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Materials Case Study 2:

Aluminium

Working Document

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NOTE FROM THE SECRETARIAT

In addition to critical metals, wood fibres and plastics, aluminium has been identified as priority material for which sustainable management throughout its lifecycle would be accompanied by significant environmental, social and economic benefits. The objective of this case study on aluminium is to analyse the environmental impacts of aluminium throughout its lifecycle and identify the best practices for its sustainable management.

This case study will be presented at the OECD Global Forum on Sustainable Materials Management to be held in Belgium from 25 to 27 October 2010 and, together with the other three case studies, will serve as a basis for the discussions of Session 1 on *Good SMM Practices in Priority Materials.*

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This report is work in progress. The opinions expressed in this paper are the sole responsibility of the author(s) and do not necessarily reflect those of the OECD or the governments of its member countries.

THE GLOBAL FLOW OF ALUMINUM 2006 TO 2025

EXECUTIVE SUMMARY

This report presents results of an investigation of the global flow of materials related to the production and use of aluminum in 2006 and makes projections to 2025. The report was prepared in cooperation with the U.S. Environmental Protection Agency for the Organisation for Economic Co-operation and Development, Environmental Policy Committee's Working Group on Waste Prevention and Recycling. The report addresses the major resource flows and effects of those flows, provides insights from a life cycle perspective, but does not address policy measures.

The report describes flow of aluminum for 2006 at a macro-level (country and global scales) based mainly on production data for bauxite, alumina, and aluminum gathered by the U.S. Geological Survey (USGS). Compared with findings from previous studies, this report estimates a similar level of the flow of primary aluminum (aluminum made from bauxite). The flow of secondary aluminum (aluminum made from fabrication and post-consumer scrap), however, is lower than that estimated by previous studies; this discrepancy should be further investigated.

The report also describes flows of materials associated with the production of primary and secondary aluminum at the micro-level. These materials include both major inputs to bauxite, alumina, and aluminum production and outputs from that production. Outputs of significant environmental concern include red mud that is produced as a result of the production of alumina from bauxite, and greenhouse gases [(GHGs) including CO_2 from electricity generation and perfluorocarbons that are produced during electrolysis] that are produced as a result of the smelting of alumina to produce aluminum.

The consumption of aluminum by end-use categories in high-income countries in comparison with that in low- to middle-income countries is analyzed. The leading use of aluminum in many high-income countries is to produce goods in the transportation sector. In low- to middle-income countries, aluminum is mainly used in the production of electrical systems and by the construction industry. Differences in the end-uses of aluminum by income have important implications for the recovery of post-consumer scrap because the in-service life of electrical systems and construction uses is much longer than that of many transportation uses.

The report investigates the end-uses of aluminum by the transportation sector in some detail. In particular, the report examines the use of aluminum in the manufacture of automobiles and commercial aircraft. Production of these goods generates different amounts of fabrication scrap and the goods have different in-service periods, which are two factors that are important to recovery of aluminum scrap.

Aluminum production and consumption may be considered as the two sides of a single coin for the purposes of materials flow analysis. Consequently, the report presents both short- and medium-term forecasts of aluminum production based on a USGS compilation of planned changes in bauxite and aluminum production capacity on a country-by-country basis and a long-term forecast (to 2025) of aluminum consumption based a new method of analyzing and projecting future aluminum flows. The method combines a model that predicts aluminum consumption from economic growth rates with information about changes in

end-use consumption that occur with changes in income to forecast levels of aluminum consumption and to draw inferences about the availability of aluminum scrap.

Based upon announced production plans, the capacity of bauxite mines worldwide is expected to increase to 270 million metric tons (Mt) by 2015 from 183 Mt in 2006, or by an almost 48 percent. Future aluminum production capacity based upon announced production plans is expected to reach 61 Mt in 2015 compared with 45.3 Mt in 2006, which is an increase of 35%, or almost 3.4% per year.

By 2025, aluminum consumption is likely increase more that 2.5 times to 120 Mt compared with 45.3 Mt in 2006. This represents a growth rate of 4.1% per year. Most of the increased consumption will take place in countries that consumed only modest amounts of aluminum in 2006. China, which consumed about 6.6 kilograms per-capita in 2006, is expected to consume 28.7 kilograms per-capita in 2025. Russia, Brazil, and India also are expected to increase their aluminum consumption significantly. Consumption in high-income countries is not expected to change significantly on a per-capita basis, but total consumption may change modestly owing to changes in population.

