2000, 2010, and 2020. In 2010, emission reductions amounting to approximately 35 million tonnes CO₂-E are achievable at an incremental cost less than \$0 per tonne CO₂-E. These represent achievable profitable reductions. Within the range of \$0 per tonne CO₂-E to \$100 per tonne CO₂-E, achievable reductions are estimated at an additional 25 million tonnes CO₂-E. Above approximately \$100 per tonne CO₂-E, the global MAC becomes relatively inelastic, which indicates the limits of the options considered. Because not all mitigation options were assessed, this analysis represents a conservative estimate of the emission reduction potential from this industry.

The greatest potential for cost-effective mitigation lies in Asia (China) and Eastern Europe and the Former Soviet Union (Russia). These regions rely on dated Soderberg technology, which offer significant GHG reduction potential.

Exhibit ES-6. Global Marginal Abatement Curve, 2000, 2010, and 2020



In other regions, such as Australasia, modern technologies that have already captured the low-cost reductions are in use. Therefore, marginal abatement costs in these regions are relatively high. Since marginal abatement costs vary significantly among regions, international co-operation through mechanisms such as emissions trading can reduce the global cost of emission reduction.

Future GHG Emissions

Estimates of energy use and emissions until the year 2020 were developed for three scenarios:

- *Business-as-usual*: Continuation of recent trends in energy and emissions through incremental improvements in the current state of technology.
- *State-of-the-art*: Represents the potential for aggressive adoption of cost-effective, state-of-the-art technologies to reduce energy use and emissions.
- *Advanced*: Represents the potential for breakthrough technologies and practices expected in the next 15 to 20 years to reduce energy use and emissions.

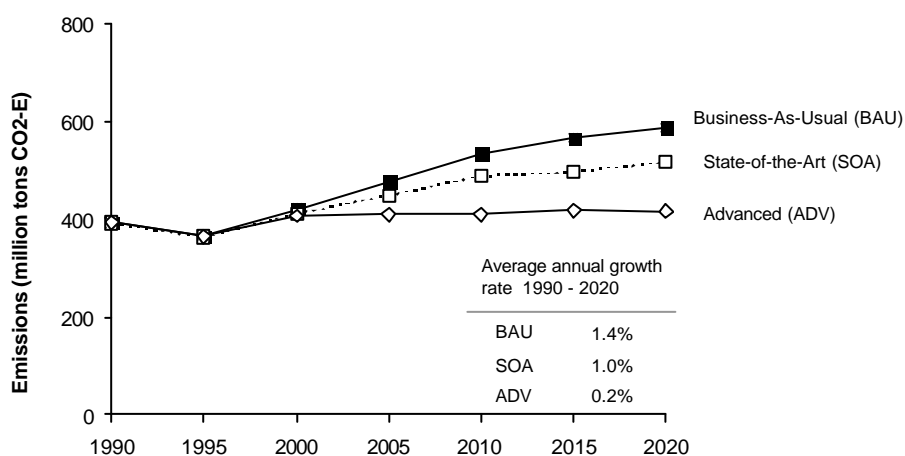
For all scenarios, world primary aluminium production is projected to increase from 23

million tonnes to 38 million tonnes from 2000 to 2020, an average annual growth rate of 2 percent. The scenarios, therefore, highlight the effect of technology on emissions levels.

Under the business-as-usual scenario emissions are expected to increase at a rate of approximately 1.4 percent per year (see Exhibit ES-7). Under the state-of-the-art scenario, emissions increase at a somewhat slower rate, 1 percent per year. The most dramatic decrease in emissions growth occurs under the advanced scenario where industry-wide GHG emissions remain almost constant at the year 2000 levels. In the advanced scenario, the introduction of the inert anode and the wettable cathode contribute in part to the overall decline in the emissions growth rate.

Estimates of future emissions levels are highly sensitive to the fuel or resources used to generate electricity supplied to the aluminium industry. Emission levels in 2020, under the business-as-usual scenario decrease by 56 percent when fossil-fuel generated electricity is replaced by hydroelectricity. Energy-sector options aimed at reducing the carbon-intensity of electricity supply will have a significant impact on global emissions.

Exhibit ES-7. GHG Emissions under Alternative Scenarios



Conclusions

The aluminium industry is highly energy intensive. Energy use accounts for a significant portion of the production costs and GHG emissions. To remain competitive, the industry has undertaken measures to increase energy and production efficiency. In addition to reducing the energy intensity of the process, these measures also reduce GHG emissions.

In 1995, GHG emissions from the aluminium industry accounted for 1 percent of global anthropogenic GHG emissions. The primary production stage contributes the majority of GHG emissions. Cost-effective technologies to reduce these emissions are currently available. Incremental reductions in the average GHG emissions rate are underway as old and obsolete plants are shut down, existing plants are retrofitted and modernised, and new plants are built with modern technology. However, the technology renewal process is slow because of the capital-intensive nature of the industry.

Promising technologies that are currently in the development phase include the inert anode and the wettable cathode. Improving the rate of recycling will also contribute to reductions in the overall energy and emission-intensity of the industry.

Expanding cooperation through the sharing of technical information, partnerships with government, and research and development efforts are expected to accelerate emission reduction efforts. In order to achieve these emissions reductions at least cost, emissions should be reduced in areas where it is cheapest to do so.

Policy options should focus on promoting research and development into GHG emission reduction measures, providing industry with incentives to reduce GHG emissions, and reducing regulatory uncertainty by providing credit to producers who voluntarily reduce emissions.

1. Objective

The objective of this study is to evaluate the scope of technical options and costs for the mitigation of greenhouse gas emissions from the life cycle of the aluminium production process. By focusing on the options and costs to reduce greenhouse gas emissions, this study complements the IEA Greenhouse Gas R&D programme's (IEA GHG) objectives to evaluate technologies for mitigation of greenhouse gas emissions and develop targets for research, development, and demonstration.

The remainder of this report is organised as follows:

2. Industry Characterisation. This chapter provides an overview of the life cycle of the aluminium production process, divides the global industry into regions that reflect the different stages of production and technological development, and discusses current production, consumption, and industry trends.

3. GHG Emissions Inventory. This chapter identifies the sources of GHG emissions, estimates energy intensity factors and GHG emission factors for each technology, and quantifies emission levels for the aluminium industry. This assessment of current emission levels provides the foundation for identifying mitigation options.

4. Identification and Assessment of Opportunities to Reduce GHG Emissions. This chapter identifies mitigation options that have the greatest potential to reduce GHG emissions in the aluminium industry. From the list of options identified, a detailed technological and engineering assessment of

Exhibit 1. Primary Aluminium Reduction Plant



GHG reductions and associated costs is conducted for select options.

5. Future GHG Emissions from the Aluminium Industry. This chapter forecasts future global emissions for the near-term (2000), medium-term (2010), and long-term (2020). These emission forecasts reflect alternative policy options and mechanisms by integrating technology diffusion rates for various mitigation options and emission reductions and varying sources of energy. The marginal costs of implementing mitigation technologies as well as the barriers to implementation are discussed.

6. Conclusion. This chapter summarises the key findings of this study.

7. References.

2. Industry Characterisation

The aluminium industry is comprised of firms that mine bauxite ore, refine raw bauxite to alumina, produce aluminium from alumina and recycled scrap, and manufacture semi-fabricated products including sheet, foil, castings, and extrusions. This chapter provides an overview of the aluminium production process, the characteristics of the prevailing technology, and the current production, consumption, and industry trends.

2.1 Life Cycle of Aluminium Production

The basic technology used by the aluminium industry has remained essentially unchanged since the Hall-Héroult process for electrolytic reduction was invented in 1886 and the Bayer process for alumina production was discovered in 1888. Generally, the industry is characterised by four stages: (1) the mining of bauxite ore; (2) the refining of bauxite to alumina (“alumina refining”); (3) the production of aluminium from alumina (“primary production”) and scrap (“secondary production”); and (4) the casting of molten aluminium into end products. The final stage – casting – is common to both primary and secondary production (Altenpohl, 1998).

2.1.1 Bauxite Mining

Bauxite, which consists mainly of aluminium hydrates, is formed by the weathering of rocks by heavy rainfall. The weathering breaks down the aluminium silicates found in most rocks and, under certain conditions, leaches out soluble constituents, concentrating the hydrated aluminium oxide. Since suitable conditions

for bauxite production occur most frequently in tropical climates, the bulk of the world’s known bauxite reserves is in tropical areas.

On average, bauxite is found at a depth of 80 feet, but can be found anywhere from zero to 600 feet beneath the surface. Nearly all bauxite mined currently 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 refinery. The mining site residues and waste are then treated and the site is restored. The bauxite is then transported to an alumina refinery.

2.1.2 Alumina Refining

Nearly all bauxite used to produce primary aluminium is subjected to the Bayer process, which removes impurities and chemically-combined water, leaving aluminium oxide in a nearly pure state. The alumina content of bauxite ores varies from one deposit to another, such that each alumina plant is almost tailor made to suit a particular bauxite.⁸

⁸ The two principal types of bauxite ores are monohydrates ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$) and trihydrates ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$). The monohydrates appear in two forms, diasporite and boehmite, of which boehmite is adaptable to the Bayer process and diasporite is not. Monohydrates are less desirable than trihydrates, which are typically found in the form of gibbsite. The trihydrates are preferred because they are more soluble in caustic solution and can be handled at a lower temperature and pressure in the Bayer process.

At the refinery, bauxite is crushed, ground, and submerged in a 140-240°C caustic soda solution. The alumina minerals in the ore react with the caustic soda and dissolve into sodium-aluminate. Most of the ore's impurities precipitate out and are removed by counter-current recantation and filtration. The aluminium trihydrate, or aluminium monohydrate, is recovered by precipitation, and is filtered, dried, and calcined to form alumina. Calcination removes the water and occurs in rotary kilns or in fluidised beds at 1100-1300°C.

Economic operation of the Bayer process requires the efficient use of energy for steam generation and calcining. The sheer increase in size of the operating units in response to vastly greater markets has permitted the most basic kind of industrial economies-to-scale through the use of larger tanks, pumps, kilns, and heating units. Alumina rotary kilns have now been replaced for the most part with the much more efficient fluidised bed kiln, which uses about one third of the fuel that is required by the rotary kiln. Furthermore, a number of alumina refineries take advantage of the benefits of cogeneration – which produces both steam and electricity.

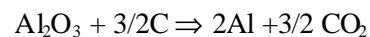
2.1.3 Primary and Secondary Production

Primary Production

Primary aluminium is produced from alumina in smelters using the Hall-Héroult process. During this process, alumina is dissolved in a molten cryolitic bath (sodium-aluminium fluoride, Na_3AlF_6), and an electric current is passed through the solution, thereby decomposing the alumina into aluminium and carbon dioxide. Aluminium is produced in large electrolytic cells called pots with a direct electric current input of more than 300,000 amperes and about four volts. The pot is a rectangular, steel shell typically eight to 13 meters long, 3 to 5 meters wide, and 1 to 1.5 meters high. It is lined with a refractory insulating shell

on which carbon blocks are placed to form a cathode. Steel collector bars are inserted into the cathode blocks to carry current away from the pot.

Molten cryolite (sodium-aluminium fluoride) is placed in the cavity formed by the cathode blocks. Anodes, also of baked carbon, are immersed in the cryolite to complete the electric path. The anodes are consumed in the electrolysis and are replaced every two to three weeks. Alumina (Al_2O_3) is fed in powder form into the pots by various means and is dissolved in the cryolite bath. Molten aluminium is produced as the anode is consumed in the following reaction:



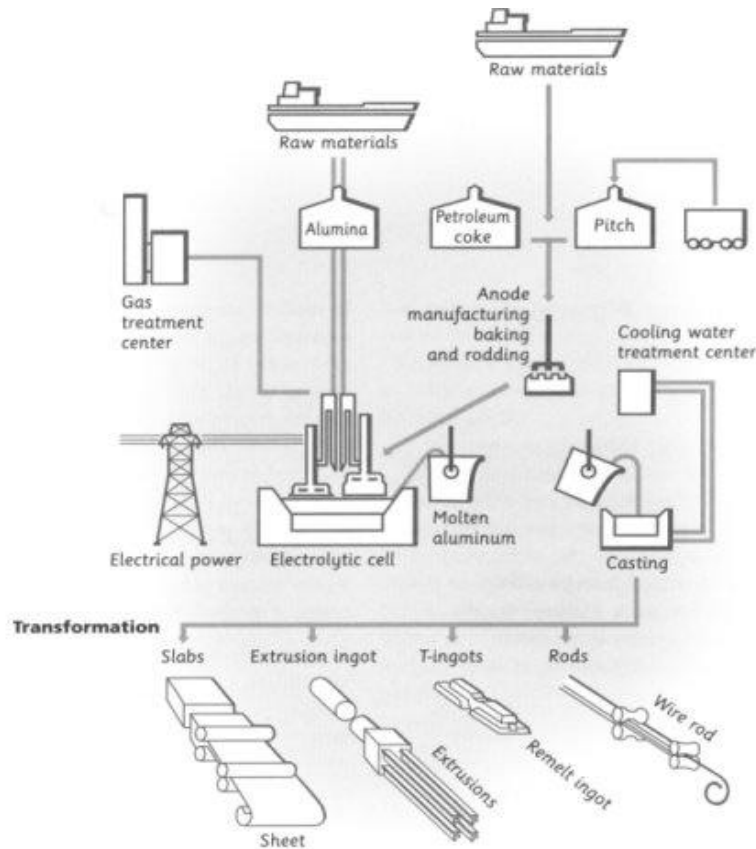
Pure aluminium forms at the cathode and is siphoned off (called tapping) periodically. The molten aluminium is then cast immediately into a variety of products, according to market specification. Exhibit 2 depicts the flow of materials in the primary aluminium production process.

The primary production process is continuous: alumina is added, anodes are replaced, and molten aluminium is siphoned off without interrupting the current in the cells. The process is energy intensive with electricity consumption per tonne of aluminium ranging from 13 kWh/kg of aluminium produced to 17 kWh/kg, depending on the cell technology type and other factors.

The two major aluminium technologies – differentiated by the type of anode used and the method by which the anode is introduced into the cell - are prebake and Soderberg.

Prebake cells use multiple anodes, which are formed and baked prior to use. Prebake cells date from 1890, but with their vastly improved design, mechanisation and fume control, they represent the major proportion of world aluminium capacity. Modern prebake cells are magnetically balanced and

Exhibit 2. Production of Primary Aluminium



fully hooded for purposes of fume capture and treatment. These cells are extensively mechanised which enables routine actions such as adjusting the electrode or adding alumina continuously to optimise cell performance.

The prebake technology has essentially two variants based on how alumina is fed to the cell: **Centre Worked Prebake (CWPB)** and **Side Worked Prebake (SWPB)**. For purposes of this study, a third variant of prebake technology is defined: **Point-Feed Prebake (PFPB)** technology, to represent the state-of-the-art in aluminium production technology. Most new production facilities are PFPB facilities. In CWPB cells, alumina is fed along the longitudinal centre line of the cell whereas in SWPB technology, alumina is fed along the longitudinal sides of the cells (see Exhibit 3). In CWPB cells,

there are two methods of feeding alumina into the cell – bar feed and point feed. In a bar feed system, the crust on the electrolytic bath is broken on the side approximately every six hours and large quantities of alumina enter the pot at one time and tend to exceed alumina solubility limits in baths. Point-feed systems enable more precise process control of alumina concentration levels, produce less sludge, and stabilise temperature. These features allow higher current efficiencies, lower energy consumption, and lower PFC emissions compared to conventional bar feeders.

Soderberg cells use a single, monolithic, carbon anode that is formed directly in the cell. The fresh anode paste is added to the top of the anode, which is made of coke and pitch, and bakes in the cell itself. Soderberg technology has two variants based upon how

the electricity is introduced to the cell, namely, **Vertical Stud Soderberg (VSS)** and **Horizontal Stud Soderberg (HSS)**. In a VSS cell, the electrical connectors or studs are placed vertically into the top of the anode. In a HSS cell, electrical connectors or studs are placed horizontally into the anode along the longitudinal length on both sides of the cell (see Exhibit 3).

Soderberg cells are less efficient than prebake cells in terms of capture and collection of fluoride fumes and hydrocarbons that are produced in the cell. Consequently, Soderberg cells, popular from the 1940s to the 1960s, have become costly to bring into compliance with emission regulations, particularly with respect to the exposure of workers to hydrocarbons (Richards, 1997).

Secondary Production

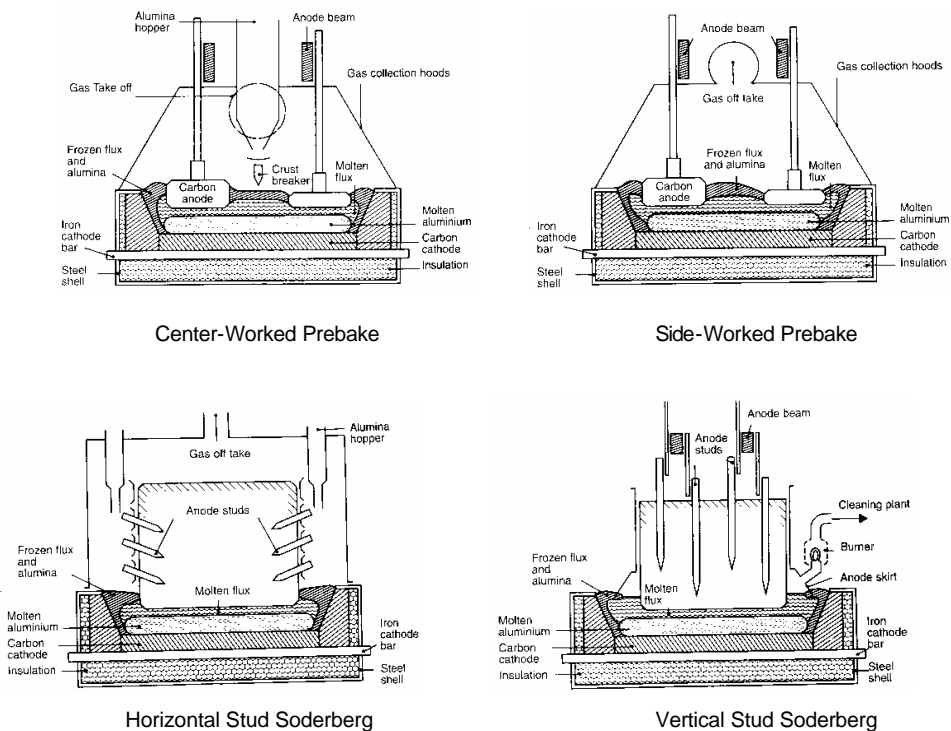
Secondary aluminium is produced from recycled scrap that is either generated at the smelter or purchased from recyclers,

brokers, or scrap yards. Aluminium scrap is categorised into two types: new and old. New scrap is generated by pre-consumer sources such as drilling and machining of aluminium castings, and scrap is generated from aluminium fabrication and manufacturing. Old scrap is material that has been used by the consumer and discarded, such as appliances, automobile and airplane parts, construction material, and used beverage containers (UBCs).

The secondary aluminium production process includes: (1) old scrap collection and sorting; (2) new scrap utilisation; (3) scrap pretreatment; and (4) melting and refining.

Old Scrap Collection and Sorting. The processes used to collect and sort old-scrap depends on the product's form and use. Non-UBC old scrap is collected by scrap dealers and then sold to the secondary facilities, where it is re-melted and usually converted to secondary alloy for use in foundries. UBCs generally do not go to

Exhibit 3. Primary Production Cell Technology Types



Source: IPAI, 1996

secondary facilities. Because of their high turnover, uniform grade of metal, and sheer volume, UBCs are recycled by the original primary producers who have already invested large sums into UBC collection infrastructure.

New Scrap Utilisation. In most cases, there is no collection or sorting involved for new scrap because it can be used directly at the smelter. When it cannot be used on-site, new scrap may be sent directly to a secondary aluminium melting/refining facility, or to a pretreatment facility. Pretreatment is required if the new scrap includes alloys.

Scrap Pretreatment. Often scrap is contaminated with dirt, oxides, or miscellaneous materials that cannot be easily separated. For example, UBCs are covered with both lacquers and sealers and therefore need to be delacquered prior to melting. Pretreatment operations include shredding and cleaning scrap prior to melting and refining. Pretreatment of scrap reduces aluminium loss within the furnace while at the same time reducing emissions of hazardous air pollutants and other toxic substances. The pretreatment process for new scrap is simplified because alloy content is known and contaminants are minimal.

Melting and Refining. These operations include melting, adding fluxing agents, removing magnesium, degassing, alloying, and skimming. Scrap is melted to adjust its composition to that required for the final product; to change it into a suitable form for casting and fabricating; and to improve metal quality with respect to reduction of gas and non-metallic inclusions. Some methods of melting involve the addition of a molten salt flux, which helps remove impurities. Magnesium removal is often necessary to meet specification requirements for several applications. In addition,

degassing is performed to remove hydrogen gas bubbles, which cause inclusions in the metal.

After the scrap has been melted and the impurities and gases removed, the molten aluminium is typically alloyed. Alloying combines the aluminium with other agents (e.g., zinc, copper, manganese, etc.) in order to produce the desired composition, quality, strength and ductility of the aluminium. Finally, periodic skimming is performed to remove the accumulation of dross, an oxide residue that contains the entrapped metal lost in the melting process. The refined aluminium is now ready for casting into a variety of end-products. Exhibit 4 depicts the flow of materials in the secondary aluminium production process.

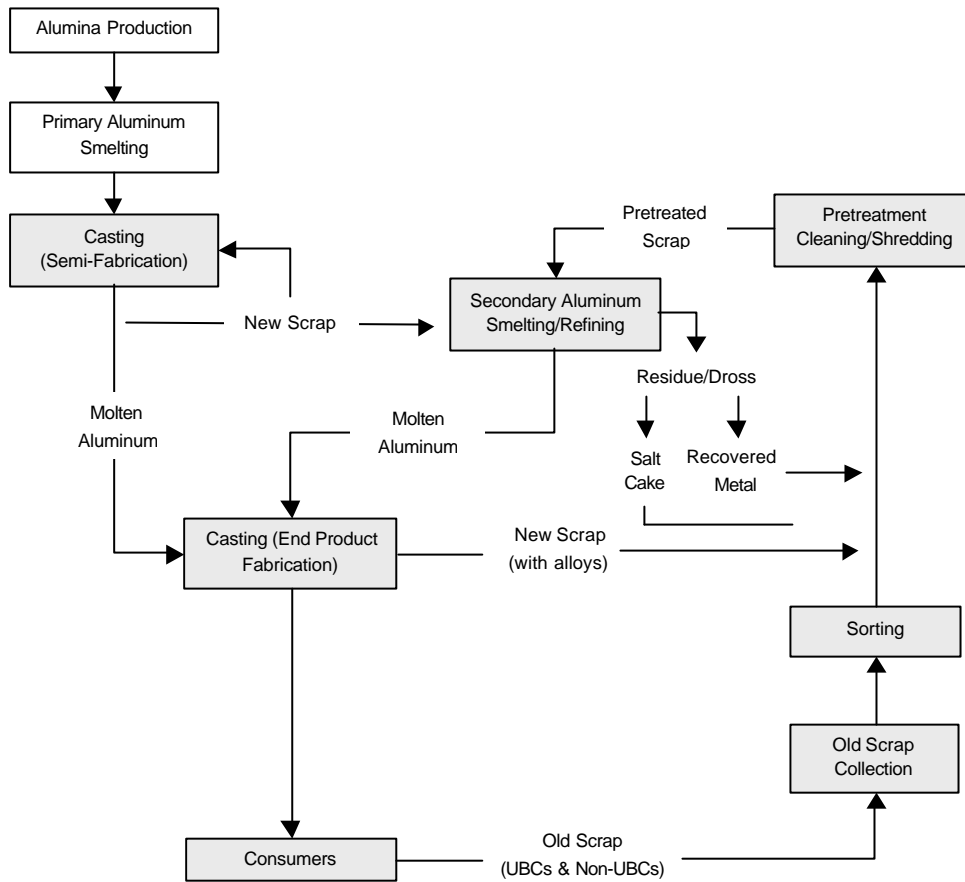
Dross and salt cake must be skimmed away from the surface after melting is complete. These residues vary greatly from plant to plant and even from furnace to furnace due to such factors as furnace temperature and contaminants in the scrap. Higher recovery efficiencies may be possible in the near future due to current efforts on recapturing aluminium from dross.

2.1.4 Casting

The casting of aluminium is similar to other metals, except that the high degree of workability of the metal favours greater use of extrusions and foil or very thin sheets. Depending on end-use or market specification, primary and secondary aluminium are cast into a variety of end-products.

Castings (ingot) consume a major share of the metal. The automobile industry, which is a large consumer of aluminium casting, buys some primary metal directly from the smelter in a molten form for this use (Altenpohl, 1999).

Exhibit 4. Secondary Aluminium Production Process



Key: Grey boxes are specific to the Secondary Production Process

Secondary metal is a common source of metal for castings and may be mixed with primary aluminium to achieve a desired quality. For other uses, ingot is converted into basic mill shapes (semi-fabrications) in hot rolling mills to produce plates, sheets, bars, and rods.

2.2 Characteristics of Prevailing Technology

Several characteristics of the prevailing technology used to produce aluminium are worth noting for the purposes of this study as they influence the rate and range of technology adoption by the industry, and hence future GHG emissions:

State of Technology. The existing technology of the industry is well developed and widely available. Although revolutionary changes are under consideration, at present a well-established technology prevails. It is readily accessible to new producers and is adaptable to less developed countries.

Scale. At most stages aluminium is a large-scale industry for sound technical reasons. Bauxite mining need not be on a large scale, but if port and rail facilities are required, a sizeable operation is necessary. Alumina production is a large-scale continuous process where great operating efficiency is gained from sizeable vessels, heating, and

materials handling equipment. Aluminium smelting is feasible on a smaller scale than alumina production, yet economies in the use of materials handling, administration, and electrical equipment and other plant, favour operations of at least 160,000 to 240,000 tonnes annual capacity. Much variation exists in the scale for various types of fabricating facilities.