To meet the projected consumption of 120 Mt of aluminum, the world will need to produce about 570 Mt of bauxite and about 230 Mt of alumina. This production will generate significant levels of wastes even if technological improvements are made to current production processes.

A key question related to this projected increase in consumption is what portion of the consumption will be satisfied by primary aluminum and what portion will be sourced from secondary aluminum, as this will have a considerable influence on the amount of GHGs generated by aluminum production. That portion of secondary aluminum that comes from new scrap is likely to increase proportionately with overall consumption. The data on changing patterns of end-use that come with increased income, however, suggest that, at least initially, the proportion of aluminum that is generated from old scrap may decrease as countries undergoing economic growth initially use aluminum to develop new infrastructure, which has a long term of in-service use. Later, recycling of post-consumer scrap could increase.

If the proportion of aluminum production that comes from primary smelters increases, at least until 2025, a reduction in GHGs from aluminum production must come from increases in the efficiency of aluminum smelters or from reduced use of fossil fuels for generation of the electricity used in aluminum production.

RÉSUMÉ

Ce rapport présente les résultats d'une étude des flux mondiaux de matières liés à la production et à la consommation d'aluminium en 2006, ainsi que des prévisions les concernant jusqu'en 2025. Il a été établi en coopération avec l'Agence pour la protection de l'environnement des États-Unis pour le Sous-groupe sur la prévention de la production de déchets et le recyclage du Comité des politiques d'environnement de l'Organisation de coopération et de développement économiques. Il analyse les principaux flux de ressources et leurs effets, et livre un éclairage du point de vue du cycle de vie, mais ne traite pas des mesures d'action publique.

Le rapport décrit les flux d'aluminium de l'année 2006 au niveau macroéconomique (à l'échelle nationale et mondiale), essentiellement à partir de données sur la production de bauxite, d'alumine et d'aluminium collectées par l'U.S. Geological Survey (USGS). Par rapport aux résultats des études antérieures, ce rapport estime que les flux d'aluminium primaire (produit à partir de bauxite) restent à peu près inchangés. Les flux d'aluminium secondaire (élaboré par recyclage de déchets de fabrication et de post-consommation) sont cependant inférieurs aux estimations des études précédentes ; cette différence devrait être analysée de façon plus approfondie.

Sont également décrits, au niveau microéconomique, les flux de matières associés à la production d'aluminium primaire et secondaire. Parmi ces matières figurent aussi bien les principales matières premières entrant dans la production de bauxite, d'alumine et d'aluminium que les produits obtenus. De graves problèmes d'environnement sont notamment posés par les boues rouges résultant de la production d'alumine à partir de bauxite, et par les émissions de gaz à effet de serre [(GES) dont le CO_2 rejeté lors de la production d'électricité et les perfluorocarbones produits pendant l'électrolyse] résultant de la fusion de l'alumine pour élaborer l'aluminium.

Le rapport analyse aussi la consommation d'aluminium par catégorie d'utilisation finale dans les pays à revenu élevé, en regard de celle des pays à faible revenu et à revenu intermédiaire. Dans nombre de pays à revenu élevé, l'aluminium est surtout utilisé pour produire des biens destinés au secteur des transports. Dans les pays à faible revenu et à revenu intermédiaire, il est principalement utilisé dans la production de systèmes électriques et dans le secteur de la construction. Ces différences d'utilisations finales liées au revenu ont des conséquences importantes pour la récupération de ferrailles après la consommation, parce que les systèmes électriques et les applications dans la construction ont une durée de vie utile beaucoup plus longue que nombre d'applications dans les transports.

Le rapport étudie de façon relativement détaillée les utilisations finales de l'aluminium dans le secteur des transports. En particulier, il se penche sur la consommation d'aluminium dans la construction automobile et la construction aéronautique commerciale. La production dans ces secteurs génère des quantités variables de déchets de fabrication, et les biens produits ont des durées de vie utile différentes, facteurs importants du point de vue de la récupération de ferrailles d'aluminium.