Capital Intensiveness. Aluminium is a capital-intensive industry. Investment for a green-field aluminium smelting facility may be on the order of \$4,000 to \$6,000 per tonne. Capital intensiveness combined with advantages to scale means that large investments are required and therefore investors are inclined to seek politically secure locations for such expensive plants.

Electric Power. Low priced electric power is important to the production of aluminium at competitive costs. Expensive power quickly makes a location undesirable for the industry under normal circumstances of exposure to trade.

Transportation. The logistics of the aluminium industry are complex. Metal is consumed mostly in the large industrial centres, but the raw materials required to make it are bulky and distant. In practice, the transportation of raw materials, while a significant element of total cost, has not controlled the location of smelters, although it has influenced the location of alumina plants.

2.3 Industry Overview

A small number of vertically integrated multinational firms dominate the aluminium industry (e.g., Alcoa, Pechiney, Kaiser, Alcan). Apart from the major international firms, a number of lesser producers exist whose operations are more restricted in scope. The remainder of the smelter capacity is controlled by governments, traders, smaller companies with one or two plants and investors. Such firms often are

less completely integrated and their geographical reach is much narrower. They may lack the organisational, technical, and financial resources to impinge seriously on the international scene and sometimes they are allied with or partially owned by major international firms (ICF, 1999).

For the purposes of this study, the global aluminium industry is divided into eight regions: North America, Western Europe, Eastern Europe and Former Soviet Union, North Africa and Middle East, Asia, Central and South America, Sub-Saharan Africa, and Australasia. The boundaries demarcating these regions are shown in Exhibit 5. These regions best characterise the global aluminium industry with respect to the different stages of production, current technologies, applicable mitigation technologies, and technology diffusion rates.⁹

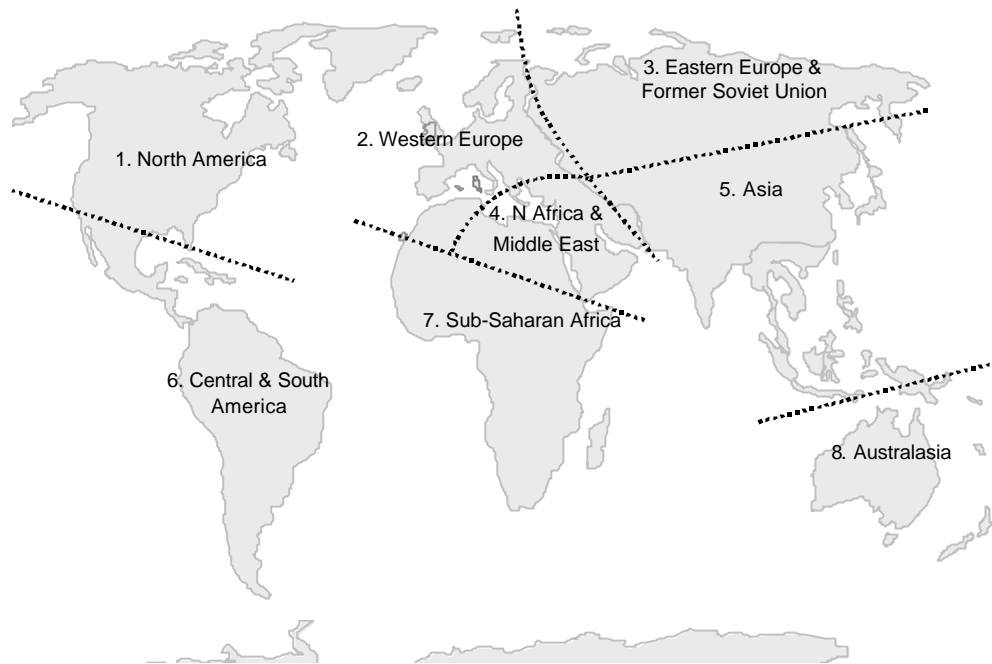
2.3.1 Current Production

In 1998, 22 million tonnes of primary aluminium were produced world-wide. Production was accomplished in just over 200 smelters located in 46 producer countries. In 1998, the rated capacity of all existing smelters was about 25 million tonnes per year. Existing primary smelters vary greatly in size with the smallest rated at just several thousand tonnes per year and the largest rated on the order of 850,000 tonnes per year at Bratsk in Russia (ICF, 1999).

Exhibit 6 shows relative production by region for each stage in the process for 1998. As shown in the figure, North America was the largest primary aluminium producer with almost 30 percent of the world total, followed by Eastern Europe & the Former Soviet Union and Western Europe with 17 and 16 percent of the world total, respectively. Of the producer countries, the United States was the largest producer with 16 percent of the world's total

⁹ For a list of countries in each region, see the Annex of this report.

Exhibit 5. Regions that Best Characterise the Global Aluminium Industry



followed by Russia with 13 percent and Canada with 11 percent.

Global secondary production in 1995 totalled 7.4 million tonnes (AA, 1997). As shown in Exhibit 6, significantly less geographical diversity exists in secondary production than in primary production. North America, Western Europe, and Asia account for over 90 percent of global secondary production. In Asia, the majority of the secondary production is in Japan. The concentration of production in developed economies indicates that countries that have historically consumed large amounts of metal will produce more secondary metal.

More than 90 percent of bauxite is mined for the eventual production of aluminium. Therefore, the market for bauxite is driven by the market for alumina. World demand for bauxite was approximately 133 million tonnes in 1998. On average, it requires three tonnes of bauxite to produce one tonne of alumina (ICF, 1999).

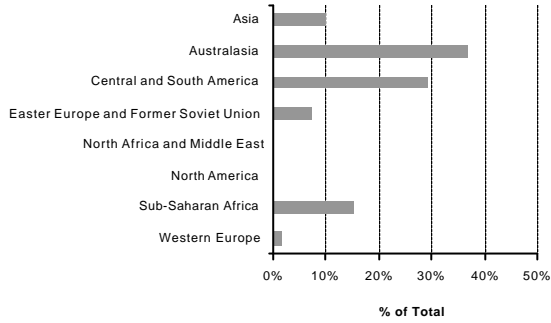
Current resources of metallurgical grade bauxite amount to between 20 and 30 billion

tonnes, and the bulk of the economic bauxite deposits are found in the tropics and Australia. The principal bauxite producing countries are Australia and Guinea, which produce over 50 percent of the world's bauxite requirements, followed by Jamaica, Brazil, and India which produce approximately 25 percent of the world's requirements (ICF, 1999).

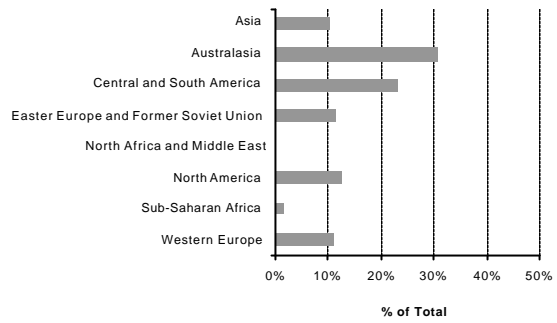
The geographic distribution of alumina and bauxite production is similar with the exception of North America, an importer of bauxite and a producer of alumina. As shown in Exhibit 6, Asia, Australasia, and Central & South America produce relatively the same amount of bauxite and alumina (as a percent of world production). Alumina refineries are often located at or near bauxite sources because transporting bauxite is costly. Alumina is then transported from refineries to smelters, typically located in regions with access to a reliable and inexpensive power supply since electricity is a major cost of primary aluminium production. For example, South American alumina is transported to North American smelters and Australian alumina to Asian

Exhibit 6. Global Production by Region

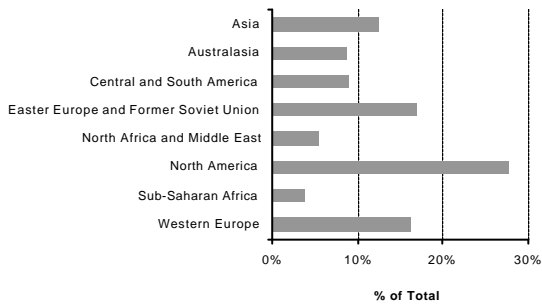
1998 Bauxite Production: 133 million tonnes



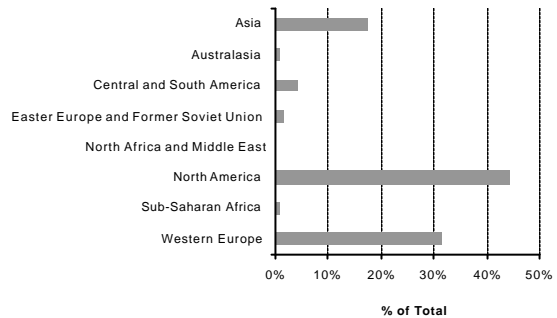
1998 Alumina Production: 44 million tonnes



1998 Primary Production: 22 million tonnes



1995 Secondary Production: 7.4 million tonnes



smelters. On average, it requires approximately two tonnes of alumina to produce one tonne of primary aluminium (ICF, 1999).

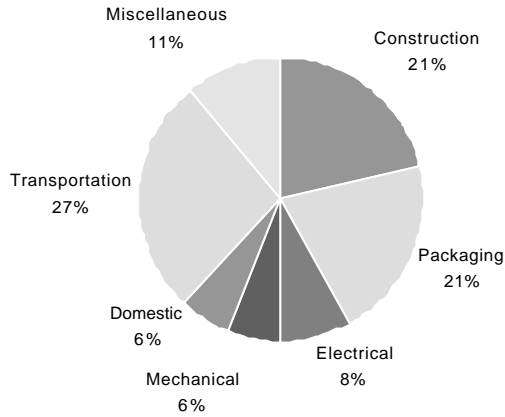
2.3.2 Current Consumption

Today, aluminium is one of the basic metals from which a wide variety of products are manufactured. In relation to other basic metals such as steel and copper, aluminium is a relatively new industry and has enjoyed constant and successful growth over the last several decades. Aluminium is used in a diverse range of applications and in various industries due to its versatility. For example, it is used in construction, transportation, electronics, and packaging. Exhibit 7 illustrates the end-use share of the global aluminium market by sector. Transportation, construction, and packaging

are the largest end uses, accounting for almost 70 percent of global consumption.

The major consumers of aluminium are developed countries. The United States, Japan, China, and Germany together consume nearly 55 percent of the world's total aluminium production. The level of economic activity in a region or country is a good measure of the level of aluminium consumption. As a primary industry item, aluminium demand depends on the manufacture and consumption of other production. If a region or country's economy is expanding and construction and manufacturing is increasing, the need for raw materials such as aluminium will tend to increase.

Exhibit 7. End-Use Share of the Global Aluminium Market



Source: ICF, 1999

2.3.3 Industry Trends

Several industry trends are worth noting on account of their significance to future industry GHG emissions.

The ratio of secondary aluminium to primary aluminium is increasing. The trend of using secondary aluminium in the place of primary aluminium is increasing. In 1975, primary metal accounted for 75 percent of the total use in the largest consuming countries. In 1998, this percentage dropped to 62 percent, or a 0.6 percent reduction in primary aluminium demand growth rate per year (ICF, 1999). In the three largest sectors for aluminium (transportation, packaging, and construction), potential for using recycled aluminium exists in virtually every application. Recent years have seen major developments in some countries, especially in the recycling of aluminium beverage cans.

Recycling is an important consideration in the context of energy consumption in the aluminium industry since the recycling of scrap aluminium requires only about 5 to 8 percent of the energy needed to produce virgin aluminium from bauxite ore. The trend toward increased recycling is favourable in terms of future industry energy

usage and, consequently, GHG emission reductions.

Soderberg technology is being replaced by Prebake technology. Soderberg cells are less efficient than prebake cells in terms of emissions capture, particularly with respect to the exposure of workers to hydrocarbons. As environmental regulations have become more stringent over time, Soderberg cells have been replaced by prebake cells. In addition to environmental concerns, smelter economics have led to a shift away from Soderberg technology. Older facilities using Soderberg technology were for the most part small in terms of overall capacity.

As time and technology have progressed, the economic dictates of new smelters have tended toward larger minimum capacities to ensure economic feasibility. Today, the minimum economic size for the majority of new green-field smelters is from 160,000 to 240,000 tonnes per year. Such facilities use prebake technology at electric current levels from 160 kA to over 300 kA. No new Soderberg plants are being constructed.

Location of new smelting capacity is driven by the availability of low priced electric power. Electricity is the feedstock of the primary production process, accounting for a significant portion of the cost of production. As a result, smelters are usually located in areas where electricity is available, reliable, and inexpensive. New primary aluminium smelting capacity is expected in less developed nations with relatively low priced electric power and labour. This expectation is borne by evidence that the focus of most new primary aluminium plants are in countries like China, India, and Mozambique.

3. GHG Emissions Inventory

An inventory of GHG emissions from the aluminium industry is a prerequisite for evaluating the feasibility and cost-effectiveness of mitigation strategies and emission reduction technologies. This chapter presents a comprehensive inventory of GHG emissions for the global aluminium industry for 1990 and 1995. The base year for the analysis is 1990, which is the base year of the United Nations Framework Convention on Climate Change (UNFCCC).

3.1 Overview of Methodology

For any given year, an inventory of global GHG emissions from the aluminium industry is estimated as the sum of the product of emission factors (e.g., kg CO₂/tonne aluminium) and production (e.g., tonnes of aluminium) for each GHG, for each technology type, for each stage in the process, and for each region. Mathematically, this is expressed as:

$$Emissions_{r,s,tt,g} = \sum_r \sum_s \sum_{tt} \sum_g (Production_{r,s,tt} \times EmissionsFactor_{r,s,tt,g})$$

where:

r = *Region*. The regions for this analysis are North America, Western Europe, Eastern Europe and Former Soviet Union, North Africa and Middle East, Asia, Central and South America, Sub-Saharan Africa, and Australasia.

s = *Stage of Process*. The stages of production are bauxite mining, alumina refining, primary and secondary

production. The primary production process includes anode production, smelting, and primary ingot casting. The secondary production process includes scrap pretreatment, melting, and refining. GHG emissions associated with transportation are excluded (e.g., transporting ore to refinery, transporting alumina to smelters, collection of scrap metal). Additionally, downstream activities, such as the replacement of steel with aluminium in automobiles, which leads to reduced GHG emissions due to increased fuel efficiency, are also excluded from this analysis (see Exhibit 8).

tt = *Technology-Type*. The technology-type groupings are used to reflect the range of energy use and emissions within technologies for a given process. For alumina refining, two technology-types are included: rotary kiln and fluidised bed calcination. Five technology-types are used to characterise primary production: HSS, VSS, SWPB, CWPB, and PFPB. Finally, for secondary production, two technology-types are used: new scrap and old-scrap.

g = *GHG*. GHG emissions include CO₂ emissions generated from combustion at the fossil fuel plants that generate energy used for each stage of the process, process related CO₂ emissions from the consumption of the carbon anode in the primary production process, and PFC emissions generated during brief upset conditions known as anode effects in the primary production process.

Based on the framework described above, emissions were estimated as follows:

Step 1. Estimate Production by Technology-Type, by Region. For each region, production levels are estimated by technology type for each stage in the process. For the stages in the primary production process, plant level data for bauxite mines, alumina refineries, and aluminium smelters were used. For the secondary production process, data were compiled at the country level and aggregated by region and technology-type.

Step 2. Develop Emission Factors by Technology-Type, by Region. Emission factors were estimated for both energy-related CO₂ emissions, process-related CO₂ emissions and process-related PFC emissions as follows:

Energy-related CO₂ emission factors. The starting point for developing of energy-related CO₂ emission factors is the compilation of energy intensity (energy consumed per unit product) data for each technology-type for each stage in the process for each region. Energy intensity by fuel type (e.g., Btu/tonne) was multiplied by CO₂ emission factors by fuel type (e.g., CO₂/Btu) to calculate energy-related CO₂ emission factors (e.g., CO₂/tonne). For electricity, the fuel or resource used to generate electricity is the most important factor influencing energy-related CO₂ emissions. Weighted average electricity emission factors were developed using regional fuel mix data.

Process-related CO₂ emission factors. The only process-related CO₂ emissions are those that result from the consumption of the carbon anode during electrolytic reduction in the primary production process. No process-related emissions are associated with bauxite mining, alumina refining or secondary production.

Process-related PFC emission factors. The primary production process is the only

source of PFC emissions. PFC emission factors for CF₄ and C₂F₆ were estimated using an IPCC recommended methodology that proposes a linear least squares relationship between PFC emission factors and anode effect minutes.

Step 3. Estimate Regional and Global GHG Emissions. For each region, stage of process, technology type, and GHG, emissions are estimated by multiplying technology-specific emission factors by appropriate production data. Aggregate regional emission estimates will result from an aggregation of emissions from all stages, all technologies, and all GHGs in a given region. Emissions are aggregated from all regions to estimate global GHG emissions for the industry.

3.2 Production

Production data for the primary stages - bauxite mining, alumina refining, and primary production - were based on detailed plant-level statistics. Data on each bauxite mine, alumina refinery and aluminium smelter were compiled from leading industry experts, up-to-date published industry data, and information gained from ICF's operations within the aluminium industry.¹⁰

The basic data elements for an individual plant include: region, country, plant name, location, vintage, 1990 and 1995 production, capacity, and technology-type. For each year, the plant level data were aggregated by region and technology-type for the primary production stages (see Exhibit 9).

¹⁰ Data sources for plant level data include Anthony Bird Associates, James King, CRU International, and ICF. The IPAI, European Aluminium Association and the US Aluminium Association were the primary data sources for country and regional level statistics.

Exhibit 8. GHG Impact of Increased Aluminium Use in the Transportation Sector

Discussion of GHG emissions in the aluminium industry typically focuses on the GHG emissions associated with its production in electrolytic cells. However, using aluminium to produce lightweight products can have an impact on GHG emissions as well.

The International Primary Aluminium Institute (IPAI) has released a report in which the net effect of substituting aluminium for steel in automobile parts is estimated (IPAI Life Cycle Working Committee, 1999). Using a typical 1995 mid-size car as a model, it was estimated that use of aluminium in place of steel had reduced the weight of the car by 100kg, owing to the lower density of aluminium. The decrease in automobile weight increases fuel efficiency which, over the lifetime of the automobile (estimated at 120,000 miles), amounts to a reduction in GHG emissions of 25.3 kg of CO₂-E per kilogram of aluminium. After factoring in CO₂-E emissions associated with the production of aluminium vs. steel parts, a net reduction of 22.2 kg of CO₂-E per kilogram of aluminium was estimated.

In the IPAI study, a number of variables had to be estimated, such as the reduction in automobile weight per kilogram of aluminium used, the number of litres of fuel saved per 100 km driven per 100 kg of weight reduction, etc. For each variable a range was chosen based upon multiple, independent data sources. The study's calculation of 22.2 kg of CO₂-E emissions reduced per kilogram of aluminium was based upon variables that were set near the middle of their ranges. Using range endpoints in the calculations, the most conservative and most optimistic emissions savings estimates were 4.0 kg and 51.2 kg of CO₂-E per kilogram of aluminium used, respectively.

A highly significant aspect of the IPAI study is the fact that over 70% of automotive aluminium for the 1995 model year came from recycled sources. The recycling of aluminium uses much less energy than primary production, and so the IPAI study used values of "CO₂-E emissions from automotive aluminium production" in its calculations that were much lower than if the parts were made from primary aluminium. Thus, the study's results would support further substitution of aluminium for steel only when the parts could be manufactured with a high percentage of recycled aluminium. John Green, a technology expert at the U.S. Aluminum Association, has argued that the recent, rapid growth in the secondary aluminium industry will ensure that a high percentage of recycled aluminium continues to be incorporated into new vehicles (Green, 1999).

The increased use of aluminium in place of steel (or other metals) in vehicles needs to be justified at the level of individual parts, and the decisions need to account for the full life cycle impacts associated with the substitution. Important determining factors will be the amount of recycled aluminium that can be incorporated into a part and the weight reduction brought about by substitution, both of which will vary depending upon structural requirements. The life cycle analysis presented in the IPAI study suggests that aluminium lightweighting has already produced some net benefits, and that additional benefits in the form of reduced CO₂-E emissions are possible.

Exhibit 9. Production by Stage of Process by Technology-Type by Region: 1990 and 1995

(Data are in '000 tonnes of product or % of regional total by technology-type)

Year: 1990

Region	Bauxite Mining	Alumina Refining			Primary Production					Secondary Production			
	('000 t)	('000 t)	% by Tech-Type		('000 t)	% by Tech-Type					('000 t)	% by Tech-Type	
	Total	Total	Fluidised Bed	Rotary	Total	CWPB	HSS	PFPB	SWPB	VSS	Total	New Scrap	Old Scrap
Asia	10,539	3,733	78%	22%	1,146	15%	9%	46%	0%	30%	1,361	59%	41%
Australasia	44,990	11,000	67%	33%	1,540	44%	0%	49%	7%	0%	38	56%	44%
Central and South America	29,475	7,170	89%	11%	1,705	51%	3%	19%	11%	16%	166	46%	54%
Eastern Europe & FSU	12,755	5,387	12%	88%	3,654	0%	10%	13%	19%	58%	0	0%	0%
North Africa & Middle East	93	0	0%	0%	367	35%	0%	39%	0%	26%	9	50%	50%
North America	550	5,550	72%	28%	5,700	27%	7%	43%	7%	16%	2,477	37%	63%
Sub-Saharan Africa	17,984	640	0%	100%	245	43%	0%	0%	38%	19%	41	60%	40%
Western Europe	6,324	5,390	65%	35%	3,850	16%	2%	36%	28%	18%	1,930	72%	28%
Total	122,710	38,870	64%	36%	18,207	22%	5%	33%	14%	25%	6,021	54%	46%

Year: 1995

Region	Bauxite Mining	Alumina Refining			Primary Production					Secondary Production			
	('000 t)	('000 t)	% by Tech-Type		('000 t)	% by Tech-Type					('000 t)	% by Tech-Type	
	Total	Total	Fluidised Bed	Rotary	Total	CWPB	HSS	PFPB	SWPB	VSS	Total	New Scrap	Old Scrap
Asia	12,888	3,863	78%	22%	1,594	20%	9%	43%	0%	28%	1,286	59%	41%
Australasia	48,332	12,785	67%	33%	1,566	40%	0%	53%	6%	0%	46	56%	44%
Central and South America	38,420	8,110	89%	11%	1,998	46%	2%	17%	20%	14%	288	46%	54%
Eastern Europe & FSU	9,313	4,512	12%	88%	4,992	0%	8%	15%	13%	63%	107	0%	0%
North Africa & Middle East	100	0	0%	0%	378	35%	0%	48%	0%	17%	7	50%	50%
North America	111	4,770	72%	28%	5,606	24%	6%	49%	6%	15%	3,285	37%	63%
Sub-Saharan Africa	19,877	630	0%	100%	253	43%	0%	0%	38%	19%	46	60%	40%
Western Europe	2,040	4,118	65%	35%	3,284	4%	0%	62%	18%	16%	2,335	72%	28%
Total	131,081	38,788	66%	34%	19,671	18%	5%	39%	11%	27%	7,401	52%	48%

Note: Technology definitions are as follows: HSS = Horizontal Stud Soderberg; VSS = Vertical Stud Soderberg; CWPB = Center Worked Prebake; PFPB = Point Feed Prebake; SWPB = Side Worked Prebake

As shown in Exhibit 9, global bauxite production increased from 123 to 131 million tonnes from 1990 to 1995. Australasia was the largest producer of bauxite in 1990 and 1995 with 37 percent of the world's production in both years. Central and South America was the second largest producer, with 24 and 29 percent of world production in 1990 and 1995, respectively.

Global alumina production remained relatively constant at 38 million tonnes from 1990 to 1995. The geographic distribution of alumina and bauxite production is similar (the exception is North America, which is an importer of bauxite and a producer of alumina). Australasia was the largest producer of alumina accounting for 28 and 33 percent of the world's production in 1990 and 1995, respectively. Central and South America were the next largest producers accounting for 18 and 21 percent of the world's production in 1990 and 1995, respectively.

Over 60 percent of world alumina is produced using the fluidised bed kiln, which consumes about one third the fuel required by the rotary kiln to produce the same amount of alumina. With the exception of Sub-Saharan Africa and Eastern Europe & Former Soviet Union, a majority of alumina production in each region uses the fluidised bed kiln.

Global primary production increased from 18.2 million tonnes to 19.6 million tonnes from 1990 to 1995, an increase of about eight percent. North America was the largest producer accounting for 31 and 29 percent of the world's production in 1990 and 1995. The geographic distribution of production changed between 1990 and 1995. Production declined in North America and Western Europe, whereas production increased significantly in Eastern Europe & the Former Soviet Union. The shift in production is an outcome of the adjustments the world aluminium industry underwent in the early 1990s to integrate Russia into the

world market. The collapse of the Soviet Union in 1989 – 1990 and subsequent decline in metal demand, particularly in the military and aerospace sectors, led to excess metal from Russia and the Commonwealth of Independent States (CIS) flooding the world market. There is a general industry consensus that the market imbalance of the early 1990s has been corrected - now that Russian aluminium has been integrated into the world market.

Over half of existing primary aluminium is produced using the more efficient PFPB and CWPB technology. These technologies are found mostly in developed nations, where environmental regulations have driven the industry away from Soderberg to the cleaner prebake technology. The less efficient VSS technology is still used by Asia and Eastern Europe & Former Soviet Union. Consequently, these regions provide significant opportunity for technological improvement and GHG emission reductions.

Secondary production data were compiled at the country level and then aggregated by region. For each region, the relative share of new and old scrap was determined based on industry knowledge. The primary source of country level secondary production data was the U.S. Aluminium Association's publication Aluminium Statistical Review (AA, 1997). This publication is considered the best source for data as it uses consistent definitions for the various types of scrap when developing the estimates.

Global secondary production rose from 6 million tonnes in 1990 to 7.4 million tonnes in 1995, with most production occurring in North America, Western Europe, and Asia (Japan). The increase in global secondary production is driven by increases in North American and Western European production. In recent years, these regions have seen significant growth in the use of aluminium in the packaging sector, and have relatively high rates of recovery of used beverage cans.

As indicated previously, secondary production is most prevalent in areas with a past history of high aluminium consumption. A consistent and abundant source of scrap provides the incentive for developing a scrap collection and reuse infrastructure. Not surprisingly, old scrap constitutes a significant portion of secondary production in these areas. In all other regions, most secondary aluminium is produced from new scrap.

3.3 Emission Factors

Greenhouse gas emissions from the aluminium production process result from three sources: (1) energy-related CO₂ emissions generated from combustion of fossil fuels for energy used in the production process; (2) process-related CO₂ emissions from carbon anode consumption in the electrolytic cell; and (3) process-related PFC emissions generated during anode effects in the electrolytic cell.

Occasionally, sulphur hexafluoride (SF₆), a potent GHG, is also used by the aluminium industry as a degassing agent in specialised applications. In these cases, it is mixed with argon and nitrogen and blown through molten aluminium as it cools. This practice is not very common. For example, it is not prevalent in any smelter in the U.S. Where it does occur in other countries, the concentration of SF₆ in the mixture is small, and it is believed that nearly all SF₆ is destroyed in the process. Consequently, the three GHG sources described above are the focus of this study.

3.3.1 Energy-Related CO₂

Energy-related CO₂ emissions occur at each stage of aluminium production as a product of the fossil fuels combusted to generate energy. The fuel or resource used to generate energy for electrolytic reduction in the primary aluminium production process is the most important factor influencing total CO₂ emissions from aluminium production.

Energy-related CO₂ emission factors for each fuel type are estimated by multiplying energy intensity (i.e., energy consumption per unit product) by fuel type by an CO₂ emission factor for each fuel type. CO₂ emission factors for each fuel type for a given product are aggregated across fuel types to provide an overall CO₂ emission factor. This can be expressed as:

$$Emissions\ Factor_p\left(\frac{CO_2}{ton}\right) = \sum_f Energy\ Intensity_{p,f}\left(\frac{mmbtu}{ton}\right) \times Emissions\ Factor_f\left(\frac{CO_2}{mmbtu}\right)$$

where:

p = *Product*. The products for each stage of the process are bauxite, alumina, primary aluminium, and secondary aluminium. Within each stage of the process, the unit of analysis is product by technology-type.

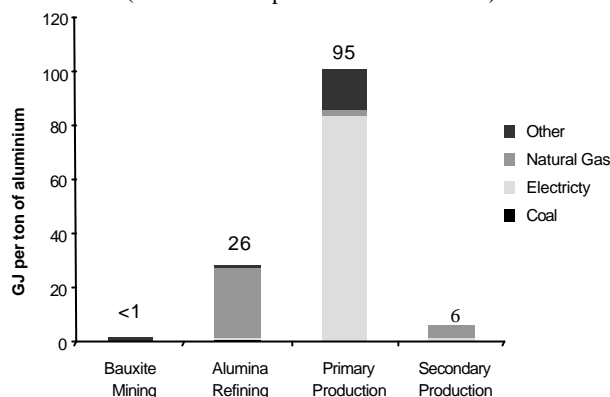
f = *Fuel type*. The following fuel types were considered: coal, natural gas, electricity, and other. The “other” category includes gasoline, propane, distillate oil and residual oil.

The processes used to estimate energy intensity by product by fuel type, CO₂ emission factors by fuel type, and CO₂ emission factors by product are described below.

Energy Intensity by Product by Fuel Type

The process of aluminium production is extremely energy intensive. Energy consumption by fuel type per unit of aluminium produced based on data from a recent survey of North American producers is shown in Exhibit 10 (AA, 1998a and USDOE/EIA, 1997). As shown in the exhibit, on a unit basis, primary aluminium production is the most energy-intensive

Exhibit 10. Per Unit Energy Consumption by Stage of Process
(Data are in GJ per tonne of aluminium)



Note It is assumed that about three tonnes of bauxite is required to produce one tonne of alumina and about two tonnes of alumina is required to produce one tonne of primary aluminium. Primary production estimates include energy for anode production, smelting, and ingot casting. Secondary production estimates include energy for scrap pretreatment, melting/refining and casting. *Source:* AA, 1998a and USDOE/EIA, 1997.

stage, requiring about 95 GJ per tonne of aluminium.

A majority of the energy used is for the electrolytic reduction of alumina to aluminium. Energy consumption in the electrolytic reduction stage can vary from 13 kWh/kg of aluminium for the state-of-the-art reduction cells to 19 kWh/kg of aluminium for older, inefficient cells. The theoretical minimum energy consumption for electrolysis is 6.4 kWh/kg of aluminium. About 45 percent of the energy input is lost as heat. Approximately half this heat is lost through the pot shell and the remainder is lost through the anodes. Specific heat loss mechanisms include radiation, thermal conductance through electrode connections and tapped metal (USDOE/EIA, 1997).

Secondary production energy intensity includes the energy associated with scrap pretreatment and melting/refining, and casting. Scrap collection and sorting related energy consumption are not included. Energy consumption for collection and sorting varies significantly depending on the product type and its end-use. For example, energy consumption for non-UBC old scrap collected by scrap dealers is primarily transportation related, which may vary significantly. Consequently, this report focuses on the energy use and related

emissions from pretreatment, melting/refining, and casting only. The advantages of secondary production in reducing the energy intensity associated with overall aluminium production are apparent as, on average, secondary production requires six percent of the energy required to produce primary aluminium. Huglen and Kvande also estimate the energy intensity for secondary production to be five to eight percent of the energy intensity for primary metal (Huglen and Kvande, 1994).

Exhibit 10 also shows the types of fuel consumed at each stage in the process. Electricity required for the reduction of alumina to aluminium is the major fuel type consumed in the primary production process, accounting for over 80 percent of total per unit energy use. Natural gas is the primary fuel used in alumina refineries, accounting for 95 percent of total per unit energy use.

The data shown in Exhibit 10 represent a composite energy intensity for each stage in the process across all technology types. As previously indicated, there is significant variation in energy requirements by technology type. The various technologies are discussed below.

Primary production technologies. According to Richards (1997), per unit electricity consumption is 13.5 kWh/kg of aluminium for the modern prebake cells (e.g., PFBP), 15 kWh/kg for other prebake cells (e.g., CWPB, SWPB), 15.9 kWh/kg for VSS cells, and 16.1 kWh/kg for HSS cells.

Alumina production technologies. The energy intensity for the fluidised bed kiln is a third less than the energy intensity for the less efficient rotary kiln.

Secondary production. The two technology-types defined for secondary production are new and old scrap. New scrap requires less energy per unit of aluminium produced than old scrap because little or no pretreatment is usually required for new scrap.

The primary source of energy intensity data for alumina refining and primary aluminium production for each region (and fuel type) was the International Primary Aluminium Institute (IPAI) publication entitled *IPAI Statistical Summary* (IPAI, 1998). The data included in this publication were based on surveys of the primary aluminium or alumina producers in IPAI member countries. The IPAI statistics by region were used along with the technology-type characteristics described above to arrive at energy intensity levels by fuel type and by technology type for each region. Data on total energy intensity (across fuel types) by technology-type for each region are presented in the Annex of this report.

CO₂ Emission Factors by Fuel Type

For all fuel types except electricity, the emission factor by fuel type was taken from the IPCC's *Revised 1996 Guidelines for National Greenhouse Gas Inventories* (see Annex). For electricity, the fuel or resource used to generate electricity is the most important factor influencing energy-related CO₂ emissions. Coal-burning power stations emit approximately one kg of CO₂ per kWh, gas-fired generators will emit approximately 0.5 kg CO₂ per kWh, and

hydroelectric generation has no associated CO₂ emissions. The current average electricity requirement for smelting purposes is about 15 kWh per tonne of aluminium. Therefore, CO₂ emissions per tonne of aluminium can range from approximately 15 tonnes CO₂ per tonne of aluminium if coal is used, to approximately 7.5 tonnes CO₂ per tonne of aluminium if gas is used, or zero if hydroelectricity is used. If the aluminium smelter is purchasing electricity from the grid, the electricity is likely to be generated from a mix of resources.

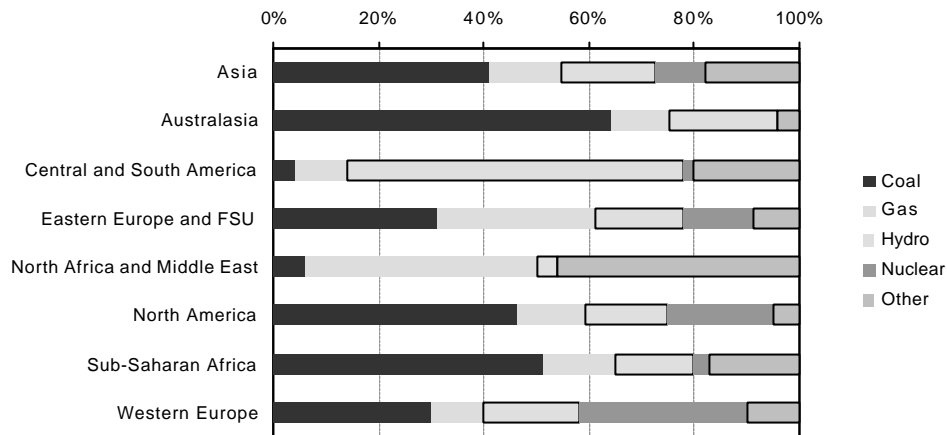
To reflect the mix of resources used to generate electricity, an emission factor is estimated for each region. Electricity emission factors can be based on: (1) regional-average fuel mix supplied to the grid; or (2) industry-average fuel mix, which is heavily dependent on hydro electricity.

The choice of electricity emission factors will affect the resulting GHG emission estimates, as well as the GHG emission reduction potential of the aluminium industry. For this study, the regional-average fuel mix is used to estimate the global GHG reduction potential of the aluminium industry.

When regional average emission factors are used, the emission reduction potential of demand reductions by the aluminium industry are considered in the broader scheme of the region's electricity supply. Thus, the estimates account for the potential emission reductions from displacing fossil fuel plants that supply electricity to the regional grid. For example, reduced electricity demand from an aluminium smelter that is supplied by a hydroelectric plant would result in excess hydroelectricity. This electricity would displace electricity supplied from base-load plants that are connected to the grid and have higher marginal costs. This displaced electricity is likely to be generated from fossil fuels, and the displacement will result in GHG emission reductions.

Exhibit 11. Regional Fuel Mix: 1995

(Data are % of total fuel consumption by region, by fuel type)



Source: IEA World Energy Outlook (IEA, 1998)

The use of industry-average emission factors would reflect the emissions associated with the energy sources that currently supply power to the aluminium industry. This fuel mix is relatively less carbon intensive than the average regional fuel mix. One could argue that an industry-average emission factor more realistically estimates current and future emission levels. Electricity supplied to the aluminium industry would not displace fossil fuel generated electricity because: (1) aluminium smelters are generally located in remote areas (e.g., Siberia), often with no or limited capacity for transfer of the generated electricity to the regional grid (captive generation) and (2) any retrofits at a smelter would lead to an increase in production of aluminium and not a reduction in electricity demand.¹¹ While both points depict the current situation regarding aluminium industry electricity usage in some areas, the future situation is uncertain.

Future economics or policy may change the current operations and dispatch of electricity. For example, under a

¹¹ The increase in production efficiency at a given smelter (also known as capacity creep) would reduce the need for additional smelting capacity, globally assuming a fixed demand for aluminium. The demand for electricity by the global aluminium industry would therefore be reduced.

deregulated electricity market, an aluminium producer with captive hydroelectric generation may find it economically advantageous to sell a portion of its captive hydropower resource when spot market electricity prices are high. Similarly, a future market for GHG emissions reduction credits could lead to a situation, where the opportunity cost of aluminium production in terms of the value of emission credits exceeds the value of aluminium produced. In such cases, the economically beneficial option for the aluminium producer would be to offset aluminium production (and therefore total electricity demand) for alternative, more value added opportunities. In another scenario, policymakers seeking the least cost GHG abatement strategy may decide to re-deploy the hydroelectric resources of the nation to displace fossil-based generation. Policy makers could mandate electricity demand reductions from given industries to free up hydroelectricity to displace fossil-based generation.¹²

Because the objective of this study is to evaluate the potential and cost of reducing GHG emissions from the aluminium

¹² There is historic precedence of legislation mandating energy demand reductions: fuel-efficiency standards for automobiles set by the U.S. in response to the energy crisis in the 1970s.

industry, regional emission factors are used. Also, the use of regional emissions factors is required by IEA GHG to ensure consistency in estimation methods across its industry studies. Regional fuel mix data were taken from the International Energy Agency's *World Energy Outlook* (IEA, 1998). The fuel mix by region for 1990 and 1995 are shown in Exhibit 11. The derived electricity generation emission factors for each region are presented in the Annex of this report.

CO₂ Emission Factors by Product

Energy-related CO₂ emission factors for each fuel type are estimated by multiplying energy intensity (i.e., energy consumption per unit product) by fuel type by an CO₂ emission factor for each fuel type. CO₂ emission factors for each fuel type for a given product are aggregated across fuel types to provide an overall CO₂ emission factor.

The estimated CO₂ emission factors for each stage of the process by technology-type are shown for each region in Exhibit 12. Across the stages of the process (and technology-types within each stage), the CO₂ emission factors reflect the differences in energy intensity, with primary production having the highest energy intensity and bauxite mining the lowest.

Within the primary production process, the energy-related CO₂ emission factors for PFPB for a given region are lower than the energy-related CO₂ emission factors for other cell technology types. At the alumina refining stage, the more energy-intensive rotary kiln technology has higher energy-related CO₂ emission factors than fluidised bed technology for a given region. The changes in emission factors between 1990 to 1995 reflect changes in both energy intensity and fuel mix.

Examining the energy-related CO₂ emission factors across regions indicates the impact of the fuel or resource used to generate electricity. Because the primary production

stage is the most electricity intensive, the variation in emission factors across regions is greatest at this stage. As shown in Exhibit 12, the 1990 emission factor for primary production varies from four to 12 tonnes of CO₂ per tonne of aluminium, a difference of over 200 percent. The emission factors for Central and South America are lower than all regions because the primary resource used is hydroelectricity.

3.3.2 Process-Related CO₂

The only process-related CO₂ emissions are those that result from the consumption of the carbon anode during electrolytic reduction in the primary production process. CO₂ is emitted during the aluminium smelting process when Al₂O₃ is reduced to aluminium using the Hall-Héroult reduction process. During normal electrolysis, the majority of CO₂ is produced as a product of the chemical reaction between the carbon anode and the alumina.

The IPCC, in its *Revised 1996 Guidelines for National Greenhouse Gas Inventories*, proposes that process-related CO₂ emission factors, measured in tonnes of CO₂ per tonne of aluminium produced, range from 1.5 for prebake cell technology to 1.8 for Soderberg cell technology (IPCC, 1997). These values were used for 1995 in this analysis. To compute the 1990 values, it was assumed that emission factors decline at 0.5 percent per year.

The estimates proposed by IPCC agree well with other estimates reported in the literature. The *Life Cycle Inventory Report for the North American Aluminium Industry* reports an average emission factor (across cell types) of 1.52 tonnes of CO₂ per tonne of aluminium produced with a standard deviation of 12 percent (AA, 1998a). Huglen and Kvande estimate 1.5 tonnes of CO₂ per tonne of aluminium produced for the best performing cells and an average of 1.74 tonnes of CO₂ per tonne of aluminium produced across all cells (Huglen and Kvande, 1994).

Exhibit 12. Energy-Related CO₂ Emission Factors: 1990 and 1995

(Data are in tonnes of CO₂/tonne of product)

Year: 1990

Region	Bauxite Mining	Alumina Refining		Primary Production					Secondary Production	
		Fluidised Bed	Rotary	CWPB	HSS	PFPB	SWPB	VSS	New Scrap	Old Scrap
Asia	0.01	1.0	2.9	9.6	9.8	8.7	9.4	10.2	0.48	0.58
Australasia	0.01	0.8	2.5	11.4	11.4	10.4	10.9	11.8	0.48	0.58
Central and South America	0.01	0.9	2.7	4.7	4.7	4.3	4.4	4.8	0.48	0.58
Eastern Europe & FSU	0.01	1.1	3.5	9.6	9.6	8.7	9.0	9.6	0.48	0.58
North Africa & Middle East	0.01	0.7	2.1	10.5	10.5	9.5	9.9	10.5	0.48	0.58
North America	0.01	1.6	5.0	10.0	10.0	9.7	9.7	10.1	0.48	0.58
Sub-Saharan Africa	0.01	0.7	2.1	11.7	11.7	10.7	11.1	11.7	0.48	0.58
Western Europe	0.01	1.1	3.4	8.0	8.0	7.3	7.5	8.0	0.48	0.58
Average	0.01	1.0	3.0	9.4	9.5	8.7	9.0	9.6	0.48	0.58

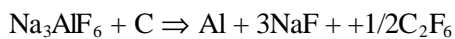
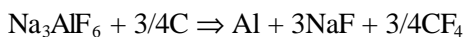
Year: 1995

Region	Bauxite Mining	Alumina Refining		Primary Production					Secondary Production	
		Fluidised Bed	Rotary	CWPB	HSS	PFPB	SWPB	VSS	New Scrap	Old Scrap
Asia	0.01	0.9	2.7	10.1	10.5	10.1	10.1	10.1	0.47	0.57
Australasia	0.01	0.8	2.4	11.4	12.4	11.4	11.4	11.4	0.47	0.57
Central and South America	0.01	1.0	2.9	4.2	4.4	4.2	4.2	4.2	0.47	0.57
Eastern Europe & FSU	0.01	1.1	3.5	8.7	9.3	8.7	8.7	8.7	0.47	0.57
North Africa & Middle East	0.01	0.7	2.1	10.3	10.9	10.3	10.3	10.3	0.47	0.57
North America	0.01	1.1	3.6	9.3	9.5	9.3	9.3	9.6	0.47	0.57
Sub-Saharan Africa	0.01	0.7	2.1	11.5	12.1	11.5	11.5	11.5	0.47	0.57
Western Europe	0.01	1.1	3.4	7.0	7.5	7.0	7.0	7.0	0.47	0.57
Average	0.01	0.9	2.8	9.1	9.6	9.1	9.1	9.1	0.47	0.57

Note: Technology definitions are as follows: HSS = Horizontal Stud Soderberg; VSS = Vertical Stud Soderberg; CWPB = Center Worked Prebake; PFPB = Point Feed Prebake; SWPB = Side Worked Prebake

3.3.3 Process-Related PFCs

When the aluminium electrolytic cell is operating normally, no measurable amounts of PFCs are produced. Two PFCs, tetrafluoromethane (CF₄) and hexa-fluoroethane (C₂F₆) are formed as intermittent by-products during operational disturbances called anode effects (AE) during the production of primary aluminium. The GWP of these compounds is relatively high. When the warming is considered over a 100-year period, one tonne of CF₄ and C₂F₆ emissions is equivalent to approximately 6,500 and 9,200 tonnes, respectively, of CO₂ emissions (IPCC, 1996). These conditions occur when the dissolved alumina oxide content in the electrolytic bath falls too low and the electrolytic bath (Na₃AlF₆) itself enters into the electrolytic reactions. During the anode effect, cell voltage increases rapidly, allowing the fluoride in the electrolytic bath to react with the carbon in the anode producing two PFCs, CF₄ and C₂F₆, due to the following reactions:



PFCs are not absorbed on the alumina and are therefore not removed by the present dry scrubbing equipment. The primary PFC emission pathway is the exhaust duct collection system, which removes gases from the pots. At most smelters, the exhaust ducts from individual pots combine into larger exhaust ducts, which typically run the length of the potroom and are several meters in diameter and hundreds of meters long. Large fans draw the exhaust through the ducts and move the exhaust gases to treatment systems that remove various constituents. Fugitive PFC emissions result when the pot hooding efficiency and operating conditions of the collection system result in less than 100 percent capture from the pot. The fugitive emissions are transported out the roof by convection or, in the case of a potroom equipped with a

secondary control system that employs roof scrubbers, by a powered ventilation fan.

In general, the magnitude of emissions for a given level of production depends on the frequency and duration of these anode effects. The more frequent and long lasting the anode effects, the greater the emissions. The methodology used to develop PFC emission factors in this study uses a linear least squares relationship between anode effect minutes per cell-day and PFC emissions, which is expressed as:

$$\text{kg PFC/tonne of Al} = \text{Slope} \times \text{AE Minutes/cell-day}$$

There is significant variation in these parameters across technology-types, and consequently AE minutes/cell-day vary across technology-types.

This relationship was first expressed by workers at Hydro Aluminium and Alcoa based on field measurements at their prebake facilities. Both companies independently arrived at a slope of 0.12 for CF₄ (IPAI, 1996). Recent field measurements in the U.S. also indicate a slope of 0.12 for CF₄ for prebake cells (Leber et al., 1998; Bouzat et al., 1996). At a recent IPCC meeting aimed at improving inventory methods, the methodology outlined above was proposed as the "good practice" method for PFC emission inventory preparation (IPCC, 1999).

The primary source of AE minutes/cell-day by technology-type data for 1990 and 1995 was the IPAI (IPAI, 1999). Slope coefficients by technology-type were taken from the IPCC report "Good Practice in Inventory Preparation for Industrial Processes and the New Gases" (IPCC, 1999). Data on the slope coefficients and AE minutes/cell-day by technology-type for each region are presented in the Annex of this report.

Exhibit 13 presents the estimated PFC emission factors weighted by production and

Exhibit 13. Production Weighted PFC Emission Factors: 1990 and 1995

Region	t CO ₂ -E/tonne Al ^a		kg CF ₄ /tonne Al		kg C ₂ F ₆ /tonne Al		C ₂ F ₆ :CF ₄	
	1990	1995	1990	1995	1990	1995	1990	1995
Asia	3.35	1.99	0.49	0.30	0.02	0.01	0.04	0.03
Australasia	3.66	1.87	0.50	0.26	0.04	0.02	0.09	0.07
Central and South America	4.74	3.83	0.64	0.51	0.06	0.05	0.09	0.10
Eastern Europe & FSU	6.42	4.08	0.87	0.57	0.08	0.04	0.10	0.07
North Africa & Middle East	3.28	1.56	0.47	0.23	0.02	0.01	0.04	0.02
North America	4.02	2.31	0.56	0.33	0.04	0.02	0.08	0.06
Sub-Saharan Africa	8.24	5.90	1.05	0.77	0.15	0.10	0.14	0.12
Western Europe	6.62	3.42	0.86	0.46	0.11	0.05	0.13	0.10
Total	5.05	3.08	0.68	0.43	0.07	0.03	0.10	0.08

a. Both CF₄ and C₂F₆ emissions are included. The GWPs used are 6,500 and 9,200 for CF₄ and C₂F₆, respectively.

Source: IPAI, 1999; IPCC, 1999

technology type for each region for 1990 and 1995. The emission factors are in tonnes of CO₂ equivalent per tonne of aluminium and in kg CF₄ and kg C₂F₆ per tonne of aluminium. As shown in the exhibit, the PFC emission factors are estimated to have decreased from 5.05 to 3.08 tonnes of CO₂-E per tonne of aluminium between 1990 and 1995, a reduction of 38 percent.

The reductions in PFC emission factors from 1990 to 1995 are a result of several factors, including industry-government emission reduction efforts in producer countries, the diffusion of modernised smelter technologies resulting from capital stock replacement, and the construction of state of the art facilities.

Industry-government partnerships have played a significant role in reducing PFC emissions. According to the USEPA report, as of November 1998, ten countries have undertaken industry-government initiatives to reduce PFC emissions from primary aluminium production: Australia, Bahrain, Brazil, Canada, France, Germany, New Zealand, Norway, United Kingdom, and the United States. These countries accounted for over 50 percent of global aluminium production in 1998 (USEPA, 1999).

Both industry and government have an interest in implementing PFC emission reduction measures because they not only reduce PFC and other greenhouse gas emissions, but can also improve process efficiency. The economic benefits of increased process efficiency are the primary motivations for industry to invest in emission reduction technologies. By participating in a government recognised program, the industry may claim credit for early actions taken to reduce emissions, so that later (lower) emission levels do not become their baseline levels.

3.4 GHG Emissions

Greenhouse gas emissions from the aluminium industry totalled 391 million tonnes of carbon dioxide equivalent (million tonnes CO₂-E) in 1990. In 1995, total aluminium industry GHG emissions were 364 million tonnes CO₂-E, a 7 percent decrease from 1990 levels. It is estimated that global emissions were about 35,000 million tonnes CO₂-E in 1995 (Harnisch et al, 1998). The aluminium industry, therefore, contributes 1 percent of total anthropogenic GHG emissions in 1995.

Exhibit 14 illustrates the relative contribution of the different stages of the aluminium production process to total 1990 and 1995 emissions. The primary production stage is the largest source of overall GHG emissions, accounting for 72 of total emissions in 1990 and 1995, respectively. Emissions from bauxite production and secondary production are negligible compared to emissions from the alumina refining and primary production stages. Secondary production contributed to one percent of total industry emissions while bauxite mining contributed 0.2 percent of total industry emissions.