Dans l'analyse des flux de matières, on peut considérer que la production et la consommation d'aluminium sont les deux faces de la même pièce. C'est pourquoi le rapport présente, d'une part, des prévisions à court et à moyen terme de la production d'aluminium fondées sur des séries de données établies par l'USGS concernant les variations prévues de la production de bauxite et d'aluminium par pays, et de l'autre, des prévisions à long terme (à l'horizon 2025) de la consommation d'aluminium calculées à l'aide d'une nouvelle méthode d'analyse et de projection des flux d'aluminium futurs. Cette méthode associe un

modèle de prévision de la consommation d'aluminium en fonction des taux de croissance économique à des informations sur les variations de la consommation finale liées à l'évolution du revenu pour établir des prévisions de la consommation d'aluminium et en tirer des conclusions sur les volumes disponibles de ferrailles d'aluminium.

Compte tenu des plans de production annoncés, la capacité des mines de bauxite devrait être portée, à l'échelon mondial, à 270 millions de tonnes (Mt) en 2015, contre 183 Mt en 2006, soit une augmentation de presque 48 %. Il est prévu, sur la base de ces plans annoncés, que la capacité future de production d'aluminium atteindra 61 Mt en 2015, contre 45.3 Mt en 2006, ce qui correspond à une hausse de 35 %, c'est-à-dire de presque 3.4 % par an.

En 2025, la consommation d'aluminium, à 120 Mt, devrait représenter plus de deux fois et demie le niveau de 45.3 Mt enregistré en 2006 ; elle aura donc crû au taux de 4.1% par an. L'augmentation de la consommation interviendra en majeure partie dans des pays qui ne consommaient que de faibles quantités d'aluminium en 2006. La Chine, qui en consommait environ 6.6 kilogrammes par habitant en 2006, devrait atteindre une consommation par habitant de 28.7 kilogrammes en 2025. Il est également prévu que la Russie, le Brésil et l'Inde accroîtront considérablement leur consommation d'aluminium. Dans les pays à revenu élevé, en revanche, la consommation par habitant ne devrait pas sensiblement varier, mais la consommation totale peut accuser de légères fluctuations en raison de l'évolution démographique.

Pour faire face à la consommation prévue de 120 Mt d'aluminium, il faudrait produire au niveau mondial environ 570 Mt de bauxite et quelque 230 Mt d'alumine. Cette production générera beaucoup de déchets, même si des perfectionnements technologiques sont apportés aux processus de production actuels.

Cet accroissement prévu de la consommation amène à s'interroger sur les proportions de celle-ci qui seront respectivement satisfaites au moyen d'aluminium primaire et secondaire, car cela aura une influence considérable sur les émissions de GES imputables à la production d'aluminium. La consommation d'aluminium secondaire issu de rebuts de fabrication augmentera sans doute proportionnellement à la consommation globale. Les données sur les évolutions de la consommation finale liées à la hausse des revenus donnent néanmoins à penser que, dans un premier temps du moins, les quantités d'aluminium produites à partir de ferraille de récupération diminueront peut-être, dans la mesure où les pays en expansion économique utiliseront d'abord l'aluminium pour construire des infrastructures qui seront utilisées pendant longtemps. Ultérieurement, le recyclage de ferrailles de post-consommation pourrait augmenter.

Si la proportion de la production d'aluminium de première fusion s'accroît, du moins jusqu'en 2025, la réduction des émissions de GES imputables à la production d'aluminium devra passer par l'amélioration du rendement des fonderies d'aluminium, ou par une baisse de consommation de combustibles fossiles dans la production de l'électricité nécessaire à l'élaboration de l'aluminium.

1. INTRODUCTION

1. This study was undertaken at the request of the U.S. Environmental Protection Agency to support the Organisation for Economic Co-operation and Development, Environmental Policy Committee's Working Group on Waste Prevention and Recycling. The Working Group commissioned case studies of four different materials to examine the role that materials flow studies might play in the development of policy to promote sustainable materials management. The Working Group identified four key questions it hopes to address through the case studies:

- 1.What are the major resource flows and environmental impacts and how are they expected to evolve in the future? To what extent is natural capital preserved?
- 2.How can new insights be gained and translated into new measures by taking a life cycle perspective? To what extent has it been possible to consider the complete material life cycle?
- 3.What policy measures have been taken or can be taken to stimulate sustainable environmental, economic, and social outcomes?
- 4.To what extents are different actors in society engaged in taking up active ethically based responsibilities for sustainable outcomes?