Exhibit 14. Emissions by Stage of Process: 1990 and 1995

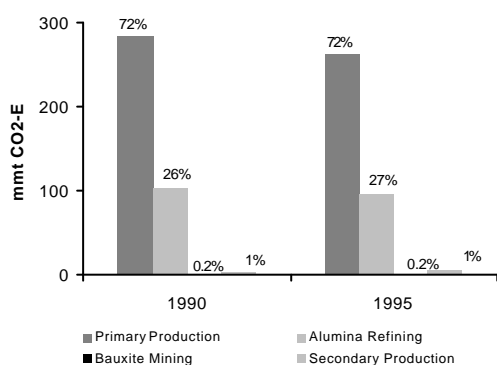
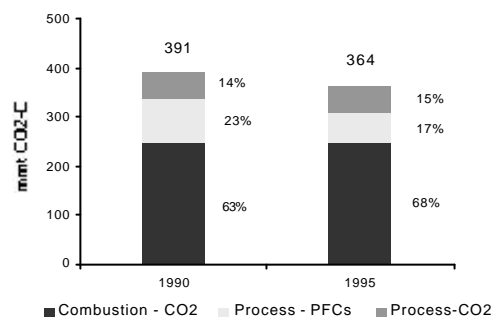


Exhibit 15 illustrates the relative contribution of the different sources of GHG emissions in 1990 and 1995. The largest source of CO₂ and overall GHG emissions from the global aluminium industry was fossil fuel combustion, which accounted for 68 percent in 1995. Emissions of PFCs and CO₂ from the primary production process accounted for 17 and 15 percent of 1995 emissions, respectively. While emissions of CO₂ from energy and the process remained relatively constant from 1990 to 1995, PFC emissions decreased 92 million tonnes of CO₂-E to 62 million tonnes of CO₂-E, a reduction of 33 percent. The decrease in total industry emissions from 1990 to 1995, therefore, is largely a result of reductions in PFC emissions.

Emissions by region and technology-type for each stage in the process are shown in Exhibit 17. North America was the largest emitter in 1990, accounting for 30 percent of industry GHG emissions. Eastern Europe & Former Soviet Union and Western Europe were the next largest, accounting for 22 and 19 percent of total emissions, respectively. In 1995, North America remained the largest emitter contributing 27 percent of total emissions, although its absolute emissions levels decreased from 89 to 75 million tonnes CO₂-E.

Exhibit 15. Emissions by GHG: 1990 and 1995



Between 1990 and 1995, Eastern Europe & Former Soviet Union's contribution to total emissions increased from 22 to 25 percent of total emissions. This trend is largely due to the shift in the geographic distribution of production between 1990 and 1995. Production declined in North America and Western Europe, relative to the Eastern Europe & the Former Soviet Union. This regional shift in production is an outcome of the adjustments the world aluminium industry underwent in the early 1990s to integrate Russia into the world market.¹³

Within the alumina refining process, rotary kilns account for over 60 percent of total emissions in both 1990 and 1995, while

¹³ The collapse of the Soviet Union in 1989 – 1990 and subsequent decline in metal demand, particularly in the military and aerospace sectors, led to excess metal from Russia and the Commonwealth of Independent States (CIS) flooding the world market.

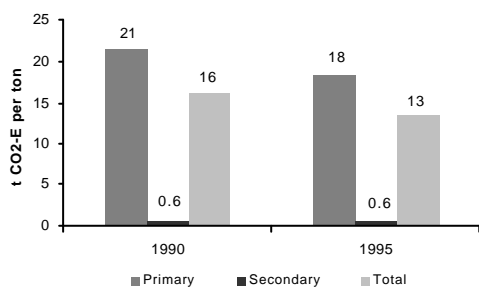
accounting for less than 40 percent of production.

Both the VSS and rotary kiln technology represent a significant portion of Eastern Europe & Former Soviet Union emissions. The replacement of these technologies with more efficient technologies presents a significant opportunity to reduce emissions, particularly in Eastern Europe & Former Soviet Union.

Exhibit 16 illustrates the impact of secondary production on the implied overall industry GHG emissions intensity.¹⁴ Emission intensity estimates were made for primary, secondary, and total aluminium production. The primary production emission intensity includes emissions from bauxite mining and alumina refining.

As shown in Exhibit 16, in 1990, producing one tonne of primary aluminium resulted in emissions of 21 tonnes CO₂-E, whereas producing a tonne of secondary aluminium resulted in emissions of 0.6 tonnes CO₂-E.

Exhibit 16. GHG Emission Intensity for Primary vs. Secondary Production



Overall industry emission intensity, which accounts for the relative share of primary and secondary production was 16 tonnes CO₂-E per tonne of aluminium in 1990. The increase in the share of secondary production of total aluminium supply (primary plus secondary production)

¹⁴ To calculate the implied emission intensity, the emission estimates were normalised by production (i.e., total emissions are divided by total production to calculate emissions per tonne of aluminium produced).

resulted in the overall industry emission intensity reducing to 13 tonnes CO₂-E per tonne of aluminium in 1995, a reduction of about 17 percent.

Exhibit 17. GHG Emissions by Region by Technology-Type: 1990 and 1995

(Data are in million tonnes CO₂-E or % of regional total by technology-type)

Year: 1990

Region	Total	Bauxite Mining	Alumina Refining				Primary Production					Secondary Production		
		mmt CO ₂ -E	mmt CO ₂ -E	% by Tech-Type		mmt CO ₂ -E	% by Tech-Type					mmt CO ₂ -E	% by Tech-Type	
		Total	Total	Fluidised Bed	Rotary	Total	CWPB	HSS	PFPB	SWPB	VSS	Total	New Scrap	Old Scrap
Asia	25	0.1	7	54%	46%	17	15%	11%	40%	0%	34%	0.8	55%	45%
Australasia	47	0.3	22	40%	60%	25	45%	0%	44%	11%	0%	0.0	52%	48%
Central and South America	30	0.2	11	74%	26%	19	46%	3%	14%	20%	17%	0.1	42%	58%
Eastern Europe & FSU	86	0.1	22	4%	96%	63	0%	9%	10%	27%	54%	0.0	0%	0%
North Africa & Middle East	6	0.0	0	0%	0%	6	36%	0%	35%	0%	29%	0.0	46%	54%
North America	117	0.0	27	46%	54%	89	26%	7%	38%	11%	18%	1.5	33%	67%
Sub-Saharan Africa	7	0.1	2	0%	100%	5	35%	0%	0%	49%	16%	0.0	56%	44%
Western Europe	75	0.0	14	38%	62%	60	14%	2%	26%	41%	17%	1.1	68%	32%
Total	391	0.8	104	37%	63%	283	20%	6%	27%	21%	25%	3.6	49%	51%

Year: 1995

Region	Total	Bauxite Mining	Alumina Refining				Primary Production					Secondary Production		
		mmt CO ₂ -E	mmt CO ₂ -E	% by Tech-Type		mmt CO ₂ -E	% by Tech-Type					mmt CO ₂ -E	% by Tech-Type	
		Total	Total	Fluidised Bed	Rotary	Total	CWPB	HSS	PFPB	SWPB	VSS	Total	New Scrap	Old Scrap
Asia	30	0.1	7	54%	46%	22	20%	10%	40%	0%	30%	0.7	55%	45%
Australasia	48	0.3	24	40%	60%	23	39%	0%	50%	10%	0%	0.0	52%	48%
Central and South America	32	0.2	13	74%	26%	19	35%	3%	12%	36%	14%	0.2	42%	58%
Eastern Europe & FSU	92	0.1	19	4%	96%	73	0%	8%	12%	20%	60%	0.1	24%	76%
North Africa & Middle East	5	0.0	0	0%	0%	5	35%	0%	46%	0%	20%	0.0	46%	54%
North America	100	0.0	23	46%	54%	75	23%	7%	44%	10%	16%	2.0	33%	67%
Sub-Saharan Africa	7	0.1	2	0%	100%	5	34%	0%	0%	50%	17%	0.0	56%	44%
Western Europe	51	0.0	10	38%	62%	39	3%	0%	50%	30%	16%	1.3	68%	32%
Total	364	0.8	97	39%	61%	262	16%	5%	33%	17%	28%	4.3	48%	52%

Note: Technology definitions are as follows: HSS = Horizontal Stud Soderberg; VSS = Vertical Stud Soderberg; CWPB = Center Worked Prebake; PFPB = Point Feed Prebake; SWPB = Side Worked Prebake

4. Identification and Assessment of Opportunities to Reduce GHG Emissions

This chapter identifies priority areas for GHG emission reductions and mitigation technologies and practices to address these priority areas. Because the aluminium life-cycle consists of a diverse set of emission sources and the number of potential mitigation options is very large, the assessment will focus on sources that are significant in terms of emissions and options that have significant potential for reducing emissions. For select options, an engineering and cost assessment is presented outlining the emission reduction potential, associated costs, and applicability.

4.1 Priority Areas for GHG Emission Reductions

Based on the emission inventory of GHG emissions for each stage and technology in the aluminium production life-cycle, priority areas for focusing the technology and cost assessment were identified. These areas encompass options that will replace the existing technologies, processes, as well as resources used to generate energy. Priority areas are as follows:

Find and use technologies that can reduce emissions at each stage of the Hall-Héroult process. The emission inventory in the previous chapter indicated that the stages of primary production (Hall-Héroult process) and alumina refining (Bayer process) were the largest sources of total 1995 emissions. In addition to energy-related CO₂ emissions, the Hall-Héroult process results in further emissions of CO₂, due to the consumption of the carbon anode, and PFC emissions, due to anode effects.

Reducing PFC emissions is an attractive mitigation option from an emissions and profitability standpoint as PFCs are high GWP gases whose generation represents inefficiency in the production process. The alumina refining process also offers significant potential for energy efficiency improvements. A majority of emissions at this stage occur during the calcination process. Replacement of rotary kiln technology with fluidised bed technology will reduce emissions significantly from this stage of the process.

Enhance primary aluminium product recovery and recycling. The GHG emissions per tonne of recycled aluminium is less than four percent of the GHG emissions per tonne of primary aluminium. As a result, the extent to which recycled aluminium contributes to the future supply will have a significant impact on future aluminium industry GHG emission levels.

Find alternative sources of aluminium or alternative production processes. The Hall-Héroult process of primary aluminium production is energy intensive. The electrolytic reduction of alumina to aluminium requires significant amounts of electricity, and the process itself is not energy efficient with electric losses on the order of 60 percent or more. An alternative, less energy and emission intensive production process to replace the Hall-Héroult process is desirable. Finding alternative sources of primary aluminium such as pulverised fly ash or minestone may also lead to reduced GHG emission rates.

Find alternatives to the fossil fuel based sources of energy. When fossil fuels are combusted for the mining and processing of the raw materials, the electrolytic reduction of alumina to aluminium, and the casting of the metal, CO₂ is emitted as a by-product of combustion. The fuel or resource used to generate electricity for electrolytic reduction is the most important factor influencing total CO₂ emissions from primary aluminium production. Reducing the amount of energy consumed from carbon-intensive fossil fuels provides an opportunity for reducing CO₂ emissions from aluminium production. This option is not specific to the aluminium industry. It is common to all processes that use energy generated from fossil fuel combustion.

Find and use technologies that can remove CO₂ from the exhaust gases. Process related CO₂ emissions result from the combustion of the carbon anode during electrolysis at the primary production stage of the process. Applying technologies that remove CO₂ from the exhaust gases can reduce these emissions. Once the CO₂ is separated from the exhaust gas it may be stored or disposed outside the atmosphere. Alternatively, the recovered CO₂ may be used for other commercial purposes.

4.2 Potential Mitigation Technologies and Practices

A set of state-of-the-art and emerging industry technologies and practices that have the potential to reduce aluminium industry GHG emissions are identified in this section. These technologies and practices are grouped into five categories based on the priority areas identified above, addressing: (1) options to improve the Hall-Héroult process; (2) options to improve the Bayer process; (3) technologies and practices to increase recycling; (4) alternatives to the Hall-Héroult process; and (5) alternative energy sources. Exhibit 22 summarises the options and for each option presents the

GHG impact area (e.g., energy-CO₂ or PFCs), availability, and applicability.

4.2.1 Options to Improve the Hall-Héroult Process

Energy accounts for about one-third of the cost of primary aluminium production. In order to minimise production costs, industry has an interest in increasing energy efficiency. Energy efficiency improvements in the aluminium production process have and are continuing to be made. In 1945, energy consumption was typically 20-25 kWh/kg of aluminium. Since then, fundamental studies and a better understanding of the process have contributed to a significant reduction in energy consumption (see Exhibit 18). Presently, energy consumption of 13 kWh/kg of aluminium can be achieved. The theoretical minimum energy consumption in aluminium electrolysis is 6.3 kWh/kg of aluminium (Grjotheim et al., 1995).¹⁵

Exhibit 18. Improvements in Hall Cell Performance in the Last 50 Years

Operational Parameters	1945	1995
Cell Amperage (kA)	25-50	175-300
Current Efficiency (%)	80-85	92-95
Energy Cons. (kWh/kg Al)	20-25	13
Cell Prod. (tonnes/year)	55	820
Prod. per Worker (t Al/yr)	7	200

Source: Grjotheim et al., 1995

Options for improving the Hall-Héroult process are evaluated in terms of their ability to increase cell amperage or current efficiency. Increasing amperage or current efficiency is important because a smelter's capacity increases in line with amperage increases and with increased current efficiency. Improving current efficiency can boost capacity and reduce the energy intensity (kWh/tonne). These improvements result in reduced GHG emissions and lower

¹⁵ The theoretical minimum is based on no heat loss from the cells.

power costs per tonne of output. Also, part or all of the power saved can be used to produce additional metal. This improvement is very important for smelters whose power supplies are constrained. Boosting the capacity of individual reduction cells also typically increases the productivity of the potroom crew, resulting in reduced labour costs.

This section discusses retrofitting existing cells and implementing advanced technologies as options to reduce energy use and GHG emissions from the primary production process.

Retrofit Existing Cells

The most direct method of making incremental process improvements is to retrofit the existing technology by undertaking improvements short of a major change in technology. This method normally involves maintaining the existing pot size, and using common retrofit technologies such as:

- Alumina point feeding;
- Process computer control;
- Conversion from wet to dry anodes (Soderberg cells only); and
- Improvements to: bath chemistry; anode design; busbar system design; and cathode shell composition and design.

Typically, several options are implemented together as part of an overall retrofit program. A portfolio of options are chosen that have synergistic effects resulting in maximum improvements in performance. If the retrofit is done properly, the payback period and financial exposure is low. These retrofits normally involve capital outlay ranging from nominal to around \$1,000 per tonne of additional capacity, depending on the technology chosen (Driscoll et al., 1997).

Alumina Point-Feeding

Point-feed systems allow higher current efficiencies and lower energy consumption compared to conventional bar feeders. In a bar feed system, the crust on electrolytic bath is broken across the length of the cell approximately every six hours and large quantities of alumina enter the pot at one time. This process tends to exceed alumina solubility limits in the cell's bath, which can cause the alumina to form an insoluble layer. In a point-feed system, small amounts of alumina (about one kg) are fed into the bath at much shorter intervals at two to five positions along the centre of the cell. This method of feeding improves the dissolution of the alumina in the bath allowing the overall bath temperature to be lowered. Thus, energy consumption is reduced.

Per unit energy consumption reductions on the order of 10 to 30 percent can be expected as a result of point-feed systems, depending on existing technology and cell design. In addition to reducing the energy requirement of the reduction process, point-feed systems are effective in reducing the number of anode effects. By reducing the number of anode effects, PFC emissions are reduced.

Conversion to the state-of-the-art PFPB technology is the most accepted route to increasing operational and environmental efficiency for bar-feed CWPB and SWPB cells. At the Albras smelter in Brazil, SWPB cells were converted to point-feeder cells, resulting in an increase in current efficiency from 88 to 92 percent (Kvande, 1997). Johansen et al. describes the successful retrofit of 100 kA prebake cells at the Sor-Norge Aluminium smelter at Husnes, in western Norway. The retrofit program, which included the installation of point feeding and process control, new pot shells, larger anodes, and busbar modification, resulted in an increase in current efficiency from 90 to 92 percent and a reduction in anode effect (AE) frequency from 0.4 to 0.1 (Johansen et al., 1999). Conversion from

bar fed CWPB to PFPB cells is continuing at smelters across the world.

Even for Soderberg cells, improvements in energy efficiency, production, and pot life can be expected from converting from Soderberg cells to prebake cells. In 1994, VAW Aluminium-Technologie designed and engineered the retrofit of VSS Soderberg pots operating at 120 kA to prebake cells with a current load of 165 kA at the Bayside Smelter. The modernisation of the Soderberg pots included changes to prebake anodes, hooding and installation of fume scrubbing system, installation of point-feeders, and pot control system.

The resulting operating parameters are shown in Exhibit 19. The cost of converting a Soderberg plant to prebake is much more than retrofitting the Soderberg cells.

Exhibit 19. Retrofit of VSS Soderberg Plants at Bayside Smelter

Characteristic	Before Retrofit	After Retrofit
Amperage (kA)	117	165
Pot voltage (V)	4.4	4.25
Current Efficiency (%)	87.7	93
Energy Cons. (kWh/kg Al)	14.9	13.6
Production (Tonnes/year)	85,420	129,000
Pot Life (Months)	33	60

Source: Vogelsang, 1996.

Process Computer Control Systems

The use of process computer control of electrolytic reduction cells has expanded rapidly in the last few decades. Modern cell lines have microcomputers that control the operations of individual cells; the micro-computer for an individual pot is connected to a central computer, which controls all automated operational procedures (Kvande, 1997). Computers control the repositioning of anodes as they are consumed and provide greater control over alumina feeding. Computers enable better prediction and suppression of anode effects and result in

increased productivity, lower energy cost, and reduced PFC emissions.

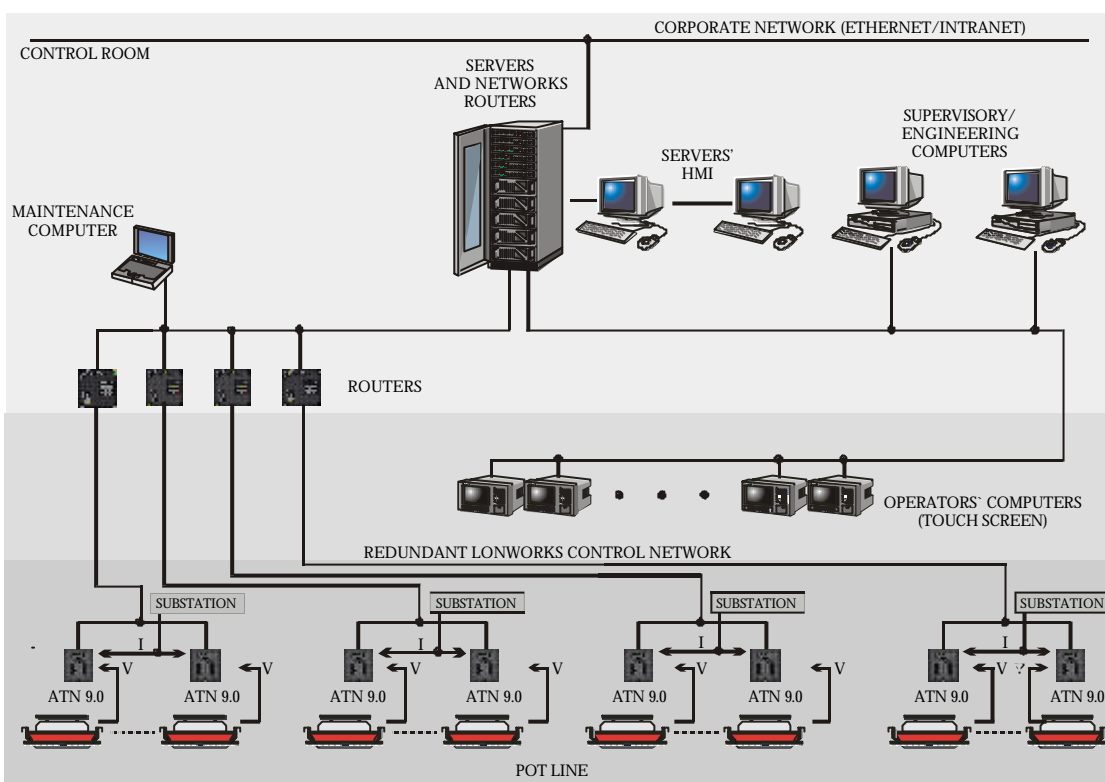
The architecture or topology of the process system varies depending on the level of control required and state of technology. For smelters that have cables from the potline to a central control or command room, a semi-distributed architecture may be most appropriate. If the potline does not have cables networked to a central location, a hybrid or fully distributed architecture may be most appropriate. Exhibit 20 presents a conceptual layout of a fully distributed process control architecture for the SCORE process control system, sold by ATAN. Many smelters employing the Kaiser cell technology use the Celtro™ process control technology. Kaiser Aluminum’s Mead facility in the United States was retrofit with the Celtro™ and reported an increase in current efficiency of one to two percent (Jeltsch et al.,1992).

Computer controls may be suitable for new and old smelters. For old smelters the installation of computer controls is a useful way to extend the useful life of the installation. Over the past decade improved computerised cell control systems have been developed and improvements in control algorithms are continuing.

Conversion from Wet to Dry Anodes (Soderberg)

In Soderberg cells, the anode is baked in the cell itself. In the conventional “wet” Soderberg anode, the physical composition of the carbon paste is almost liquid. This design allows the carbon paste to settle and fill in voids around the anode support studs. As a consequence of this composition, pitch in liquid form tends to accumulate on the top surface of the anode. This liquid pitch tends to flow into the stud holes during the stud pulling operation (during replacement). When this happens, the pitch will catch fire and smokes as it comes in contact with the hot zone portion of the anode.

Exhibit 20. Process Computer Control System



Source: ATAN, producer of SCORE computer control system (ATAN, 1999).

Soderberg anodes are also prone to incidents such as stud blows and casing leaks. During these incidents, the fluid paste drains from the anode surface through the holes and cracks in the anode or between the casing wall and the anode and flow down into the cell bath. The result is a localised severe increase in hydrocarbon emissions and in some instances fire and damage to the pot and adjacent equipment.

The “dry” anode concept, introduced by Sumitomo Aluminium in the 1970s, is a solution to the environmental problems associated with “wet” anodes. In the dry anode, the pitch binder content was reduced in the anode paste to create a plastic paste, eliminating the flow of liquid pitch into the stud holes during anode pulling operation. To reset the stud, a special stud hole paste is added to the vacated stud hole; the paste melts and the stud can be reset. The

inherent composition of the anode paste used virtually eliminates the possibility of liquid pitch finding its way into the electrolytic bath making for a safer and cleaner operation. In addition to reducing hydrocarbon emissions, the dry anode reduces pot carbon consumption and energy requirements for anode operation, resulting in lower GHG emissions per unit of aluminium produced.

Other Retrofit Options

Other retrofit improvements in the production process that enhance the performance of the existing cell are listed below (in order of increasing complexity and capital outlay).

Improvements in the chemical bath. Improvements in bath composition can lower temperatures, raise current efficiency,

lower voltage, maintain operating stability and decrease emissions, while preventing alumina sludge build-up under the metal pads. Ideal bath composition can vary by cell; thorough stoichiometric analyses can determine the most efficient composition. Increasing bath height also has implications for lower energy use.

Design changes in carbon anodes. Increasing anode size, expanding cell sidewalls, and reducing the anode-cathode distance have synergistic effects that not only reduce cell voltage but also make the process more stable by reducing magnetohydrodynamic (MHD) forces. Increasing anode size results in decreased anodic current density, increased aluminium productivity through increased cell amperage, increased current efficiency, and reduced anode consumption because of lower anode temperature.

Design and material changes in cathode shell. Improvements in insulation and use of lower-resistance cathode materials can reduce heat loss. With these materials, heat previously lost through the cell walls can be redirected back into smelting. Computer models are used to evaluate the impact of changes in cathode design on thermal performance prior to actual implementation.

Busbar system modification. Many older cells have busbar systems with poor magnetic fields and a hump-shaped distortion of the metal pad in the centre of the cell. The poor magnetic conditions reduce current efficiency. Rearrangement of the busbar system can improve the magnetic balance of the cell. Modifying the busbar is often expensive, with long conversion times. Often times the possibilities for modification are limited by the existing busbar/ cell-arrangement.

These retrofit options can save significant amounts of energy. Energy intensity reductions ranging from 15 to 30 percent can be expected as a result of these retrofit options. The retrofit options discussed are

implemented after extensive computer modelling and large-scale development work is conducted on test cells.

Advanced Technologies

Advanced technologies are currently under development or have been seriously considered and are expected to have an impact on the industry over the next 20 to 30 years. Two key advanced technologies that are in the research and development stages are the inert anode and wettable cathode.

Inert Anode

The development of inert, dimensionally stable, non-carbon anodes that are not consumed in the electrolytic process represents the major potential advancement in the aluminium production process. Nickel oxide-rich nickel ferrite, doped with copper powder or short copper fibres, and ceramic materials are the primary materials being tested in the development of inert anodes. Energy efficiency increases, ranging from 10 to 25 percent, are expected. The higher efficiencies will be achieved when the inert anode is coupled with a stable, wetted cathode (see below). Costs of production would also be reduced significantly as a carbon baking facility would no longer be required and the anodes would not need to be replaced every two to three weeks. Furthermore, these non-carbon anodes would remove the source of carbon for PFC generation, thereby eliminating PFC emissions (AA, 1998b).

Inert anode research is being pursued aggressively through government-industry research and development efforts. Field testing of inert anodes is currently underway at a number of facilities. One of the main problems with the inert anode is its inability to survive in the current cell environment (e.g., high bath temperature, corrosive bath). A commercially viable design is expected by 2020 (Green, J., 1999).

Wettable Cathode

Wettable cathodes have the potential to increase the cell's stability, increase current efficiency, and reduce specific energy consumption. The undulating surface of molten aluminium in the electrolytic cell creates a large gap (approximately 1.5 inches) between the anode and cathode. This gap causes greater consumption of electricity than is required to produce aluminium. The more the anode-cathode distance can be reduced, the greater the energy savings.