2. This study of aluminum addresses the first two questions.

2. BACKGROUND AND METHODOLOGY

2.1 Life Cycle of Aluminum

3. Aluminum is one of the most important metals used by modern societies. Aluminum's combination of physical properties results in its use in a wide variety of products, many of which are indispensable to modern life. Because of its light weight and electrical conductivity, aluminum wire is used for long distance transmission of electricity. Aluminum's strength, light weight, and workability have led to increased use in transportation systems including light vehicles, railcars, and aircraft as efforts to reduce fuel consumption have increased. Aluminum's excellent thermal properties and resistance to corrosion have led to its use in air conditioning, refrigeration, and heat exchange systems. Finally, its malleability has allowed it to be rolled and formed into very thin sheets used in a variety of packaging.

4. Figure 1 is a generalized model of the entire life cycle, or flow, of aluminum. Primary aluminum production begins with the mining of bauxite, which is processed first into alumina and subsequently into aluminum metal. The main wastes from bauxite mining are tailings produced by grinding and washing the bauxite. The processing of bauxite to alumina involves initial chemical processing of the bauxite. The main waste from

Figure 1. Global Aluminium Flows in 2006

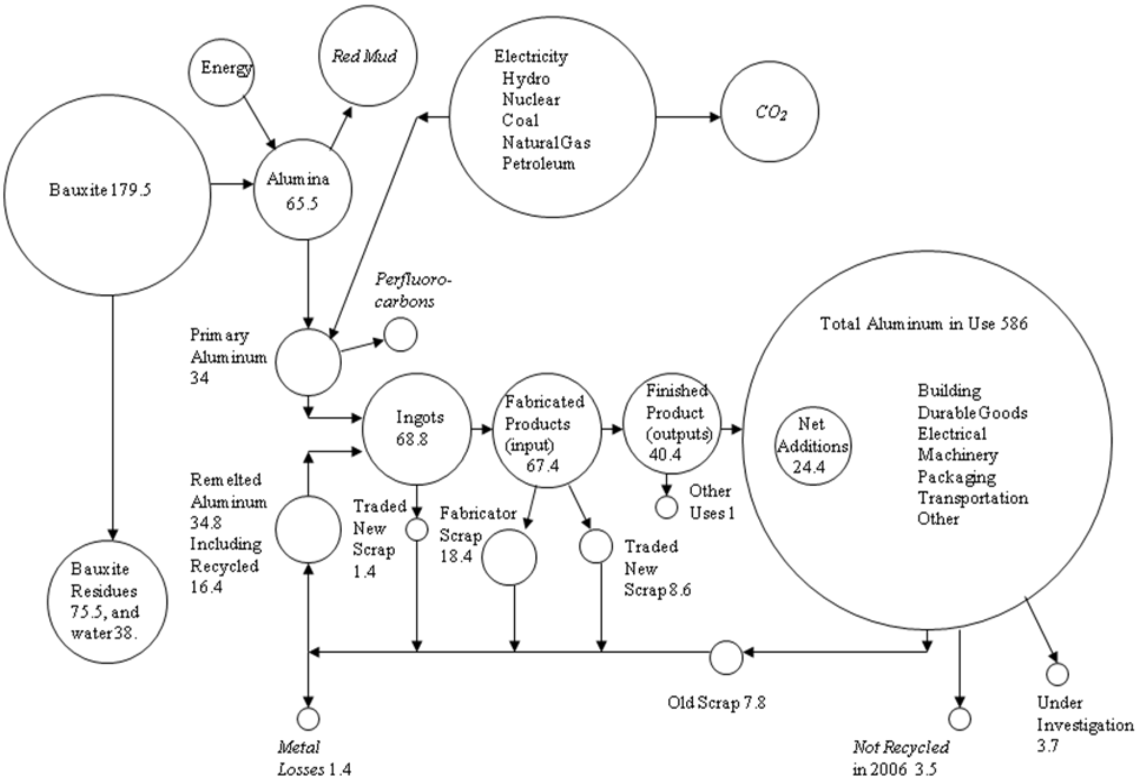

Figure 1. Global Aluminum Flows in 2006 (data in tons; emissions in italics; figure modified from Martchek, undated).

5. alumina refining is the production of “red mud,” a solid waste that is usually disposed of in a landfill. The electrolysis of alumina to produce aluminum involves the use of aluminum fluoride, carbon anodes, and large amounts of electricity. The most significant waste products from the production of aluminum from alumina are air emissions including perfluorocarbon gases and carbon dioxide from the production of anodes and electricity.

6. Following smelting of the alumina to produce aluminum, the metal is poured into several basic shapes. These shapes are then fabricated into semi-manufactured goods and then processed into finished goods. Fabrication may involve rolling of the metal into sheets, casting the metal into shapes, drawing the metal into wire, or extrusion of the metal to produce different shapes. Waste, or scrap, from fabrication and manufacture is variable depending on individual processes. For example, cutting of aluminum sheet produces significant amounts of scrap while casting aluminum parts produces little scrap. Scrap from fabrication and manufacture of finished goods is generally recycled and is called new scrap. The main end uses, or classes, of aluminum-bearing goods include buildings (construction), durable goods, electrical (power), machinery, packaging, and transportation. Old, or post-consumer, scrap is generated at varying rates for different types of goods depending on the in-service life of the goods and the economics of collecting and recovering aluminum from the good.

2.2 Previous Studies

7. The present report relies upon several seminal studies of U.S. and global aluminum flows. Martchek (2006) describes a model developed by Alcoa Inc. to provide estimates of the global aluminum flows and system losses from 1950 to 2003. Resource requirements and life cycle flows were estimated by

combining aluminum flows with global average life cycle flow data developed from producers through the International Aluminium Institute (IAI). The model shows mass flows for primary and secondary (recycled) aluminum, including material from fabrication and manufacture of finished products; total aluminum in use; and three classes of losses (losses in recycling, material sent to landfills, and material under study). Recycled material is broken into four classes—aluminum skimmed in ingot production, internal scrap generated in the aluminum smelter, new scrap generated by fabricators, and old scrap generated by consumers of final goods. The amount of aluminum in the different types of scrap was estimated by teams of experts using statistical data and technical literature on aluminum production. The model used historic end-use data from regional aluminum associations to estimate future disposition of aluminum production. Martchek (2006) also presents data on past production of greenhouse gases (GHGs) and estimates of future GHG emissions from aluminum production owing to increased use of recycled (secondary) aluminum and to reductions in emissions in the production of primary aluminum.

8. Martchek (2007) presents updated estimates of global aluminum flows in 2006 and estimates of the amount of GHG emissions generated by the major steps leading to the production of aluminum ingot. IAI presents updated (2005) life cycle data for primary aluminum including raw materials and energy use, air and water emissions and solid wastes generated (International Aluminium Institute, 2007).

9. In recent years, numerous reports on the flow of metals have appeared in the technical literature (see for example reports by Graedel and his colleagues at the Center for Industrial Ecology at Yale University). Two reports that are applicable to aluminum flows include those of Chen and others (2009) and Hatayama and others (2007).

2.3 Methodology of Present Study

10. The methodology developed in the Alcoa and IAI studies require some data and capabilities that were not available for this study. In particular, this study lacked long-term data on end-uses of aluminum in different regions, data on within smelter flows, and the availability of experts to estimate recycling rates. These deficiencies placed constraints on the study and required the development of an alternative methodology to estimate present and future aluminum flows. This study used data for 2006 so that flows common to this study and the IAI model can be compared and so more detailed flows from the Alcoa and IAI studies can be used with this study to obtain a more complete picture of flows associated with aluminum production and use.

11. The forecast in the present study is based on a model that relates resource consumption (use) to average national income as measured by Gross Domestic Product (GDP) per-capita. Previous studies (DeYoung and Menzie, 1999; and Menzie, DeYoung, and Steblez, 2001) have shown that industrial consumption of metals such as copper and aluminum is low at low levels of income and high but stable once a threshold income is reached. As countries increase their per-capita income, industrial consumption increases rapidly until the threshold is reached. Previous studies also show that the 20 most populous countries typically consume about 70% of global production. As a result, this study focuses on high-income, populous countries, and selected populous countries experiencing rapid economic growth.

12. This study summarizes global, macro-level aluminum mass flows in terms of production of bauxite, alumina, primary and secondary aluminum, and apparent consumption of aluminum. All production data, except the estimated secondary aluminum production for Russia, are taken from the aluminum chapter (Bray, 2010a) of Volume I of the USGS Minerals Yearbook (MYB) and various country chapters of Volume III of MYB respectively. An estimate of Russia's secondary aluminum production was made based upon Grishayev and Petrov (2008). Consumption data were taken from various publications of the World Bureau of Metal Statistics or were calculated from USGS production data and trade data from the United Nations Comtrade database.