The development of an inert titanium diboride and graphite (TiB₂-G) cathode (also called the wettable cathode) permits cell designs in which the molten aluminium product can be drained from the cathode to collection sites within the cell leaving only a thin film of metal at the cathode surface. Normal undulations due to electromagnetic stirring and gas bubble driven circulation are virtually eliminated with wettable cathodes. This stability permits cells with reduced anode spacing. In combination with advanced process sensors and control systems to optimise cell operation, the potential energy savings are estimated to be as high as 15 to 20 percent.

This technology has been field-tested and is undergoing materials failure analysis. A commercially viable design is expected in the next 10 to 20 years.

4.2.2 Options to Improve the Bayer Process

The Bayer process is the prevalent technology for converting bauxite into alumina for subsequent reduction into aluminium. The Bayer-process technology has been improved over the years by more efficient conservation of heat, greater recovery of soda, and the development of continuous flow instead of batch processing. The increase in the size of the operating units in response to vastly greater markets for alumina has permitted the most basic kind of industrial economies-to-scale

through the use of larger tanks, pumps, kilns, and heating units. The two main options for improving the Bayer process are replacing rotary kilns with fluidised bed kilns and increasing cogeneration use.

Replace Rotary Kilns with Fluidised-Bed Kilns

Alumina calciners represent a significant energy use in many alumina plants. In the final stage of the Bayer process, calcination in rotary kilns or in fluidised beds at 1100 to 1300°C converts the hydroxide to a dry white power, alumina. The rotary kiln produces a fragile grade of alumina that tends to break up during dry scrubbing to yield a high proportion of fines that are released into the potroom environment. Fine grade alumina has less fluidity and dissolves slower than coarser aluminas. This grade is considered less desirable than the alumina produced by the fluidised bed process. The fuel demand of a fluidised bed kiln is about one third the fuel demand of the rotary kiln. As a result, rotary kilns are being replaced with the much more efficient fluidised bed kiln.

Enhance Combined Heat and Power (CHP) Integration

Cogeneration, or combined heat and power (CHP), produces both electricity and process steam. Steam can be used at different stages in the Bayer process like causticisation, digestion, desilication, precipitation, evaporation, among others. Typically, the cogeneration facilities will consist of multiple gas-fired turbine units whose exhaust is used in a waste heat boiler with or without supplemental fuel firing, depending on the steam to power balance requirements (Nunn, 1999). The primary fuel consumption in cogeneration plant will be 15 percent less than a conventional boiler and power supply (Mishra et al., 1999).

In addition to reducing the cost of production and increasing the overall plant efficiency, a cogeneration system has

another advantage – it supplies a stable source of power¹⁶. Unplanned outages result in fatigue and thermal stresses on equipment and reduce equipment life. In addition, because the time required for start-up and stabilisation of Bayer's circuits is high, frequent power interruptions, even for relatively shorter duration, could cause substantial loss of production.

The current economics of the Bayer process warrant that all alumina facilities have to be CHP integrated in order to compete in the world market.

Options to Increase Recycling

One of the largest potential for energy saving and GHG reduction is through recycling of aluminium. On a per tonne basis, recycling aluminium uses about five percent of the energy required to produce primary aluminium and releases less than four percent of the GHGs released when producing primary aluminium. The technical ease with which aluminium can be identified, re-melted, and used as a near equivalent to primary aluminium makes recycling very attractive. Increases in aluminium recycling can be achieved by increasing recycling rates and metal recovery efficiency.

Increase the Rate of Recycling

The use of post-consumer recovered aluminium is limited by the recycling rate achieved (i.e., quantity recovered/quantity consumed). Due to its value and ease of reuse, nearly all of new scrap is already recycled. To increase recycling rates, the following actions may be appropriate.

Implement Program for UBC Collection

Used cans may often be recycled and back on the market in the form of new beverage

¹⁶ Disruptions in power may be common in developing countries, where power supply from the grid may be unstable due to the wide gap between supply and demand.

containers in as little as 90 days. The UBC collection and recycling rate is increasing and in 1995 the United States and Japan reached rates over 60 percent. In Western Europe the recycling of aluminium beverage cans increased from 30 percent in 1995 and 37 percent in 1996 to 40 percent in 1997 (AA, 1999; Richards, 1997). With increasing public awareness and the continuous expansion of the collection infrastructure, the overall recycling rates are expected to continue to rise. In other regions, the infrastructure for UBC collection does not exist, which continues to limit the overall recycling ratio.

Develop or Improve Infrastructure for Scrap Collection

In regions where the UBC recovery rate is already high (e.g., U.S., Western Europe, Japan), non-UBC old scrap is the most promising source of growth for secondary production. The availability of old scrap for recycling is largely dependent on the life span of the aluminium products consumed. The recovery cycle varies from an extremely short period in the case of UBCs to as long as 50 years in electrical transmission and some construction applications. For transportation, which is an important sector for secondary growth, the average is approximately ten years. In many countries, an extensive infrastructure does not exist for non-UBC old scrap and, thus, much of this scrap (e.g., aluminium foil, automobile parts, siding, and construction material) is presently discarded (exceptions are North America, Western Europe, and Japan). One way to remedy this is to establish the infrastructure for collecting non-UBC old scrap. The initial cost of infrastructure development and subsequent collection and recovery costs are difficult to quantify.

Increase Metal Recovery Efficiency

Secondary aluminium cannot be continuously recycled. This limitation is due to two factors: aluminium losses that occur during the re-melting process, and

contamination of metal with trace amounts of other metals that limit the ability to obtain proper alloy specifications. Exhibit 21 provides typical furnace melt losses for different types of scrap.

Exhibit 21. Typical Furnace Melt Loss

Material	Melt Loss (% of the metal melted)
Clean scrap (also primary aluminium)	0.5 – 1.0
Heavy mill scrap & unalloyed ingot	1.5 – 3.0
UBCs and painted scrap	5.0 – 15

Source: USDOE/OIT, 1997.

Higher recovery efficiencies may be possible in the near future due to current efforts on recapturing aluminium from dross. However, the lack of comprehensive information on the characteristics of by-products is often a barrier to their utilisation. To improve the metal recovery efficiency, the following options exist:

Enhance Dross Metal Recovery

Dross metal recovery technologies separate dross/salt cake into individual constituents and recycle the aluminium and salt fractions back into the secondary facilities. Thus, metal recovery from dross provides energy savings and GHG emission reductions by increasing the aluminium recovery rate per tonne of scrap. Furthermore, this technology avoids landfilling the 550,000 tonnes/year of salt fluxes, aluminium, and non-metallic oxide residues and, thereby, further preserves the benefits of aluminium recycling. Potential energy savings range from 1.5 percent for new scrap to eight percent for old scrap (AA, 1997).

Develop Innovative Decoating Equipment

Innovative scrap decoating equipment increases facility production as a result of decreasing furnace melt loss as dross; reduces fuel consumption by more efficient use of the heat supplied by scrap organics;

and, thereby, reduces energy intensity and GHG emissions. Energy savings of about 12 percent are expected from the adoption of this technology.

Improve Furnace Efficiency

The conventional side-wall reverberatory furnace typically used in the secondary sector has relatively low energy efficiency. Replacement of this furnace by equipment such as the DC plasma arc melting technology and the vertical floatation melter will significantly increase energy efficiency and reduce GHG emissions and dross formation. Energy savings on the order of 35 percent are anticipated as a result of improved furnace efficiency.

4.2.3 Alternatives to the Hall-Héroult Process

Alternative, more economical, less energy and emission intensive, methods of producing aluminium to replace the Hall-Héroult process are desirable. In addition to alternative processes, finding alternative sources of primary aluminium, such as pulverized fly ash (PFA) or minestone, are available.

Alternative Production Processes

Currently, no alternative production processes exist that could displace the existing Hall-Héroult process. One process, direct carbothermic reduction has been demonstrated in a pilot 150 KA facility (Richards, 1997). The carbothermic reduction process uses a combination of a fossil-fuelled shaft furnace with supplementary electric heat or an electric arc furnace to produce primary aluminium from low-cost domestic materials instead of imported bauxite or alumina. Several alternative versions of the direct reduction carbothermic process for aluminium have been developed (Reynolds, Alcoa, Kuwahara). The refining step, crucial to the success of the project, still represents a major technical obstacle.

The direct carbothermic reduction process, if successfully developed to operate on a commercial scale, would be significantly more energy efficient than conventional Hall-Hèroult cells. Energy consumption savings are estimated to be approximately 25 percent of the energy used in Hall-Hèroult cells. Although, process-related CO₂ emissions from the carbothermic process are expected to be double that of the current Hall-Hèroult process.

Richards (1997) indicates that currently limited interest exists in this process because of the familiarity with the existing process and the enormous cost of demonstrating the direct carbothermic process (\$250 million) (Richards, 1997).

Alternative Sources of Aluminium

Throughout the history of the aluminium industry there have been persistent attempts to find substitutes for bauxite as the basic source of metal. Bauxite used for metallurgical purposes is usually between 45 percent and 55 percent alumina. However, there are specific bauxites, which due to their mechanical properties and other economic factors, can be used commercially to produce metallurgical grade alumina. Pulverised fly ash (PFA) and minestone are two alternatives to bauxite that have been successful in actual production environments. The potential for PFA and minestone to replace bauxite supply are discussed below.

Pulverised Fly Ash (PFA)

PFA can contain up to 35 percent alumina and may offer an economic opportunity as a raw material for alumina production instead of bauxite. Refining alumina from PFA requires direct hydrochloric acid (HCl) leaching of the fly ash followed by ion exchange of the leachate to separate the process liquor into recoverable compounds, which includes alumina. Studies have shown that the overall process becomes competitive with the Bayer process when the

PFA delivery costs are not considered and for alumina prices in the range of \$240 per tonne.

Minestone

Minestone is from coal mining, which is thought to consist of aluminium bearing materials in quantities that may present an alternative to bauxite as a source of aluminium. The exact composition or the characteristic of minestone has not been determined. The composition would greatly affect the manner in which the material would have to be processed to extract the aluminium compounds. Historically, materials other than bauxite require more complex and less economical processing. An example of minestone is kaolin clay. Kaolin clay can be used instead of bauxite in what is known as the Alcoa Smelting Process. The clay is leached with hydrochloric acid (HCl) to produce aluminium chloride, AlCl₃, which is then calcined to produce alumina.

The process is competitive with the Bayer/Hall-Hèroult process, since it is a multiple bipolar system as opposed to the conventional monopolar Hall cells. This significantly reduces the capital used in constructing the cell lines. The process, however, requires a reactor to convert chlorine evolved from the cells to aluminium chloride by reaction with alumina, clay, or bauxite. This requirement offsets much of the cell's capital and operating cost advantage even though power consumption is reduced to about 11 kWh per kg of aluminium.

This technology will be likely not be commercialised by 2020 because of high capital costs. In addition, aluminium producers are reluctant to invest in highly capital intensive new technologies with their associated higher risks relative to conventional technologies.

4.2.4 Alternative Sources of Energy

Reducing the electricity consumed from carbon-intensive fossil fuels provides an opportunity for reducing energy-related CO₂ emissions. Renewable resources, such as hydropower, or alternative energy processes, such as Norsk Hydro's Hydrokraft, are potential substitutes for self-generated coal and natural gas, and purchased electricity. The Hydrokraft process is a new technology to produce electricity based on natural gas in a large-scale hydrogen power plant and has the potential to reduce CO₂ emissions by as much as 90 percent compared with conventional gas-fired power plants (Norsk Hydro, 1999).

The mitigation potential and costs for alternative sources of energy were not analysed in detail in this report. The mitigation potential of zero-emission technology is represented by an electricity generation scenario that assumes 75 percent of the electricity is generated from hydroelectric resources. The costs of these mitigation technologies are the subject of other reports.

4.2.5 CO₂ Capture Technologies

Several technologies have been demonstrated successfully that can remove CO₂ from flue gases. The CO₂ can be separated during or after the production process and then stored or disposed outside the atmosphere. Because significant quantities of CO₂ are produced during the primary production stage as a result of the combustion of the carbon anode during electrolysis, the potential to capture CO₂ is examined.

To maintain a good working atmosphere and acceptable climatic conditions in the pot room, relatively large quantities of air are required to remove the energy and fumes released from the electrolytic cells. Large fans draw the heat and fumes from the cells through ducts to the fume control systems. Heat and pollutants escaping to the pot room

are transported out the roof by convection or, in the case of a pot room equipped with a secondary control system that employs roof scrubbers, by a powered ventilation fan.

The dilution of CO₂ rich exhaust gas by ventilation air results in extremely low concentrations of CO₂ (on the order of 2 to 5 percent). The low CO₂ concentrations make CO₂ capture an unsuitable mitigation option. Without a complete overhaul of the existing cell and pot room design to prevent extensive dilution of exhaust gas, CO₂ capture technologies are not likely to be applied at primary production facilities.

The composition of the exhaust gas is another factor that may inhibit CO₂ capture (Roberts, R., 1999). The fumes from the electrolytic cells are emitted as gases, vapours, and as entrained liquid droplets and solid dust. The vapours condense nearly completely into liquid aerosols and then solidify to submicron particulate aggregates of complex composition upon cooling. The various constituents that are found in the exhaust gas include: hydrocarbons, hydrogen fluoride (HF), CO₂, CO, CF₄, C₂F₆, silicon tetrafluoride (SiF₄), sulfur dioxide (SO₂), dihydrogen sulfide (H₂S), carbon disulfide (CS₂), carbon sylsulfide (COS), calcium fluoride (CaF₂), aluminium fluoride (AlF₃), chiolite (Na₅AlF₁₄), cryolite (Na₃AlF₆), carbon soot (C), water. The varied composition of the exhaust gas makes it difficult to process the gas to recover CO₂. Further research is required to understand the precise implications of the different constituents of the exhaust gas on the applicability of CO₂ capture technologies.

Exhibit 22. Summary of Potential GHG Mitigation Technologies and Practices

Option	GHG Impact Area				Availability	Description/Applicability
	Energy- CO ₂	Process- CO ₂	PFCs	Industry GHG Intensity		
Options to Improve the Hall-Héroult Process						
Retrofit Existing Cells						
• Alumina Point Feed Systems	✓	✓	✓	✓	Currently	Point feeders enable more precise control of alumina feeding
• Process Computer Control Systems	✓	✓	✓	✓	Currently	Computers control the repositioning of anodes, alumina feeding.
• Conversion from Wet to Dry Anodes	✓	✓		✓	Currently	Reduces hydrocarbon emissions and energy requirements in Soderbergs
Convert to PFPB Technology	✓	✓	✓	✓	Currently	Convert Soderberg, bar-fed CWPB, and SWPB cells to PFPB cells
Use Advanced Technologies						
• Inert Anode	✓	✓	✓	✓	2020	Non-carbon, dimensionally stable anode; potential for retrofit
• Wettable Cathode	✓	✓		✓	2010 – 2020	TiB ₂ -G cathode allows closer anode-cathode spacing, reducing energy loss
Options to Improve the Bayer Process						
Replace Rotary Kilns with Fluidised Bed Kilns	✓			✓	Currently	Fluidised bed kilns produce use a third less energy than rotary kilns
Enhance Combined Heat and Power Integration	✓			✓	Currently	Most alumina refineries are already CHP integrated at some level
Options to Increase Recycling						
Increase the Rate of Recycling						
• Increase Efforts for UBC Collection				✓	Currently	Promote recycling in regions that do not currently have UBC recycling
• Improve Non-UBC Collection Infrastructure				✓	Currently	Develop/improve collection infrastructure for non-UBC old scrap
Increase Metal Recovery Efficiency						
• Enhance Dross Metal Recovery	✓			✓	2000-2005	Recovers aluminium oxides from dross/salt cake melt loss
• Develop Innovative Decoating Equipment	✓			✓	Currently	Decreases melt loss, less fuel use per unit of metal
• Improve Furnace Efficiency	✓			✓	Currently	Advanced furnaces can enhance energy efficiency significantly
Alternatives to the Hall-Héroult Process						
Alternative Production Processes						
• Carbothermic Reduction Process	✓	✓	✓	✓	2010	Not expected to displace the existing Hall-Héroult process
Alternative Sources of Aluminium						
• Pulverised Fly Ash (PFA) & Minestone	✓	✓	✓	✓	Currently	Not economic under current market conditions compared to existing process
Alternatives Sources of Energy	✓			✓	Currently	Renewable energy or alternative energy processes, e.g., Norsk Hydro's Hydrocraft
CO₂ Capture Technologies	✓			✓	Currently	Not feasible due to dilution of exhaust gas with air and gas composition.

4.3 Assessment of Select Mitigation Technologies and Practices

The number of potential mitigation options identified is extremely large. From this list, a set of state-of-the-art and emerging industry technologies and practices were selected for a detailed engineering and cost assessment. In the assessment, the emission reductions and associated costs for each option are calculated.

Each option selected for the cost assessment is expected to: (1) have a significant potential to reduce *overall* industry GHG emissions; (2) be commercially available by 2020; and (3) be quantifiable in terms of costs. Only options that met all the criteria outlined above were considered for the detailed cost analysis. Exhibit 23 indicates which options met the above criteria.

As indicated in Exhibit 23, there was inadequate cost data to conduct a detailed assessment of options to increase recycling.

Exhibit 23. Selection of Potential GHG Mitigation Options for Cost Analysis

Option	Potential to Reduce Overall Industry GHG Emissions	Commercially Available by 2020	Cost Data Available	Option Selected for Cost Analysis
Options to Improve the Hall-Hérault Process				
Retrofit Existing Cells				
• Alumina Point Feed Systems	High	✓	✓	✓
• Process Computer Control Systems	High	✓	✓	✓
• Conversion from Wet to Dry Anodes	Medium	✓	✓	✓
• Other	High	✓	x	x
Convert to PFPB Technology	High	✓	✓	✓
Use of Advanced Technologies				
• Inert Anode	High	x	x	x
• Wettable Cathode	High	✓	x	x
Options to Improve the Bayer Process				
Replace Rotary Kilns with Fluidised Bed Kilns	High	✓	✓	✓
Enhance CHP Integration	Low	✓	✓	x
Options to Increase Recycling				
Increase the Rate of Recycling				
• Increase Efforts for UBC Collection	High	✓	x	x
• Improve Non-UBC Collection Infrastructure	High	✓	x	x
Increase Metal Recovery Efficiency				
• Enhance Dross Metal Recovery	Low	✓	✓	x
• Develop Innovative Decoating Equipment	Low	✓	✓	x
• Improve Furnace Efficiency	Low	✓	✓	x
Alternatives to the Hall-Hérault Process				
Alternative Production Processes				
• Carbothermic Reduction Process	High	x	x	x
Alternative Sources of Aluminium				
• Pulverised Fly Ash (PFA) & Minestone	Low	x	x	x
Alternatives Sources of Energy	High	✓	x	x
CO₂ Capture Technologies	Low	✓	x	x

Because this option has the potential to impact industry GHG emissions significantly, it is an area that warrants a closer look. An analysis of the impact of increasing recycling rates follows after the cost assessment of primary production and alumina refining GHG mitigation options.

4.3.1 Methodology

For each mitigation option selected, the emission reductions and associated costs are estimated for a hypothetical facility. The capital cost, incremental operation and maintenance (O&M) cost, and incremental production associated with implementing the mitigation technology are used to estimate the net levelised cost in \$/year over the lifetime of the project. The cost estimates will represent the cost to private decision makers to implement each option. The technology's ability to reduce energy-related CO₂ emissions, and process-related CO₂ and PFC emissions are also estimated in tonnes of CO₂-equivalent per year. The annual cost is divided by annual reductions to estimate cost per tonne of emissions reduced (\$/tonne of CO₂-equivalent) for each option in each region. All costs are expressed in 1995 US\$.

The sample facility characteristics shown in Exhibit 24 were used to develop the basic assumptions used in the economic analysis of the various mitigation options. While the facilities constructed for purposes of this analysis are hypothetical, their defining characteristics (e.g., capacity, amperage, etc.) are representative of the relevant characteristics of facilities that could implement the mitigation options discussed.

Baseline operating costs by region were estimated for each technology type based on detailed operating cost information for individual smelters. This information has been supplied as part of information on individual smelter facility costs and is the average for each region weighted by facility capacity. The calculations are based upon operating costs as estimated for 1998 on a

facility by facility basis. Each technology was evaluated individually.

In addition to the specific characteristics shown in Exhibit 24, general assumptions regarding likely costs were used based on ICF's experience as a result of ongoing engineering construction efforts in the aluminium industry and from the published literature.

4.3.2 Options to Improve the Hall-Héroult Process

The primary production options selected for the cost assessment are the installation of alumina point-feed systems, process computer control, conversion from wet to dry anodes, and conversion to PFPB technology. The applicability and effectiveness of each option varies depending on several factors, including technology type, location, cell and potroom design. Typically, several options are implemented together as part of an overall retrofit program.

When implemented together, the options have synergistic effects resulting in maximum improvements in performance. In some instances, the implementation of a particular option is not technically feasible without a certain other option. For example, the gains from point-feeding cannot be realised if a computer control system is not already in place. For purposes of the cost analysis, the following mitigation option groupings are defined (in order of increasing complexity and capital outlay):

Retrofit – Minor: Includes the installation of process computer control systems or refinement of control algorithms of existing process control systems.

Retrofit – Major: Includes the installation of point-feed systems and process computer control in prebake cells. For Soderberg cells, this option includes conversion from wet to dry anodes in addition to point-feed and process computer control systems.

Retrofit – Minor

The results of the minor retrofit option are summarised in Exhibit 25. Retrofitting existing cell lines with computer controls will increase current efficiency by two to three percent, reduce anode consumption per unit production by two percent, and reduce anode effect frequency by 15 to 40 percent (Ghosh, 1997; Genzie et al., 1999; Hackett et al., 1995; Jeltsch et al., 1992; Johansen et al., 1999; Vogelsang et al., 1996). The potential to reduce AE frequency through process computer control is greatest for Soderberg cells. Estimated reductions in GHG emissions per tonne range from 0.2 to 2 tonnes of CO₂-E/tonne of aluminium. Across technology-types, the per unit reductions are largest for Soderberg cells and lowest for PFPB cells. Across regions, the per unit reductions expected are quite similar. The Central and South America region has the lowest expected reduction

across regions due to its regional fuel mix being predominantly hydro, resulting in a low energy-related CO₂ emission factor.

For the plant configured in Exhibit 24, retrofitting cells with process computer controls will require a total initial investment of about \$6 to \$8 million. The retrofit option, by increasing current efficiency, produces more metal for the same amount of energy. The value of incremental production, determined using the assumed increase in current efficiency and long term price of aluminium is estimated to range from \$5 to \$10 million per year. The capital cost and benefits data are used with estimated incremental operational costs for each region to calculate the net levelised cost for each region and technology-type. As indicated in Exhibit 25, the net levelised cost is negative for several regions and technology-types, indicating

Exhibit 24. Characteristics of the Typical Facility

Characteristic/Technology -Type	VSS	HSS	SWPB	CWPB	PFPB
Primary Production Facility					
Plant Capacity (tonnes/year)	200,000	200,000	200,000	200,000	200,000
Number of Pots	600	600	450	450	350
Cell Amperage (kA)	100	100	150	150	180
Electricity Consumption (kWh/tonne)	15,800	16,000	15,000	15,000	13,500
Process-CO ₂ Emissions (t CO ₂ /tonne)	1.5	1.5	1.4	1.4	1.4
Anode Effect (AE) Frequency	2.8	0.9	0.3	0.3	0.2
Price of Aluminium (\$/tonne)	1,500	1,500	1,500	1,500	1,500
Baseline Operating Costs (\$/tonne) ¹					
Asia	1,291	1,537	- ²	1,220	1,267
Australasia	-	-	1,031	1,014	935
Central and South America	1,369	1,601	1,109	1,210	1,093
Eastern Europe and FSU	1,318	1,443	1,224	-	1,121
North Africa & Middle East	1,217	-	-	1,060	942
North America	1,226	1,296	1,188	1,361	1,130
Sub-Saharan Africa	1,049	-	1,107	1,029	-
Western Europe	1,365	-	1,363	1,307	1,111
Alumina Refining Facility	Rotary	Fluidised Bed			
Plant Capacity (tonnes/year)	660,000	660,000			
Fuel Energy Utilisation (MJ/tonne Al ₂ O ₃)	28,800	9,600			
CO ₂ Emission Factor (t CO ₂ /tonne)	1.0	0.3			

1. Cost factors reflect difference in power cost, labour, utilisation efficiency, and median age of plant installation.

2. Baseline cost estimates could not be developed as there is no production for this technology-type in this region

Note: Technology definitions are as follows: HSS = Horizontal Stud Soderberg; VSS = Vertical Stud Soderberg; CWPB = Center Worked Prebake; PFPB = Point Feed Prebake; SWPB = Side Worked Prebake

that the option is profitable. For VSS smelter retrofits, Sub-Saharan Africa is the most profitable. Retrofitting HSS is not profitable in any region. Retrofitting prebake cells is most profitable in Australasia, North Africa and the Middle East, and Sub-Saharan Africa.

As shown in Exhibit 25, the emission reduction cost-effectiveness of this option ranges from -\$59 to \$97 per tonne of CO₂-E. Retrofitting prebake cells in Central and South America is most profitable. Retrofitting cells of all technology-types is profitable in Australasia and Sub-Saharan Africa.

Computerised cell control technology has greatest efficacy with the newer and more advanced applications of the mitigation technologies. Smelters with these technologies are amenable to the technology upgrades. The newer prebaked installations are set up in such a manner that lends the operation more toward monitoring and adjustments on an individual anode basis.

The distribution of technologies in different regions is the product of different eras in aluminium capacity expansion. For example until recently Sub-Saharan Africa had not seen any capacity expansion for decades. Hence, the facilities and the reduction technology used in that region are not up to date. However, recent capacity additions, which have been sizeable, have been with the latest and most up to date type of reduction cells available.

Retrofit – Major

The results of the major retrofit option are summarised in Exhibit 26. Retrofitting existing cell lines with point-feed systems, computer controls, and converting from wet to dry anodes (Soderberg cells only) will increase current efficiency by two to six percent, reduce anode consumption per unit production by two percent, and reduce anode effect frequency by 10 to 50 percent. Estimated reductions in GHG emissions per

tonne range from 0.2 to 2.7 tonnes of CO₂-E/tonne of aluminium. The pattern of per unit reductions across regions and technology types is similar to the minor retrofit option. Across technology-types, the per unit reductions are largest for Soderberg cells and lowest for the efficient PFPB cells. Across regions, the per unit reductions expected are quite similar with lowest expected reduction in Central and South America due to its predominantly hydro regional fuel mix (Ghosh, 1997; Genzie et al., 1999; Hackett et al., 1995; Jeltsch et al., 1992; Johansen et al., 1999; Vogelsang et al., 1996).

Point feeding appears to significantly enhance smelter reduction operations. The benefit to cost of modifying facilities is especially worthwhile for prebaked operations where the modifications are less drastic. As such, these actions appear to be most worthwhile in those regions where the cost associated with modification is lowest.

The major retrofit option will require a total initial investment of about \$60 million for Soderberg cells and about \$5 to \$8 million for prebake cells. The retrofit option, by increasing current efficiency, produces more metal for the same amount of energy. The value of incremental production, determined using the assumed increase in current efficiency and long term price of aluminium is estimated to range from \$7 to \$18 million per year. The capital cost and benefits data are used with estimated incremental operational costs for each region to calculate the net levelised cost for each region and technology-type. As indicated in Exhibit 26, the net levelised cost is negative for prebake cells, indicating that the option is profitable. This retrofit option is not profitable for Soderberg cells in any region. Retrofitting prebake cells with point-feed systems is most profitable in Australasia and Sub-Saharan Africa.

The differences in the estimates of cost per tonne of carbon are partially due to the opportunity available. A significant portion

of the smelters in China is Soderberg in design. This technology type, along with the regional fuel mix, causes improvements in both operations and process emissions to be greater relative to the levels of production. The emission reductions are, therefore, greater in this region. Conversely, the vintage of South American smelters dictates (1) more prebake facilities of a more modern design and (2) less cost per tonne of capacity to effect changes. As shown in Exhibit 26, the emission reduction cost-effectiveness of this option ranges from -\$49 to \$313 per tonne of CO₂-E. Retrofitting prebake cells in Central and South America is most profitable.

Exhibit 25. Results for Retrofit-Minor

	VSS	HSS	SWPB	CWPB	PPPB
Energy and Emission Reductions					
Energy Intensity Reductions (%) ¹	3%	2%	3%	3%	2%
CO ₂ Process Emission Reductions (%) ²	2%	2%	2%	2%	2%
Anode Effect Frequency Reduction (%)	42%	30%	21%	21%	15%
Emission Reductions (tonnes CO ₂ -E/tonne) ³					
Asia	1.99	1.29	0.76	0.56	0.35
Australasia	1.92	1.25	0.70	0.49	0.30
Central and South America	1.79	1.18	0.56	0.36	0.20
Eastern Europe and Former Soviet Union	1.94	1.27	0.72	0.52	0.32
North Africa and Middle East	1.99	1.29	0.76	0.56	0.35
North America	1.97	1.28	0.75	0.54	0.33
Sub-Saharan Africa	2.03	1.31	0.80	0.60	0.37
Western Europe	1.89	1.23	0.66	0.46	0.27
Cost and Benefits					
<u>Benefits</u>					
Increase in Current Efficiency (%)	3%	2%	3%	3%	2%
Incremental Production (\$million/year)	10.25	5.37	10.25	10.25	7.35
<u>Costs</u> ⁴					
Capital Costs (\$million)	4.18	4.18	4.36	4.98	5.61
Capital Recovery (\$million/year)	0.55	0.55	0.57	0.65	0.74
Net Levelised Costs (\$million/year)					
Asia	-0.25	1.07	⁵	-0.66	0.04
Australasia	-	-	-2.13	-2.17	-1.71
Central and South America	0.32	1.32	-1.56	-0.74	-0.88
Eastern Europe and Former Soviet Union	-0.05	0.71	-0.72	-	-0.73
North Africa and Middle East	-0.79	-	-	-1.84	-1.67
North America	-0.72	0.15	-0.98	0.37	-0.68
Sub-Saharan Africa	-2.02	-	-1.58	-2.06	-
Western Europe	0.29	-	0.30	-0.03	-0.78
Cost-Effectiveness (\$/tonne CO₂-E)					
Asia	-4	31	-	-10	1
Australasia	-	-	-40	-40	-45
Central and South America	12	97	-59	-28	-47
Eastern Europe and Former Soviet Union	-1	24	-12	-	-18
North Africa and Middle East	-12	-	-	-27	-35
North America	-11	5	-15	6	-15
Sub-Saharan Africa	-27	-	-21	-27	-
Western Europe	6	-	7	-1	-24

1. Reduction in per unit electricity consumption (equivalent to current efficiency).

2. Reductions in carbon anode consumption per unit of aluminium produced.

3. Includes energy-related CO₂, process-related CO₂, and PFCs. For energy-related CO₂, the regional grid fuel mix is used to estimate the baseline emission factor. Baseline PFC emission factors are estimated using the slope method. See Chapter 2 for more detail on the method.

4. Capital costs include the cost of installation. A discount rate of 10 percent and a lifetime of 15 years is assumed for estimating the levelised cost. The net levelised cost estimate includes incremental operating costs.

5. No baseline cost information, as there is no production by this technology-type in the region.

Note: All costs are in 1995 US\$. Technology definitions are as follows: HSS = Horizontal Stud Soderberg; VSS = Vertical Stud Soderberg; CWPB = Center Worked Prebake; PPPB = Point Feed Prebake; SWPB = Side Worked Prebake

Exhibit 26. Results for Retrofit-Major

	VSS	HSS	SWPB	CWPB	PFPB
Energy and Emission Reductions					
Energy Intensity Reductions (%) ¹	6%	4%	5%	4%	2%
CO ₂ Process Emission Reductions (%) ²	2%	2%	2%	2%	2%
Anode Effect Frequency Reduction (%)	53%	17%	25%	25%	11%
Emission Reductions (tonnes CO ₂ -E/tonne) ³					
Asia	2.67	1.02	0.95	0.62	0.32
Australasia	2.55	0.94	0.86	0.55	0.28
Central and South America	2.31	0.79	0.68	0.41	0.18
Eastern Europe and Former Soviet Union	2.59	0.97	0.89	0.57	0.29
North Africa and Middle East	2.67	1.03	0.95	0.62	0.32
North America	2.64	1.00	0.93	0.60	0.31
Sub-Saharan Africa	2.74	1.07	1.00	0.66	0.35
Western Europe	2.49	0.90	0.81	0.51	0.25
Cost and Benefits					
<u>Benefits</u>					
Increase in Current Efficiency (%)	6%	4%	5%	4%	2%
Incremental Production (\$million/year)	18.48	12.27	13.67	10.93	7.35
<u>Costs</u> ⁴					
Capital Costs (\$million)	59.09	62.23	8.25	8.06	5.61
Capital Recovery (\$million/year)	7.77	8.18	1.08	1.06	0.74
Net Levelised Costs (\$million/year)					
Asia	6.32	9.38	⁵	-0.34	0.04
Australasia	-	-	-2.52	-1.96	-1.71
Central and South America	7.36	9.94	-1.76	-0.43	-0.88
Eastern Europe and Former Soviet Union	6.69	8.55	-0.64	-	-0.73
North Africa and Middle East	5.35	-	-	-1.60	-1.67
North America	5.48	7.27	-0.99	0.76	-0.68
Sub-Saharan Africa	3.14	-	-1.78	-1.84	-
Western Europe	7.30	-	0.72	0.33	-0.78
Cost-Effectiveness (\$/tonne CO₂-E)					
Asia	51	116	-	-5	1
Australasia	-	-	-35	-34	-45
Central and South America	151	313	-49	-15	-47
Eastern Europe and Former Soviet Union	62	122	-8	-	-18
North Africa and Middle East	43	-	-	-22	-35
North America	46	95	-11	11	-15
Sub-Saharan Africa	22	-	-18	-23	-
Western Europe	85	-	12	7	-24

1. Reduction in per unit electricity consumption (equivalent to current efficiency).
2. Reductions in carbon anode consumption per unit of aluminium produced.
3. Includes energy-related CO₂, process-related CO₂, and PFCs. For energy-related CO₂, the regional grid fuel mix is used to estimate the baseline emission factor. Baseline PFC emission factors are estimated using the slope method. See Chapter 2 for more detail on the method.
4. Capital costs include the cost of installation. A discount rate of 10 percent and a lifetime of 15 years is assumed for estimating the levelised cost. The net levelised cost estimate includes incremental operating costs.
5. No baseline cost information, as there is no production by this technology-type in the region.

Note: All costs are in 1995 US\$. Technology definitions are as follows: HSS = Horizontal Stud Soderberg; VSS = Vertical Stud Soderberg; CWPB = Center Worked Prebake; PFPB = Point Feed Prebake; SWPB = Side Worked Prebake

4.3.3 Options to Improve the Bayer Process

The alumina refining option selected for the cost assessment is the replacement of rotary by fluidised bed kiln. The capital cost of replacement is estimated at \$20 million for a 660,000 tonne per year facility. Energy savings on the order of \$1.5 million per year are expected as a result of the savings in fuel oil that is used for the calcination process due to the relative efficiency of the fluidised bed process. This study estimates that there could be savings in operating costs of approximately \$100,000 per year for such a plant. However, this estimate may vary from site to site. As a conservative and simplifying assumption, only energy savings are included in the benefits calculation. Energy-related CO₂ emissions are expected to decrease by approximately 450,000 tonnes of CO₂-E, a reduction 67 percent. The cost-effectiveness of this option is estimated at \$1 per tonne of CO₂-E.

4.3.4 Impact of Increased Recycling

The extent to which secondary aluminium production contributes to the future aluminium supply will have a significant impact on future aluminium industry energy usage because producing secondary aluminium requires only about five percent of the energy required to produce primary aluminium. The GHG emissions associated with primary production include process CO₂ and PFC emissions and combustion CO₂ emissions from bauxite mining, alumina refining, and primary aluminium production. On the other hand, only combustion CO₂ emissions are associated with secondary production.

An industry average emission factor can be derived using a weighted average of emissions and production from each stage of the process. Exhibit 27 shows industry average emission factors¹⁷ by region that are

¹⁷ For this analysis, emissions from refining and bauxite mining were distributed evenly among regions.

expected in the year 2000 and the secondary production ratio, which is the ratio of secondary aluminium to primary aluminium. These industry average emission factors vary widely ranging from 10.5 tonnes CO₂-E/tonne aluminium in North America to 35.6 tonnes CO₂-E/tonne aluminium in Sub-Saharan Africa. The world average is estimated to be 14.9 tonnes CO₂-E/tonne aluminium. Variations by region can be attributed to the efficiency of the primary production process and the current rate of aluminium recycled.

Exhibit 27. Estimated Recycling Ratio by Region, 2000

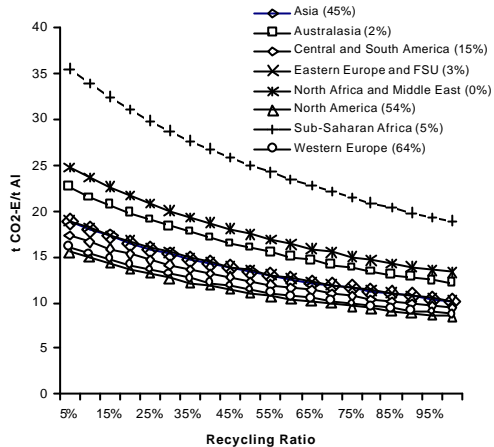
Region	Industry Emission Factor (CO ₂ -E/t Al)	Secondary Prod. Ratio (Percent)
Asia	13.8	45%
Australasia	23.2	2%
Central & S. America	15.9	15%
Eastern Europe & FSU	19.3	3%
N. Africa & M. East	25.8	0%
North America	10.8	54%
Sub-Saharan Africa	35.6	5%
Western Europe	10.5	64%
World	14.9	33%

Increasing the ratio of secondary aluminium to primary aluminium will reduce industry emission factors for a given region. The extent to which emission factors can be reduced is shown in Exhibit 28. The mitigation potential of increasing recycling is greatest the steeper the slope of the curve and the lower the current recovery rate is (i.e., the higher point on the curve).

The rate of change in the absolute emissions will depend on the production levels of primary and secondary aluminium. Improving the secondary production ratio depends on the region's ability to collect and recover old scrap from the waste stream. This ability, in turn, depends on the use cycle of metal-containing products, the past

rate of absorption into such uses, and the cost of collection and recovery.

Exhibit 28. Industry Average Emission Factors at Various Levels of Recycling, 2000



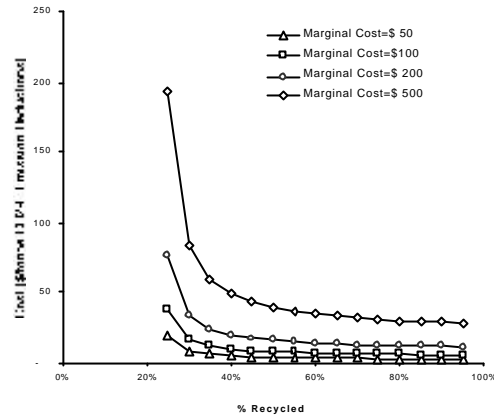
Note: The current recycling ratio for each region is indicated in parentheses in the legend.

The marginal cost of increasing secondary production will depend on the collection and recovery infrastructure in place, the volume of aluminium by product type in the waste stream annually, as well as the current recycling and recovery rates.

For illustrative purposes, Exhibit 29 shows the per unit cost of emissions reductions for a range of recycling rates, at different marginal costs of secondary production (i.e., incremental cost associated with producing secondary aluminium instead of producing primary aluminium). Because this marginal cost is uncertain and variable, a range of costs are shown, from \$50 to \$500/tonne.

As shown in the exhibit, for a given marginal cost of secondary production, the cost of emission reductions decreases as the percent recycled increases. This is because recycled aluminium has lower emissions per unit product than primary aluminium, as discussed earlier.

Exhibit 29. Cost Per ton of Emissions Reduction versus Percent Recycled



5. Future Greenhouse Gas Emissions, Reductions, and Costs

This chapter forecasts future global emissions for the near-term (2000), medium-term (2010), and long-term (2020). These emission forecasts reflect alternative policy options and mechanisms by integrating technology diffusion rates for various mitigation options and emission reductions and varying sources of energy. The marginal costs of implementing mitigation technologies as well as the barriers to implementation are discussed.

5.1 Primary Aluminium Demand Forecast

Demand for primary aluminium is dependent on a number of factors making forecasting future demand a difficult task. Primary aluminium demand depends on several factors:

- economic activity of a region,
- price of aluminium compared to competing material,
- end-uses for aluminium,
- potential for primary aluminium to replace other metals or materials, and
- potential for primary aluminium to be replaced by other metals or materials, including secondary aluminium.

Detailed historic end-use data necessary to develop a relationship for forecasting do not exist. Therefore, using a “bottom-up” or engineering approach to forecast primary aluminium is not feasible. For this analysis, primary aluminium demand is forecast using a “top-down” approach, which relates economic activity levels to primary

aluminium demand. Primary aluminium demand is assumed to increase as a function of a regions Gross Domestic Product (GDP). This relationship is expressed as follows:

$$\frac{\partial AD_R}{\partial t} = \alpha \frac{\partial GDP_R}{\partial t}$$

where AD is demand for primary aluminium in region R, α is the correlation factor, and GDP is the Gross Domestic Product for each region R. The correlation factor (α) between primary aluminium demand and GDP depends on a number of factors including the country’s level and stage of economic development. Two trends evident in most industrialised or mature economies aid in estimating this correlation factor for different regions.

Contribution of metal-intensive industrial sectors to economy changes with the level of economic activity. In the early stages of a country’s economic development, the metal-intensive industrial sectors tend to grow at a faster rate than the economy as a whole. However, as the economy matures, other sectors of the economy begin to play a larger role in economic growth. As these sectors grow, the intensity of use for metals declines.

Substitutability of aluminium for other metals increases with increasing levels of economic activity. Aluminium has obtained and continues to obtain a significant portion of its growth from substitution of other more established basic metals of iron, steel, and copper. Substitution normally requires a certain level of economic activity. Before this level is met, metal demand concentrates

on the more established basic metals. During this time, aluminium demand and its intensity of use remain fairly constant and low. However, once the threshold is passed aluminium demand experiences rapid growth.

Primary aluminium demand is forecast by region using regional GDP projections from the Organization for Economic Cooperation and Development (OECD) and the World Bank until the year 2010 (ICF, 1999). GDP projections are not available from this source after 2010; therefore, regional GDP forecasts from the U.S. Energy Information Agency are used to project demand from 2010 to 2020 (EIA, 1999). Changes in projected economic activity are converted into changes in primary aluminium demand by varied ratios. These varied ratios are based upon the stage of economic growth of the region. Primary aluminium demand is then estimated by multiplying the derived change in aluminium demand by the aluminium demand in the previous time period as follows:

$$AD_t = \Delta AD \times AD_{t-5}$$

Primary aluminium demand is expected to increase from 21 million tonnes in 1998 to over 35 million tonnes in 2020 (see Exhibit 30). Demand for primary aluminium in Asia is expected to increase at the highest rate relative to the other regions. In contrast, demand for primary aluminium in North America and Western Europe is expected to remain relatively constant. This constant demand is expected given the nature of the economies in these regions, as well as the increasing demand for secondary aluminium.

5.2 Production Forecasts

Forecast of production of bauxite, alumina, primary aluminium and secondary aluminium are presented in Exhibit 32. The following section discusses the methods used to project production levels from 2000 to 2020.

Exhibit 30. Forecasted Primary Aluminium Demand

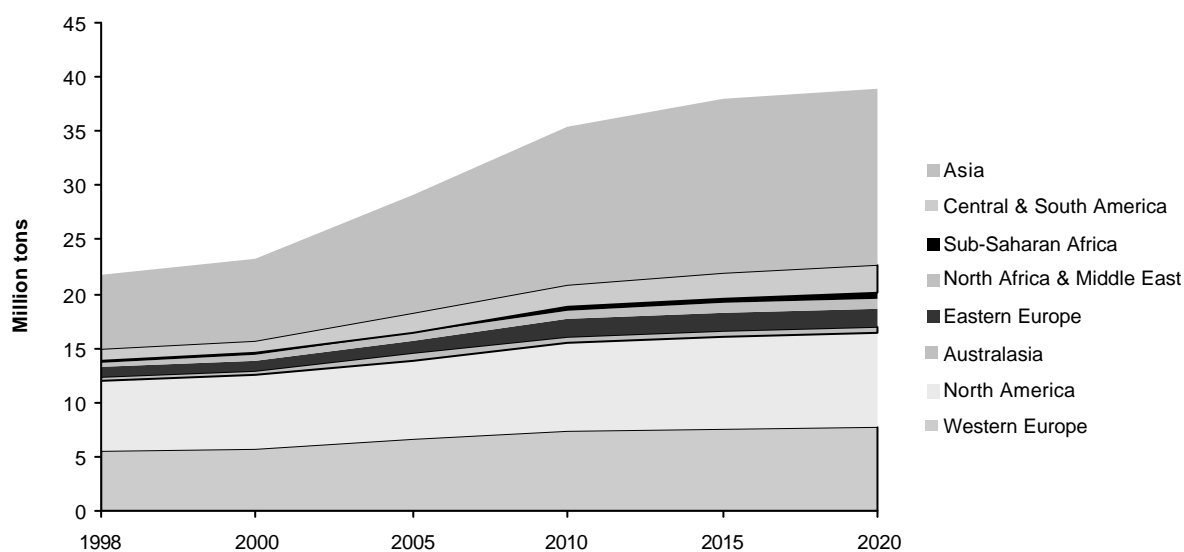


Exhibit 31. Expected New Capacity by Region, 2000-2010

(Data are in '000 tonnes)

Region	2000-2005		2005-2010	
	Capacity	Probability	Capacity	Probability
Asia	810	43%	440	27%
Australasia	620	31%	0	0%
Eastern Europe & FSU	70	50%	0	0%
Mid East & North Africa	460	70%	1,770	67%
North America	440	53%	240	50%
Latin America	0	0	400	60%
Sub-Saharan Africa	0	0	485	55%
Western Europe	0	0	230	70%
Total	2,400	47%	3,565	59%

Source: ICF, 1999; Expected new capacity from 2010 to 2020 is not available.

5.2.1 Primary Production

Primary aluminium production is expected to increase from 23 million tonnes to 38 million tonnes from 2000 to 2020, a growth rate of 2 percent per year. The regional distribution of primary production highlights the shifting location of primary production operations over time. Of particular significance is the shift in production away from Japan and the corresponding increases in South America and Australia. Correspondingly, modest growth has occurred in Canada. Australasia, with its vast reserves of bauxite and alumina, continues to be a potential source for new capacity, increasing its proportion of world production over time. Capacity is not expected to grow in the United States and Western Europe due to the age of facilities and the competition for electric power.

Global primary aluminium production is expected to meet global primary aluminium demand. For the years from 2000 to 2010, the regional production is estimated based on assumptions about increased capacity by region, expected smelter closings, and capacity increases from ongoing improvements (Exhibit 31). For 2010 to 2020, regional production changes are expected to change at the same rate as

regional changes between 2005 and 2010, assuming that new smelters and ongoing process improvements will continue in the same regions as the previous time period.

5.2.2 Alumina Refining

World production of alumina is projected to grow from 45 million tonnes in 2000 to 74 million tonnes in 2020 (see Exhibit 32). In 1990, the top producer was Australasia, followed by Central and South America, North America and Western Europe. Recent expansions in alumina production have occurred in Australia and are planned in India, Brazil, and China. Over the time period of the forecast, Australasia, Central and South America, and Asia will see the largest production increases.

The forecast of world alumina production is driven by the forecast of world primary aluminium production. On a global level, it is assumed that the historic rate of alumina production to aluminium production remains constant at 1.95. The regional production of alumina is based on expected regional capacity changes in alumina refineries from 2000 to 2010.

Exhibit 32. Forecasted Production by Stage of Process, by Region

(Data are in '000 tonnes of product)

Region	Bauxite Mining					Alumina Refining				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
Asia	14,088	16,588	16,588	18,926	20,598	4,870	6,908	7,471	8,195	8,920
Australasia	49,182	51,282	51,282	58,510	63,679	13,974	15,989	17,170	18,834	20,498
Central and South America	39,170	41,410	41,410	47,246	51,421	9,856	10,456	12,969	14,226	15,483
Easter Europe and FSU	20,363	22,013	22,663	25,857	28,142	5,244	6,074	7,959	8,730	9,502
North Africa and Middle East	850	850	850	970	1,055	142	248	261	286	312
North America	111	111	111	127	138	5,632	6,292	6,633	7,276	7,919
Sub-Saharan Africa	19,877	27,077	29,077	33,175	36,106	605	1,188	1,670	1,832	1,994
Western Europe	3,840	4,040	4,340	4,952	5,389	4,857	5,653	7,651	8,392	9,134
Total	147,481	163,371	166,321	189,762	206,529	45,180	52,807	61,784	67,772	73,760

Region	Primary Production					Secondary Production				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
Asia	2,852	3,766	4,297	4,651	5,005	1,286	1,371	1,462	1,523	1,586
Australasia	1,985	2,279	2,279	2,279	2,279	48	49	51	53	55
Central and South America	2,041	2,739	3,364	3,781	4,198	311	330	350	363	377
Easter Europe and FSU	3,847	3,989	4,187	4,319	4,451	122	131	140	150	161
North Africa and Middle East	1,424	1,897	3,530	4,620	5,709	7	7	8	9	9
North America	6,288	7,109	7,592	7,914	8,237	3,380	3,454	3,530	3,644	3,762
Sub-Saharan Africa	943	1,478	2,078	2,478	2,879	46	48	51	53	56
Western Europe	3,789	3,823	4,357	4,712	5,068	2,430	2,511	2,594	2,720	2,852
Total	23,169	27,081	31,684	34,755	37,826	7,631	7,902	8,185	8,514	8,857

5.2.3 Bauxite Mining

World production of bauxite is projected to increase from 147 million tonnes to 207 million tonnes from 2000 to 2020, a growth rate of 2 percent per year (see Exhibit 32). The forecast of world production of bauxite is based on the alumina production forecast, assuming a constant alumina to bauxite production ratio over time. On average, 3 tonnes of bauxite are required to produce one tonne of alumina, which implies a 33 percent alumina recovery rate from average grade bauxite.

5.2.4 Secondary Production

Secondary production of aluminium is expected to grow from about 7.6 thousand tonnes to 8.9 thousand tonnes in 2020, or at a growth rate of 1 percent per year (see Exhibit 32). Secondary production is highest in North America, Western Europe, and Asia (Japan). Currently almost 100 percent of new scrap is recycled in all regions. Therefore, future growth in secondary production is expected to come from growth in old scrap. Production of aluminium from old scrap is dependent on a variety of determinants including the use cycle of aluminium-containing products, the past rate of absorption into such uses, existence of an infrastructure for scrap collection, and the cost of collection and recovery. The lack of collection and recovery infrastructure is a limiting factor in the production of secondary aluminium.

The forecast of regional secondary aluminium is based on historic levels of secondary recovery and expected rates of recycling, based on industry opinion. This “top-down” approach is applied because the level of detailed historic and future end-use data necessary to develop a robust estimate from the bottom up is not available. A “bottom-up” estimate requires past and expected flow of aluminium into various uses, the length of time the aluminium will remain in these products, and the percentage of recovery at the end of the period. This

information is not available nor easily estimated. These factors vary considerably. For example, the recovery cycle varies from an extremely short period in the case of containers to as long as 50 years in electrical transmission and construction. The proportion of aluminium which is recoverable also varies widely among end uses. For example, aluminium available in large chunks or where channels of recovery are well developed would be expected to show the best recovery. However, aluminium may be moving into uses where recovery ratios will be low: containers, window frames, nails, among others. The uncertainty surrounding secondary production is greater than for primary production.