13. Micro-level flows of materials associated with the production of primary aluminum are presented as a model of materials inputs to and outputs from the production of primary aluminum from bauxite (Goonan and Bleiwas, written communication), which is based upon data from IAI and the European Aluminium Association (EAA). The model consists of three submodels: a model of the inputs to and outputs from bauxite mining, alumina production, and primary aluminum production. The alumina and primary aluminum models cover two cases—a model of world plants and a model of European plants. An additional model examines the inputs to and outputs from the secondary aluminum production process. These models are used to estimate inputs to and outputs from various parts of the bauxite to alumina to aluminum and the aluminum remelt production processes.

14. Aluminum consumption per-capita and the end-uses of aluminum were examined for the following high-income countries and low- and middle-incomes with rapidly growing economies—Argentina, Brazil, China, France, Germany, India, Japan, Mexico, Russia, the United Kingdom, and the United States. End-use data are reported for different classes for different countries. In spite of differences in classification, the end-use data suggest some broad changes in the end uses of aluminum as income increases. The end-use statistics have been compared with light vehicle manufacturing and vehicle aluminum intensity data (Ducker, 2008) to further specify the use of aluminum. Data on commercial aircraft production and weight were collected for four important aircraft manufacturers—Airbus, Boeing, Bombardier, and Embraer. An estimate that 80% of the weight of an aircraft is aluminum was used with these data to estimate the aluminum in use in commercial aircraft. For vehicles and aircraft, scrap that was generated in the process of manufacture was estimated.

15. Future mass flows of aluminum are estimated by two methods. Short- to medium-term (2008 to 2015) flows were estimated using aluminum outlooks published in the regional summary chapters of MYB V. III (Anderson and others, 2010, p. 1.27; Fong-Sam and others, 2009, p. 1.17; Levine and others, 2010, p. 1.35; Mobbs and others, 2010, p. 1.9; Yager and others, 2010, p. 1.18). The outlooks are compilations based upon industry announcements of new or expanded plant capacity. Longer-term flows are estimated using a logistic regression linking aluminum consumption per-capita to Gross Domestic Product per-capita, which is a measure of income. The model uses the logistic regression, population growth rates and 10-year forecasts of economic growth for each of the 20 most populous countries to estimate future consumption. Estimates of aluminum consumption are combined with the models of materials inputs and outputs to make status quo estimates of material requirements and wastes generated.

3. FINDINGS

3.1 Global Mass Flows of Aluminum

16. This report considers material flows related to the production, use, and recycling of aluminum at both macro- and micro-levels. The macro-level flows include the production from bauxite, alumina, and primary aluminum; the consumption of aluminum by end-use, and the production of secondary aluminum. Micro-level flows of materials associated with the production of primary and secondary aluminum include the inputs to and outputs from the production of bauxite, alumina, primary aluminum, and secondary aluminum. These flows are presented in terms of 1 ton of output of each product. Environmental issues related to the production of each product are discussed in terms of the outputs that result in the issue.

3.1.1 Macro-Level Flows of Aluminum--Production

17. Production data on bauxite, alumina, and primary and secondary aluminum production are presented in Tables 1 - 3 respectively. Data on location, ownership, and production capacity of the majority of the

bauxite, alumina, and aluminum production facilities are presented in Appendices 1 - 3 respectively. For most facilities, Appendices 1 - 3 reflect their characteristics in 2007.

3.1.1.1 Bauxite

18. Based upon data in Volumes I and III of Minerals Yearbook, just over 183 million metric tons (Mt) of bauxite were produced in 2006—50 Mt in the Americas, 104 Mt in Asia, 9.6 Mt in Europe and Eurasia, and 18.8 Mt in Africa and the Middle East. Six countries each produced more than 10 Mt of bauxite (Australia 61.8 Mt, China 27 Mt, Brazil 22.8 Mt, Guinea 16.3 Mt, Jamaica 14.9 Mt, and India 13.9 Mt) and together accounted for 85% of global production. The distribution of bauxite production reflects the geologic history and climatic factors that favor the formation of bauxite as well as economic factors such as the cost of production at individual sites.

Table 1. Global production of bauxite in 2006.