5.3 Development of Mitigation Scenarios

To examine the impact of the adoption of mitigation options discussed in this paper on industry energy use and GHG emissions, alternative technology adoption scenarios are developed. These scenarios reflect different rates of market diffusion for options over time based on when the options are likely to become commercially available and the extent of expected industry usage. Because the aluminium industry is energy-intensive and relies heavily on electricity for production, the GHG emission estimates are sensitive to the fuel-mix used to generate electricity. Therefore, three energy cases are developed to show the impact of the fuel mix. This section presents a forecast of CO₂-equivalent emissions from 1990 until 2020 in 5-year increments for the mitigation scenarios.

5.3.1 Description of Alternative Scenarios

Estimates of energy use and GHG emissions until the year 2020 are developed for three alternative scenarios: business-as-usual, state-of-the-art, and advanced. For each scenario, production levels are held

constant; the impact that the diffusion of technologies has on the level of greenhouse gas emissions is then isolated. Exhibit 33 summarises the conceptual definitions and major assumptions underlying each scenario.

For each mitigation scenario, three alternative energy supply cases are developed to show the sensitivity of GHG emissions in the aluminium industry to the fuel mix of electricity supply. These energy supply cases are discussed below.

Exhibit 33. Description of Alternative Scenarios

Scenario/Description	Business-as-Usual (BAU)	State-of-the-Art (SOA)	Advanced (ADV)
Conceptual Definition	Reflects a continuation of recent trends in energy and emissions through incremental improvements in the current state of technology.	Represents the potential for aggressive adoption of cost-effective, state-of-the-art technologies to reduce energy use and emissions.	Represents the potential for breakthrough technologies and practices expected in the next 10 to 15 years to reduce energy use and emissions.
Operational Definition	Overall industry energy intensity declines at the historical rate of 0.5 percent per year.	Higher technology diffusion rates than BAU. Energy and emission reductions are incremental to BAU. Energy intensity declines at 1 percent per year.	Diffusion of advanced technologies. Energy and emission reductions are incremental to BAU. Energy intensity declines at 1.5 percent per year.
Technology Diffusion Assumptions	<ul style="list-style-type: none"> All new alumina refineries will use fluidised bed calcination. Replacement of existing rotary kilns by fluidised kilns will occur in most regions. By 2020, half the existing rotary calciners will be replaced by fluidised bed calciners. Prebake smelters production efficiency improvement will continue at 0.5 percent per year, which will be a function of increased efficiency. Any new smelter will be PFPB with at least the level of efficiency considered average for the technology Soderberg – HSS smelters will be phased out and their capacity not replaced. VSS smelters will all be using dry anode practices and have the minimal level of computer control on all smelters by 2020. 	<ul style="list-style-type: none"> All new alumina refineries will use fluidised bed calcination. Replacement of existing rotary kilns by fluidised kilns will occur in most regions. Half of the calciners will be fluidised bed by 2015 and another 10 percent by 2020. Prebake smelters will go aggressively to PFPB's with conversion of all SWPB's by 2020. Production efficiency for the other variations of prebake will occur at 6 percent per year, with 50 percent of the CWPB's converting to PFPB. Major Soderberg retrofits will occur in all VSS locations. Where possible or economically feasible, VSS facilities will convert to PFPB. This conversion will usually be in areas where the fuel mix for electricity is thermally based. HSS smelters will cease to exist. 	<ul style="list-style-type: none"> All new alumina refineries will use fluidised bed calcination. Replacement of existing rotary kilns by fluidised kilns will occur in most regions. By 2010, all rotary kilns will be replaced by fluidised bed kilns. Potential for inert anodes and wettable cathodes in newer PFPB's. All prebake technology will be Point Feed with most advanced control features currently available in use. Major Soderberg retrofits will occur in all VSS locations. Where economic, VSS facilities will convert to PFPB. This conversion will usually be in areas where the fuel mix for electricity is thermally based. HSS smelters will cease to exist.

Technology definitions are as follows: HSS = Horizontal Stud Soderberg; VSS = Vertical Stud Soderberg; CWPB = Center Worked Prebake; PFPB = Point Feed Prebake; SWPB = Side Worked Prebake

Base Case: This case uses emission factors derived from the regional average fuel mix supplied to the grid. Forecasts of the regional fuel mix supplied to the electricity grid for a given region for 2000 to 2020 were taken from IEA's World Energy Outlook

High Case: This case uses emission factors derived from a fuel mix of 100 percent coal. This scenario provides an upper bound on emission levels and potential emission reductions for a given scenario. This scenario is not designed as a representation of reality, rather it showcases the sensitivity of the emission levels and mitigation efforts to the fuel mix.

Low Case: This case uses emission factors derived from a fuel mix of 100 percent hydroelectricity. This scenario is used to provide a lower bound on emission levels and potential emission reductions.

Given the reliance of the aluminium industry on hydroelectric power, GHG emissions estimated using region-average emission factors may be higher than actual emissions from the aluminium industry. However, the emission reductions estimated using

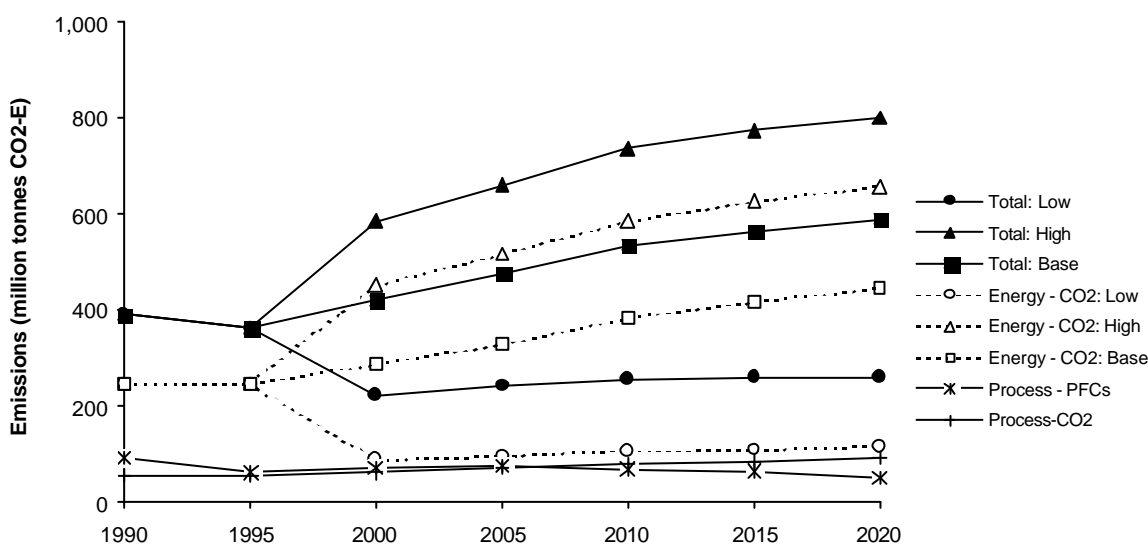
emission factors based on current electricity supply to the industry does not account for the potential emission reductions from displacing fossil fuel plants that supply electricity to the regional grid. To estimate the global emission reductions that can be achieved by mitigation options in the aluminium industry, the use of regional emission factors, or the base case, is the most appropriate.

5.3.2 Business-as-usual Emissions Forecast

Global greenhouse gas emissions are expected to increase from about 390 million tonnes CO₂-E to 590 million tonnes CO₂-E from 1990 to 2020. On a regional level, trends in emissions are driven largely by trends in production. The largest growth in greenhouse gas emissions is expected in Asia and North Africa and the Middle East where primary production capacity is expected to increase significantly.

Exhibit 33 shows the contribution of each GHG emission source to overall industry emissions. The majority of CO₂-E emissions result from fossil fuel combustion, even in the low energy supply case. Process

Exhibit 34. BAU Emissions Forecast by Gas under Alternative Energy Supply Scenarios



PFC emissions, which contributed to about one fourth of overall emissions in 1995, are expected to decline over time even as primary production increases. The declining rate of PFC emissions is largely the result of industry efforts towards achieving fewer anode effects in cells as well as the shift from VSS to prebake technology. Process CO₂ emissions are expected to increase slightly over the term of the forecast, and will contribute more to overall emissions than PFC emission by 2015. Technology and process improvements that increase the consumption efficiency of the carbon anode reduce the rate of these emissions over time.

5.3.3 State-of-the-Art and Advanced Emissions Scenario

Greenhouse gas emissions from aluminium production are expected to increase from about 390 million tonnes in 1990 to over 590 million tonnes CO₂-E in 2020 under the business-as-usual scenario. If higher technology diffusion rates are achievable, GHG emissions will increase at a slower rate. Under the state-of-the-art (SOA) scenario, emissions reach just over 500 million tonnes in 2020, an average annual growth rate of one percent since 1990.

If advanced technology is developed, including inert anodes and wettable

cathodes, and becomes commercially available before 2020, emissions from the aluminium industry will remain relatively constant at 2000 levels up to 2020, despite significant increases in production.

Exhibit 35 shows the emission forecast under different scenarios from 1990 to 2020 using the base case for energy supply.

5.4 Mitigation Potential and Associated Costs

This section analyses the mitigation potential and associated costs for emission reductions in 2010.

5.4.1 Marginal Abatement Curves

Marginal abatement curves (MACs) are developed to illustrate the amount of reductions possible at various costs and are derived by rank ordering individual opportunities by cost per tonne. Any point along a MAC represents the marginal cost of abating an additional amount of CO₂-E emissions. Exhibit 36 presents the global MAC for the aluminium industry and shows estimated potential reductions at various costs of CO₂-E (\$ per tonne of CO₂-E) for 2000, 2010, and 2020.

Exhibit 35. Emission Forecast Under Different Scenarios, 1990-2020

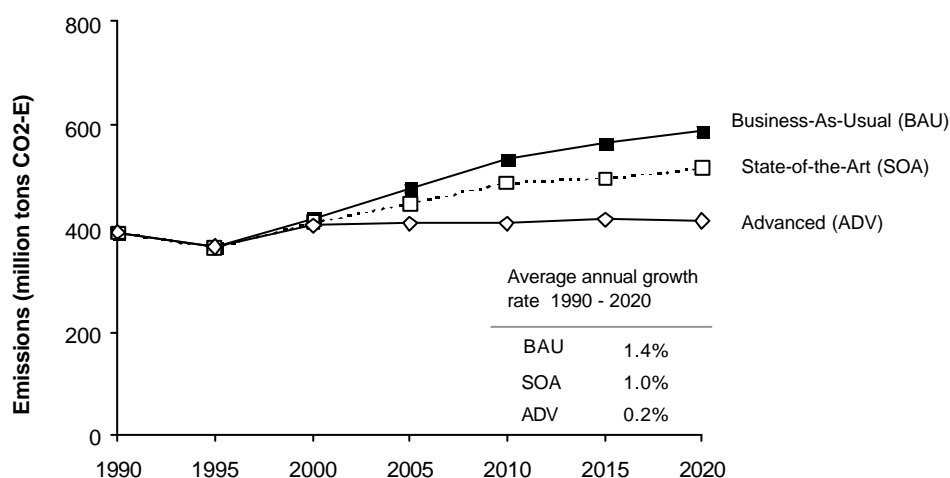
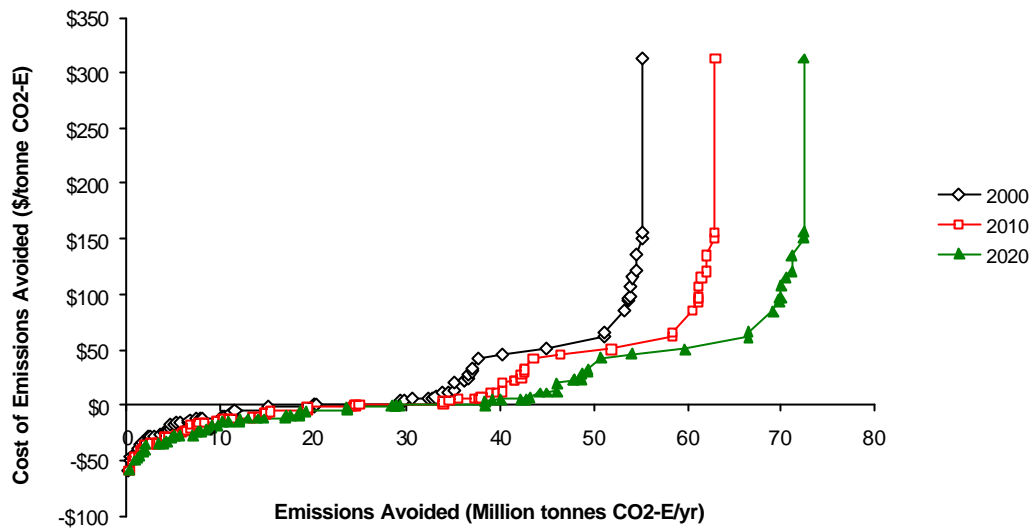


Exhibit 36. Global Marginal Abatement Curve: 2000, 2010, and 2020



For 2010, up to 67 million tonnes CO₂-E of reductions are estimated to be possible globally. Baseline emissions are estimated to be 533 million tonnes CO₂-E in 2010, assuming the BAU base case energy supply scenario. Consequently, CO₂-E emissions reductions representing about 13 percent of baseline emissions can be achieved.

The MAC for 2010 illustrates three key findings. First, emission reductions amounting to 35 million tonnes CO₂-E, are achievable at incremental costs less than \$0 per tonne CO₂-E. The reductions are profitable. Second, within the range of \$0 per tonne CO₂-E to \$100 per tonne CO₂-E, profitable reductions are estimated at an additional 25 million tonnes CO₂-E emissions. Third, above about \$100 per tonne CO₂-E, the MAC becomes relatively inelastic, which indicates the limits of the options considered.

Regional MACs were developed for each of the eight world regions of this study (see Exhibit 37). These MACs illustrate the differences in abatement costs and emission reduction potential. The potential to reduce emissions is largely a function of the magnitude of production and the degree of

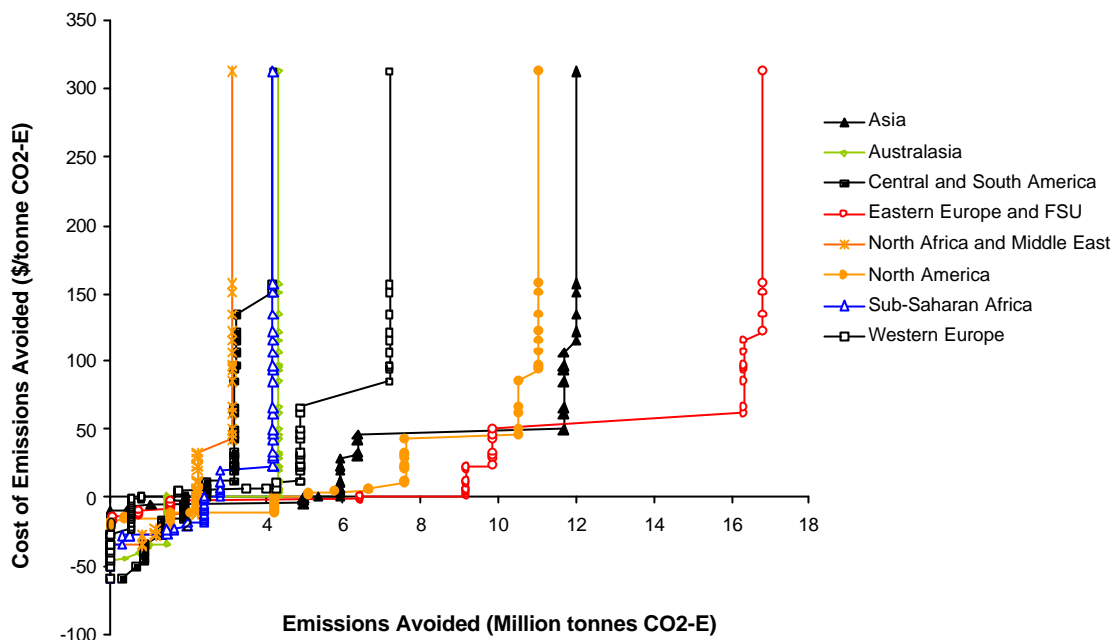
modern technology diffused in the region. Eastern Europe and the Former Soviet Union show the greatest reduction potential, or 16 million tonnes CO₂-E, whereas North Africa and the Middle East show the least, able to reduce less than 3 million tonnes CO₂-E.¹⁸

While all regions show the potential to reduce emissions cost-effectively, the greatest potential for negative cost options lies in Asia (China) and Eastern Europe and the Former Soviet Union (Russia). These regions rely on dated Soderberg technology, which offer significant GHG reduction potential.

In other regions, such as Australasia, modern technologies are already in use, and these technologies have already captured the low-cost reductions. Therefore, marginal abatement costs in these regions are relatively high. Since marginal abatement costs vary significantly among regions, international co-operation through mechanisms such as emissions trading can reduce the global cost of emission reduction.

¹⁸ Data used to generate the MACs are in the Annex of this report.

Exhibit 37. Marginal Abatement Curves by Region. 2010



GHG emissions can be reduced in the region where the marginal abatement costs are the lowest.

5.4.2 Cost of Achieving Quantified Emission Reductions

A comparison of emission reduction costs on a regional level is interesting, specifically in the context of the Kyoto Protocol. The Kyoto Protocol, drafted in 1997 but not yet ratified¹⁹, calls for Annex B Parties²⁰ to prepare inventories, report national GHG mitigation efforts, and set timetables for reducing emissions. The protocol includes six GHGs: CO₂, CH₄, N₂O,

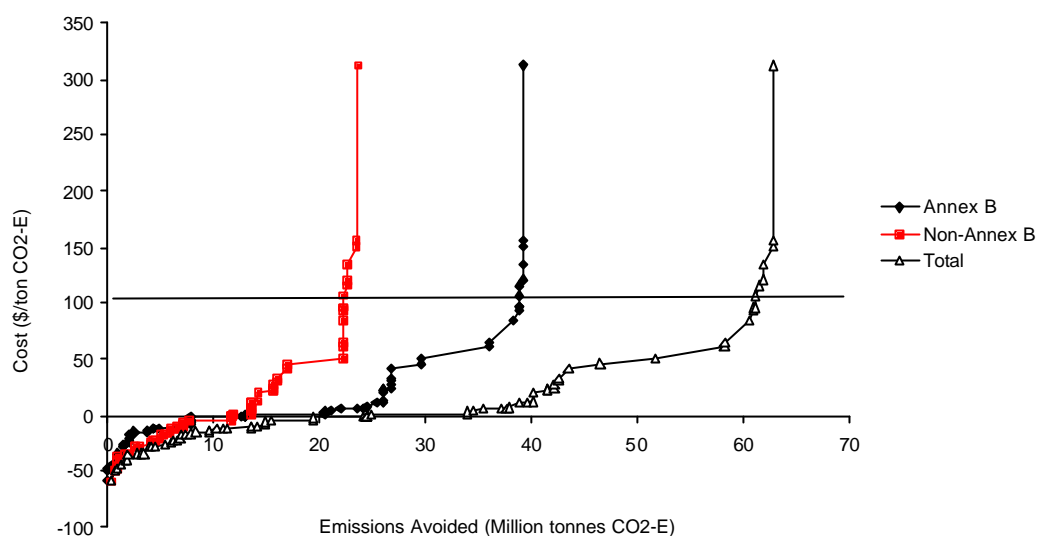
hydrofluorocarbons (HFCs), PFCs, and sulphur hexafluoride (SF₆). Emissions targets for the United States, the European Union, and Japan have been set at 7 percent, 8 percent, and 6 percent, respectively, below 1990 emissions levels for all six gases. Emission reductions will be measured against a baseline, which has been agreed as the 1990 emission levels. A provision has been made for HFC, PFC and SF₆ emissions in which countries can use either 1990 or 1995 as the base-line year for these gases. Each country may decide which baseline to use based on their specific circumstances. The commitment period for Annex B Parties has been established for 2008-2012.

¹⁹ The Kyoto Protocol will become legally binding ("enter into force") ninety days after the date on which not less than 55 Parties to the Convention ratify, and must include at least 55 percent of the 1990 total CO₂ emissions from Annex I Parties. Annex I Parties include Organisation for Economic Co-operation and Development (OECD) member countries, except Mexico, and countries with economies in transition to market economies.

²⁰ Annex B countries include Annex I (except Belarus and Turkey), Croatia, Liechtenstein, Monaco, and Slovenia.

The Kyoto Protocol is designed to promote cost-effective mitigation strategies and allow Parties a variety of options to reduce emission levels. First, the Kyoto Protocol delineates six GHGs and allows countries to reduce any combination of these GHGs. Second, the Protocol outlines three policy mechanisms including joint implementation among Annex I Parties (Article 6), the Clean Development Mechanism (CDM) (Article

Exhibit 38. Marginal Abatement Curves for Annex B and non -Annex B, 2010



12), and national emissions trading (Article 17). These mechanisms provide the framework for international efforts to reduce carbon equivalent emissions on both the project level and on the national level.

Implementation of the three policy mechanisms outlined in the Kyoto Protocol may help countries to reach their emission reduction agreements. From an economic perspective, international co-operation can significantly reduce the costs of achieving quantified emission reductions or increase the quantity of reductions at a given cost.

Exhibit 38 highlights the potential GHG emission reductions available in Annex B and non-Annex B in 2010. For a cost of \$100 per tonne CO₂-E, approximately 40 million tonnes CO₂-E reductions are available in Annex B whereas 20 million tonnes CO₂-E are available in non-Annex B. If Annex B can undertake mitigation efforts in both Annex B and non-Annex B, global emission reductions of 60 million tonnes CO₂-E can be achieved at the same cost, or \$100 per tonne CO₂-E.

5.4.3 Key Barriers to Implementation of Mitigation Options

A number of barriers inhibit the wider diffusion of emission reduction technologies and practices within the aluminium industry. Key barriers and possible responses are discussed below.

Economic. The key economic barriers are access to capital and price uncertainty.

Access to capital. While a number of mitigation options were found to be cost-effective in this analysis, these options may be capital intensive. Producers may lack the capital necessary for investment in major retrofits. For example, in Russia, raising capital to make such improvements is difficult due to the current economic and political conditions.

Price uncertainty. Aluminium producers are currently price-takers. If the price of aluminium is low, they run the risk of closing down. Uncertainty about future prices leads to reluctance in undertaking capital intensive improvements that will

reduce energy use and emissions. Companies should explore actions to reduce exposure to price risk (e.g., long-term contracts or options trading). Future policies on energy (deregulation) and environment (CO₂ tax) may affect the price of electricity. The implied cost of energy-efficiency measures will be effected.

Technical. Current understanding of the electrolytic processes limit the development of emissions reduction measures (e.g., in areas such as the electrode kinetics of PFC generation). Basic science and technology research focused on understanding the conditions that cause anode effects and those that can limit them are necessary. Further research and development into the fundamentals of the electrolytic process may accelerate the development of the inert anode and wettable cathode, which can withstand the demanding cell environment.

Lack of information. Lack of familiarity and technical information on performance characteristics of emission reduction technologies may limit their use. Information sharing, on the technical or programmatic issues associated with implementing new technologies, may encourage producers to act. Industry associations and international collaboration will facilitate information sharing and help producers identify cost savings measures, as well as emission.

Lack of infrastructure for recycling. In a number of countries the infrastructure to recover and recycle aluminium is not developed or not well developed. Often, recycling does not occur, or cannot occur, where no recycling infrastructure is present. As a result, material for which demand exists and for which a willingness to recycle exists, is not recycled. Governments can play a role in establishing this infrastructure, the initial cost of which may otherwise be a barrier to recycling (e.g., deposit container laws, curb-side recycling programs).

Regulatory uncertainty. The future regulation of the aluminium industry is uncertain in a number of world regions. While some producer nations may currently have regulations that limit GHG emissions (e.g., Norway), others are still in the process of developing a climate policy.

If producers act to reduce emissions before policies are in place, they may be at a disadvantage as their later (lower) emissions levels will become the new baseline. In addition, producers may lose these low cost options for reduction, assuming a producer will implement options based on least marginal cost. Under this scenario, producers that act early will have to implement higher cost options if future policies do not recognise early action. This situation may put early actors at a competitive disadvantage.

Given this uncertainty, a number of producers have entered into voluntary agreements with their national government.

6. Conclusions

The aluminium industry is a relatively small contributor to total global anthropogenic GHG emissions. Total GHG emissions from the aluminium industry were estimated to be 391 million tonnes CO₂-E in 1990 and 364 million tonnes CO₂-E in 1995. Total anthropogenic emissions of GHGs are estimated to be about 35,000 million tonnes CO₂-E in 1995. The aluminium industry contributed 1 percent of total anthropogenic GHG emissions in 1995.

The majority of GHG emissions are a result of fossil fuel combustion used to provide energy for the mining and processing of raw materials, power electrolytic reduction of alumina to aluminium, and cast metal. The fuel or resource used to generate energy for the electrolytic reduction is the most important factor influencing total CO₂ emissions from aluminium production. CO₂ emissions per tonne of aluminium vary by a factor of five depending on whether coal or hydroelectricity is used as a source of power for the electrolytic reduction.

Primary aluminium production is the most energy and emissions-intensive stage in the process of aluminium production. Of the CO₂ emissions from fossil fuel combustion, the majority is a result of generating electricity required for the Hall-Héroult process. Energy use accounts for a significant portion of the production costs and GHG emissions. To remain competitive, the industry has undertaken measures to increase energy and production efficiency. In addition to reducing the energy intensity of the process, these measures also reduce GHG emissions.

North America and Eastern Europe and the Former Soviet Union were the largest sources of GHG emissions in 1995. These regions have the largest share of primary aluminium production and tend to have older technologies. The analysis presented in this report is based on best available information. As new information becomes available, estimates for these countries can be revised. For example, data for China and Russia are uncertain as little published data exist for these countries.

Technologies for reducing GHG emissions are well demonstrated and readily available. Energy and emissions reductions can be achieved by installing improved cell technologies with higher amperages, installing computer control systems, instituting better operating practices in new and existing smelters, and increasing recycling. The greatest potential in the short to medium-term is options to improve the energy-efficiency of the Hall-Héroult process and reduce the occurrence of anode effects that generate PFC emissions. In the long term, inert anodes and wettable cathodes have the promise of eliminating process emissions and reducing the energy intensity of the Hall-Héroult process.

Significant cost-effective GHG mitigation options are available globally. Approximately 35 million tonnes of CO₂-E reductions can be achieved at a negative cost in 2010 and are available in each of the eight world regions of this study. The existence of negative cost options depends on the existence of substantial market or institutional imperfections that prevent cost-effective emission reduction measures from being taken. The key question is whether such imperfections can be removed cost

effectively by policy measures. Also, given difference in marginal emission reduction costs among countries, international co-operation can significantly reduce the global cost for emission reduction.

Increased recycling will have a significant impact on industry energy use and emissions. Increasing recycling offers considerable potential to reduce overall industry-average emission factors; however, key implementation barriers exist. The lack of infrastructure in some regions, the cost of collection and recovery, and the competitiveness of the industry keeps the market share from increasing rapidly. Further analysis of the cost of recovering secondary aluminium is necessary. Currently, cost data and recovery rates for old scrap are very limited for both developed and developing countries. In order to assess the impact of this option, further study is required.

Future GHG emissions from the aluminium industry are expected to increase globally from 2000 to 2020, but at a slower rate than aluminium production. World primary aluminium production is projected to increase from 23 million tonnes to 38 million tonnes from 2000 to 2020, an average annual growth rate of 2 percent. Growth in GHG emissions is expected to be lower than the growth in production due to the implementation of cost-effective technologies that improve operational and production efficiency. Diffusion of advanced technologies, such as the inert anode and wettable cathode, have the potential to stabilise industry emissions at 1990 levels by the year 2020.

Policy options should focus on promoting research and development into GHG emission reduction measures and providing industry with incentives to reduce GHG emissions. Government policy should encourage the use of energy efficient technologies, support the sharing of technical information, reduce regulatory uncertainty, and promote research and

development efforts. Policy makers should also reduce regulatory uncertainty by providing credit for voluntary actions to reduce emissions. If policies do not recognise voluntary action, producers that act prior to national regulations or an international crediting system may be at a disadvantage if their later (lower) emissions levels become the new baseline against which future emission reductions will be measured. Marginal abatement costs will be higher. By removing this regulatory uncertainty, policymakers provide incentive for producers to act now to reduce emissions. On a global level, least cost emissions reductions will be achieved through international co-operation mechanisms such as emissions trading.

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Exhibit A-1. List of Countries in Each Region*

1. Asia	2. Australasia	3. Central and South America	4. Eastern Europe and FSU	5. North Africa and Middle East	6. North America	7. Sub-Saharan Africa	8. Western Europe
China	Australia	Argentina	Albania	Bahrain	Canada	Cameroun	Austria
India	New Zealand	Brazil	Azerbaijan	Egypt	Mexico	Ghana	France
Indonesia		Dominican Republic	Bosnia-Herzegovina	Iran	USA	Mozambique	Germany
Japan		Guyana	Croatia	UAE		Nigeria	Greece
Korea		Haiti	Kazakhstan			Sierra Leone	Hungary
Malaysia		Jamaica	Kosovo			South Africa	Iceland
		Suriname	Montenegro			Zimbabwe	Ireland
		Venezuela	Poland				Italy
			Romania				Netherlands
			Russia				Norway
			Serbia				Spain
			Slovakia				Sweden
			Slovenia				Switzerland
			Tajikistan				Turkey
			Ukraine				UK

*Countries listed are those that have either bauxite mines, alumina refineries, or aluminium smelters.

Exhibit A-2. Per Unit Electricity Consumption for Primary Aluminium Production

(Data are in kWh/tonne of Aluminium)

1990

Region	CWPB	HSS	PBPF	SWPB	VSS	Weighted Avg. Production
Asia	15,704	16,026	14,103	15,362	16,796	16,080
Austrasia	16,209	16,209	14,673	15,440	16,796	15,397
Central and South America	16,418	16,418	14,748	15,483	16,858	16,067
Eastern Europe and Former Soviet Union	16,251	16,251	14,708	15,200	16,251	15,897
North Africa and Middle East	16,181	16,181	14,663	15,200	16,181	15,590
North America	16,744	16,827	16,182	16,262	16,953	16,518
Sub-Saharan Africa	16,181	16,181	14,663	15,200	16,181	15,590
Western Europe	16,251	16,251	14,708	15,200	16,251	15,897
Average:	16,242	16,293	14,806	15,418	16,533	16,113

1995

Region	CWPB	HSS	PBPF	SWPB	VSS	Production Weighted Avg.
Asia	16,057	16,698	16,057	16,057	16,057	16,114
Austrasia	15,238	16,698	15,238	15,238	15,238	15,238
Central and South America	15,580	16,707	15,580	15,580	15,580	15,607
Eastern Europe and Former Soviet Union	15,490	16,698	15,490	15,490	15,490	15,603
North Africa and Middle East	15,817	16,698	15,817	15,817	15,817	15,817
North America	15,951	16,294	15,951	15,951	16,430	16,048
Sub-Saharan Africa	15,817	16,698	15,817	15,817	15,817	15,817
Western Europe	15,490	16,698	15,490	15,490	15,490	15,603
Average:	15,680	16,649	15,680	15,680	15,740	15,800

Source: Production weighted estimates across technology-types were from the IPAI Statistical Summary, Volume 7 (1990 –1994) and Volume 9 (1993-1997). The breakdown by technology-type was calculated using the relative production by technology-type in each region and relative ratios of per-unit electricity consumption by technology-type from Richards, 1997.

Exhibit A-3. Regional Fuel Mix Data

Year	Fuel –Type	Asia	Australasia	Central and South America	Eastern Europe and FSU	North Africa and Middle East	North America	Sub-Saharan Africa	Western Europe
1990	Coal	38.2%	60.7%	3.8%	34.3%	4.8%	45.2%	53.3%	32.5%
	Gas	11.4%	8.8%	10.0%	27.5%	38.0%	14.7%	11.3%	9.2%
	Hydro	22.2%	25.8%	61.7%	16.8%	6.1%	17.3%	17.1%	19.3%
	Nuclear	7.7%	0.0%	1.6%	10.5%	0.0%	16.3%	2.4%	26.2%
	Other	20.5%	4.7%	22.9%	10.9%	51.2%	6.7%	16.0%	12.9%
1995	Coal	41.0%	64.3%	4.0%	31.0%	6.0%	46.0%	51.0%	30.0%
	Gas	13.5%	10.8%	10.0%	30.0%	44.0%	13.0%	14.0%	10.0%
	Hydro	18.0%	20.7%	64.0%	17.0%	4.0%	16.0%	15.0%	18.0%
	Nuclear	9.5%	0.0%	2.0%	13.0%	0.0%	20.0%	3.0%	32.0%
	Other	18.0%	4.2%	20.0%	9.0%	46.0%	5.0%	17.0%	10.0%
2000	Coal	25.0%	62.7%	5.0%	30.0%	7.3%	46.3%	49.0%	28.3%
	Gas	19.7%	12.4%	12.0%	34.3%	46.3%	16.7%	17.7%	16.3%
	Hydro	12.0%	19.4%	61.7%	15.7%	4.7%	14.7%	14.0%	17.0%
	Nuclear	16.7%	0.0%	2.0%	12.0%	0.0%	17.7%	2.7%	28.7%
	Other	26.7%	5.5%	19.3%	8.0%	41.7%	4.7%	16.7%	9.7%
2010	Coal	45.5%	59.4%	7.0%	28.0%	10.0%	47.0%	45.0%	25.0%
	Gas	18.5%	15.6%	16.0%	43.0%	51.0%	24.0%	25.0%	29.0%
	Hydro	14.5%	16.9%	57.0%	13.0%	6.0%	12.0%	12.0%	15.0%
	Nuclear	8.5%	0.0%	2.0%	10.0%	0.0%	13.0%	2.0%	22.0%
	Other	13.0%	8.1%	18.0%	6.0%	33.0%	4.0%	16.0%	9.0%
2020	Coal	48.5%	58.1%	7.0%	23.0%	9.0%	55.0%	43.0%	18.0%
	Gas	23.5%	16.2%	30.0%	54.0%	60.0%	24.0%	33.0%	45.0%
	Hydro	11.5%	16.0%	47.0%	11.0%	3.0%	11.0%	10.0%	14.0%
	Nuclear	7.0%	0.0%	1.0%	5.0%	0.0%	7.0%	1.0%	16.0%
	Other	9.5%	9.6%	15.0%	7.0%	28.0%	3.0%	13.0%	7.0%

Source: IEA World Energy Outlook, 1998.

Exhibit A-4. Emission Factors by Fuel-Type

Emission Factors by Fuel-Type

Fuel Type	t CO ₂ -E/GJ
Coal	0.09
Gas	0.05
Hydro	0.00
Nuclear	0.00
Other	0.07

Source: IPCC Revised Guidelines for Greenhouse Gas Inventories, 1997.

Electricity Generation Emission Factors Based on Regional -Fuel Mix

(Data are in t CO₂-E/GJ)

Region	1990	1995	2000	2005	2010	2015	2020
Asia	0.054	0.056	0.050	0.051	0.060	0.061	0.063
Australasia	0.064	0.067	0.067	0.067	0.067	0.068	0.068
Central and South America	0.024	0.022	0.024	0.025	0.027	0.029	0.031
Eastern Europe and FSU	0.052	0.049	0.050	0.050	0.051	0.052	0.053
North Africa and Middle East	0.058	0.059	0.058	0.057	0.057	0.057	0.057
North America	0.053	0.052	0.054	0.056	0.058	0.061	0.065
Sub-Saharan Africa	0.066	0.066	0.065	0.065	0.065	0.065	0.065
Western Europe	0.043	0.039	0.041	0.042	0.044	0.044	0.044

Source: Calculated based on regional fuel mix data and emission factors by fuel-type.

Exhibit A-5. PFC Emissions Data

Slope Coefficients by Technology Type

Tech Type	CF ₄	C ₂ F ₆
CWPB	0.14	0.018
PFPB	0.14	0.018
SWPB	0.29	0.029
HSS	0.18	0.018
VSS	0.068	0.0027

Source: IPCC Workshop on Good Practices in Inventory Preparation, Washington D.C., 1999.

Production Weighted AE Minutes Per-Cell Day by Technology-Type

	1990	1995
CWPB	3.41	1.56
PFPB	2.30	1.10
SWPB	6.49	5.33
HSS	3.50	3.12
VSS	10.28	7.07

Note: 1991 data used for HSS

Source: IPAI, 1999.

Exhibit A-6. Production Forecasts

(Data are in '000 tonnes of product)

Primary Production

Region	1990	1995	2000	2005	2010	2015	2020
Asia	1,146	1,594	2,852	3,766	4,297	4,651	5,005
Australasia	1,540	1,566	1,985	2,279	2,279	2,279	2,279
Central and South America	1,705	1,998	2,041	2,739	3,364	3,781	4,198
Eastern Europe and Former Soviet Union	3,654	4,992	3,847	3,989	4,187	4,319	4,451
North Africa and Middle East	367	378	1,424	1,897	3,530	4,620	5,709
North America	5,700	5,606	6,288	7,109	7,592	7,914	8,237
Sub-Saharan Africa	245	253	943	1,478	2,078	2,478	2,879
Western Europe	3,850	3,284	3,789	3,823	4,357	4,712	5,068
Total	18,207	19,671	23,169	27,081	31,684	34,755	37,826

Secondary Production

Region	1990	1995	2000	2005	2010	2015	2020
Asia	1,361	1,286	1,286	1,371	1,462	1,523	1,586
Australasia	38	46	48	49	51	53	55
Central and South America	166	288	311	330	350	363	377
Eastern Europe and Former Soviet Union	-	107	122	131	140	150	161
North Africa and Middle East	9	7	7	7	8	9	9
North America	2,477	3,285	3,380	3,454	3,530	3,644	3,762
Sub-Saharan Africa	41	46	46	48	51	53	56
Western Europe	1,930	2,335	2,430	2,511	2,594	2,720	2,852
Total	6,021	7,401	7,631	7,902	8,185	8,514	8,857

Production Forecasts (cont'd)

(Data are in '000 tons of product)

Bauxite Production

Region	1990	1995	2000	2005	2010	2015	2020
Asia	10,539	12,888	14,088	16,588	16,588	18,926	20,598
Australasia	44,990	48,332	49,182	51,282	51,282	58,510	63,679
Central and South America	29,475	38,420	39,170	41,410	41,410	47,246	51,421
Eastern Europe and Former Soviet Union	12,755	9,313	20,363	22,013	22,663	25,857	28,142
North Africa and Middle East	93	100	850	850	850	970	1,055
North America	550	111	111	111	111	127	138
Sub-Saharan Africa	17,984	19,877	19,877	27,077	29,077	33,175	36,106
Western Europe	6,324	2,040	3,840	4,040	4,340	4,952	5,389
Total	122,710	131,081	147,481	163,371	166,321	189,762	206,529

Alumina Production

Region	1990	1995	2000	2005	2010	2015	2020
Asia	3,733	3,863	4,870	6,908	7,471	8,195	8,920
Australasia	11,000	12,785	13,974	15,989	17,170	18,834	20,498
Central and South America	7,170	8,110	9,856	10,456	12,969	14,226	15,483
Eastern Europe and Former Soviet Union	5,387	4,512	5,244	6,074	7,959	8,730	9,502
North Africa and Middle East	-	-	142	248	261	286	312
North America	5,550	4,770	5,632	6,292	6,633	7,276	7,919
Sub-Saharan Africa	640	630	605	1,188	1,670	1,832	1,994
Western Europe	5,390	4,118	4,857	5,653	7,651	8,392	9,134
Total	38,870	38,788	45,180	52,807	61,784	67,772	73,760

Exhibit A-7. Data for Marginal Abatement Curves

Region Name	Option Tech Type	Cost (\$/tonne)	Emissions Reduction Factor (tonnes CO ₂ -E/tonne)	Capacity Eligible (‘000 tonnes)	Incremental Emissions Reduction (‘000 tonnes CO ₂ -E)	Cumulative Emissions Reduction (‘000 tonnes CO ₂ -E)
Central and South America	Retrofit-Minor - SWPB	\$ (59.16)	0.56	535	302	302
Central and South America	Retrofit-Major - SWPB	\$ (49.48)	0.68	535	367	669
Central and South America	Retrofit-Minor - PB-PF	\$ (46.71)	0.20	1,018	208	877
Central and South America	Retrofit-Major - PB-PF	\$ (46.71)	0.18	1,018	184	1,061
Australasia	Retrofit-Minor - PB-PF	\$ (44.77)	0.30	1,294	388	1,448
Australasia	Retrofit-Major - PB-PF	\$ (44.77)	0.28	1,294	356	1,804
Australasia	Retrofit-Minor - CWPB	\$ (40.50)	0.49	827	407	2,211
Australasia	Retrofit-Minor - SWPB	\$ (39.66)	0.70	158	110	2,321
Australasia	Retrofit-Major - SWPB	\$ (34.80)	0.86	158	136	2,457
North Africa and Middle East	Retrofit-Minor - PB-PF	\$ (34.67)	0.35	2,586	900	3,356
North Africa and Middle East	Retrofit-Major - PB-PF	\$ (34.67)	0.32	2,586	837	4,193
Australasia	Retrofit-Major - CWPB	\$ (34.12)	0.55	827	453	4,646
Sub-Saharan Africa	Retrofit-Minor - PB-PF	\$ (33.52)	0.37	874	328	4,974
Sub-Saharan Africa	Retrofit-Major - PB-PF	\$ (33.52)	0.35	874	306	5,280
Central and South America	Retrofit-Minor - CWPB	\$ (28.01)	0.36	1,355	488	5,768
Sub-Saharan Africa	Retrofit-Minor - CWPB	\$ (27.32)	0.60	286	171	5,939
North Africa and Middle East	Retrofit-Minor - CWPB	\$ (27.18)	0.56	597	334	6,274
Sub-Saharan Africa	Retrofit-Minor - VSS	\$ (26.78)	2.03	487	986	7,260
Western Europe	Retrofit-Minor - PB-PF	\$ (23.68)	0.27	2,121	581	7,841
Western Europe	Retrofit-Major - PB-PF	\$ (23.68)	0.25	2,121	529	8,370
Sub-Saharan Africa	Retrofit-Major - CWPB	\$ (22.79)	0.66	286	189	8,559
North Africa and Middle East	Retrofit-Major - CWPB	\$ (22.13)	0.62	597	371	8,929
Sub-Saharan Africa	Retrofit-Minor - SWPB	\$ (20.89)	0.80	431	346	9,275
Eastern Europe and FSU	Retrofit-Minor - PB-PF	\$ (17.60)	0.32	215	68	9,343
Eastern Europe and FSU	Retrofit-Major - PB-PF	\$ (17.60)	0.29	215	63	9,406
Sub-Saharan Africa	Retrofit-Major - SWPB	\$ (17.51)	1.00	431	431	9,837
North America	Retrofit-Minor - SWPB	\$ (15.37)	0.75	509	380	10,217
Central and South America	Retrofit-Major - CWPB	\$ (15.15)	0.41	1,355	552	10,769
North America	Retrofit-Minor - PB-PF	\$ (14.96)	0.33	3,882	1,299	12,068
North America	Retrofit-Major - PB-PF	\$ (14.96)	0.31	3,882	1,204	13,273
Eastern Europe and FSU	Retrofit-Minor - SWPB	\$ (12.30)	0.72	944	679	13,952

Exhibit A-7. Data for Marginal Abatement Curves

Region Name	Option Tech Type	Cost (\$/tonne)	Emissions Reduction Factor (tonnes CO ₂ -E/tonne)	Capacity Eligible (‘000 tonnes)	Incremental Emissions Reduction (‘000 tonnes CO ₂ -E)	Cumulative Emissions Reduction (‘000 tonnes CO ₂ -E)
North Africa and Middle East	Retrofit-Minor - VSS	\$ (11.75)	1.99	347	690	14,641
North America	Retrofit-Major - SWPB	\$ (11.48)	0.93	509	472	15,113
North America	Retrofit-Minor - VSS	\$ (11.32)	1.97	1,100	2,168	17,281
Asia	Retrofit-Minor - CWPB	\$ (9.82)	0.56	885	494	17,775
Eastern Europe and FSU	Retrofit-Major - SWPB	\$ (8.09)	0.89	944	842	18,617
Asia	Retrofit-Major - CWPB	\$ (4.79)	0.62	885	548	19,165
Asia	Retrofit-Minor - VSS	\$ (3.75)	1.99	1,989	3,953	23,118
Eastern Europe and FSU	Retrofit-Minor - VSS	\$ (0.89)	1.94	2,501	4,863	27,981
Western Europe	Retrofit-Minor - CWPB	\$ (0.56)	0.46	554	253	28,234
Asia	Retrofit-Minor - PB-PF	\$ 0.84	0.35	1,086	377	28,611
Asia	Retrofit-Major - PB-PF	\$ 0.84	0.32	1,086	350	28,961
Asia	Rotary Kiln to Fluidized Bed - Rotary	\$ 0.97	0.69	850	582	29,544
Australasia	Rotary Kiln to Fluidized Bed - Rotary	\$ 0.97	0.69	4,207	2,883	32,427
Central and South America	Rotary Kiln to Fluidized Bed - Rotary	\$ 0.97	0.69	865	593	33,020
Eastern Europe and FSU	Rotary Kiln to Fluidized Bed - Rotary	\$ 0.97	0.69	3,955	2,710	35,730
North America	Rotary Kiln to Fluidized Bed - Rotary	\$ 0.97	0.69	1,334	914	36,644
Sub-Saharan Africa	Rotary Kiln to Fluidized Bed - Rotary	\$ 0.97	0.69	630	432	37,076
Western Europe	Rotary Kiln to Fluidized Bed - Rotary	\$ 0.97	0.69	1,441	988	38,063
North America	Retrofit-Minor - HSS	\$ 4.52	1.28	510	652	38,715
North America	Retrofit-Minor - CWPB	\$ 5.84	0.54	1,591	861	39,576
Western Europe	Retrofit-Minor - VSS	\$ 6.25	1.89	913	1,722	41,299
Western Europe	Retrofit-Minor - SWPB	\$ 6.54	0.66	769	508	41,807
Western Europe	Retrofit-Major - CWPB	\$ 6.73	0.51	554	283	42,089
North America	Retrofit-Major - CWPB	\$ 11.11	0.60	1,591	956	43,045
Western Europe	Retrofit-Major - SWPB	\$ 11.61	0.81	769	625	43,670
Central and South America	Retrofit-Minor - VSS	\$ 12.31	1.79	381	682	44,353
Sub-Saharan Africa	Retrofit-Major - VSS	\$ 22.47	2.74	487	1,334	45,687
Eastern Europe and FSU	Retrofit-Minor - HSS	\$ 23.65	1.27	527	667	46,353
Asia	Retrofit-Minor - HSS	\$ 30.89	1.29	336	433	46,786
North Africa and Middle East	Retrofit-Major - VSS	\$ 42.73	2.67	347	927	47,713
North America	Retrofit-Major - VSS	\$ 46.38	2.64	1,100	2,903	50,616
Asia	Retrofit-Major - VSS	\$ 50.73	2.67	1,989	5,311	55,927

Exhibit A-7. Data for Marginal Abatement Curves

Region Name	Option Tech Type	Cost (\$/tonne)	Emissions Reduction Factor (tonnes CO ₂ -E/tonne)	Capacity Eligible (‘000 tonnes)	Incremental Emissions Reduction (‘000 tonnes CO ₂ -E)	Cumulative Emissions Reduction (‘000 tonnes CO ₂ -E)
Eastern Europe and FSU	Retrofit-Major - VSS	\$ 61.84	2.59	2,501	6,483	62,410
Western Europe	Retrofit-Major - VSS	\$ 85.23	2.49	913	2,271	64,681
North America	Retrofit-Major - HSS	\$ 94.50	1.00	510	512	65,193
Central and South America	Retrofit-Minor - HSS	\$ 97.09	1.18	75	89	65,282
Asia	Retrofit-Major - HSS	\$115.55	1.02	336	344	65,626
Eastern Europe and FSU	Retrofit-Major - HSS	\$121.54	0.97	527	512	66,138
Central and South America	Retrofit-Major - VSS	\$150.97	2.31	381	882	67,020
Central and South America	Retrofit-Major - HSS	\$313.04	0.79	75	59	67,079

Exhibit A-8. Emissions Forecasts

(Data are in million tonnes of CO₂-E)

Base Case – Regional Fuel Mix

Region	Business-As-Usual (BAU)					State-of-the-Art (SOA)					Advanced (ADV)				
	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
Asia	47	60	71	75	77	46	56	64	63	64	45	51	53	54	54
Australasia	54	60	59	60	60	53	58	56	56	57	53	55	49	48	45
Central and South America	35	41	48	53	57	34	38	44	46	50	33	36	38	41	43
Eastern Europe and FSU	78	79	81	80	78	76	74	73	68	65	74	65	58	60	62
North Africa and Middle East	19	25	44	56	66	18	23	41	51	61	19	23	37	43	45
North America	111	124	129	135	139	108	117	118	119	122	108	107	97	94	89
Sub-Saharan Africa	19	27	35	39	42	18	25	31	33	36	18	23	27	30	32
Western Europe	59	59	66	68	69	57	56	60	60	61	56	49	48	46	44
Grand Total	421	475	533	566	588	411	449	488	496	516	407	408	407	416	413

High Case – 100% Coal, 0% Hydro

Region	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
Asia	67	86	94	98	99	65	80	84	83	82	65	74	71	71	70
Australasia	62	69	68	68	68	61	66	65	63	64	61	63	57	55	52
Central and South America	58	71	84	90	96	56	65	75	77	80	56	63	67	71	72
Eastern Europe and FSU	106	107	110	109	106	104	102	101	94	89	102	90	82	84	86
North Africa and Middle East	27	35	64	81	97	26	33	60	74	89	26	33	55	64	68
North America	151	167	172	174	174	148	158	157	153	152	148	146	131	122	111
Sub-Saharan Africa	23	34	44	50	54	23	32	40	43	46	22	29	35	39	41
Western Europe	91	91	101	105	108	89	86	92	92	94	88	77	74	72	67
Grand Total	587	661	737	776	802	572	622	673	678	696	568	574	572	578	567

Low Case – 0% Coal, 100% Hydro

Region	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020	2000	2005	2010	2015	2020
Asia	22	27	28	28	28	22	26	25	24	25	21	22	20	20	19
Australasia	32	34	34	35	36	31	34	33	34	35	31	31	27	27	27
Central and South America	26	30	34	36	37	26	28	31	32	34	25	25	26	27	27
Eastern Europe and FSU	44	44	44	42	39	43	40	39	34	33	41	33	28	29	29
North Africa and Middle East	5	7	11	14	16	5	6	11	13	15	5	6	8	8	6
North America	53	57	56	57	56	52	54	52	51	51	51	47	40	38	36
Sub-Saharan Africa	9	12	13	14	14	9	11	11	11	12	8	9	8	9	9
Western Europe	32	32	35	35	35	32	30	31	30	31	31	25	24	23	22
Grand Total	224	242	255	260	260	219	229	234	229	236	214	198	181	181	177