	Metric tons
Brazil	22,836,000
Guyana	1,479,000
Jamaica	14,865,000
Suriname	4,924,000
Venezuela	5,928,000
Total	**50,032,000**
Australia	61,780,000
China	27,000,000
India	13,940,000
Indonesia	1,502,000
Malaysia	92,000
Pakistan	7,000
Vietnam	30,000
Total	**104,351,000**
Bosnia and Herzegovina	854,000
France	168,000
Greece	2,163,000
Hungry	538,000
Kazakhstan	4,860,000
Russia	1,000,000
Total	**9,583,000**
Ghana	886,000
Guinea	16,300,000
Iran	500,000
Mozambique	11,000
Sierra Leone	1,072,000
Tanzania	5,000
Total	**18,774,000**
World Total	**182,740,000**

3.1.1.2 Alumina

19. Global alumina production in 2006 was 74 Mt—20.9 Mt were produced in the Americas, 35.1 Mt in Asia, 17.2 Mt in Europe and Eurasia and 0.8 Mt in Africa and the Middle East. Six countries produced more than 4 Mt of alumina—Australia 18.3 Mt, China 13.7 Mt, Brazil 6.8 Mt, Russia 6.4 Mt, the United States 4.7 Mt, and Jamaica 4.1 Mt—and they account for about 72% of global alumina production. Not all alumina is used to produce aluminum; about 10% of alumina is used to produce refractory and other chemical products. Thus, about 67 Mt of alumina were available for aluminum production. The fact that four of the six leading alumina producers are also among the six leading bauxite producers follows from the transportation advantage obtained by co-locating alumina production facilities near bauxite mines and thereby avoiding the cost of transporting the waste material associated with the bauxite.

Table 2. Global production of alumina in 2006.

	Metric tons
Brazil	6,793,000
Canada	1,281,000
Jamaica	4,100,000
Suriname	2,153,000
United States	4,700,000
Venezuela	1,892,000
Total	**20,919,000**
Australia	18,312,000
China	13,700,000
India	2,800,000
Japan	330,000
Total	**35,142,000**
Azerbaijan	363,000
Bosnia and Herzegovina	394,000
France	200,000
Germany	850,000
Greece	775,000
Hungry	270,000
Ireland	1,800,000
Italy	1,090,000
Kazakhstan	1,515,000
Montenegro	237,000
Romania	622,000
Russia	6,399,000
Spain	1,000,000
Ukraine	1,672,000
Total	**16,187,000**
Guinea	545,000
Iran	250,000
Total	**795,000**
World Total	**73,043,000**

3.1.1.3 Aluminum

20. Global aluminum production in 2006 was about 45.9 Mt; 34 Mt was primary aluminum produced by processing bauxite to alumina and then smelting the alumina to produce aluminum, and 11.8 Mt was secondary aluminum that was recovered from new scrap generated in the aluminum production process and old or post-consumer scrap. The Americas produced 7.82 Mt of primary aluminum, Asia 13.0 Mt, Europe and Eurasia 9.4 Mt, and Africa and the Middle East 3.86 Mt. Eight countries produced at least 1 Mt of primary aluminum production—China 9.36 Mt, Russia 3.72 Mt, Canada 3.05 Mt, the United States 2.28 Mt, Australia 1.93 Mt, Brazil 1.61 Mt, Norway 1.42 Mt, and India 1.10 Mt. Together these eight countries accounted for about 72% of global primary aluminum production. Five of the six leading producers of primary aluminum were also among the six leading producers of alumina. Canada, which does not produce bauxite and was not one of the six leading producers of alumina, was the third leading producer of primary aluminum. Abundant hydroelectricity led to the location of aluminum smelters in Canada. Aluminum smelting is energy intensive; changes in the price and availability of energy result in the location of new smelters in areas with cheap and available energy. The availability of abundant supplies of natural gas has led to the development of significant aluminum smelters in Bahrain and the UAE in recent years. Both countries produced more than 850,000 t of aluminum in 2006. New aluminum smelters are being built in Iceland, such as the Fjardaal smelter, because of the availability of abundant electricity generated from hydropower and geothermal power. The imposition of carbon taxes or carbon emissions pricing could significantly affect the location of aluminum smelters as companies move facilities to countries with abundant, cheaper energy. The closure of several aluminum smelters in the United States in recent years has been in response to increased energy costs.

21. Of the secondary aluminum, the Americas produced 4.46 Mt, Asia 3.57 Mt, and Europe and Eurasia 3.77 Mt. Production of secondary aluminum in Africa and the Middle East was negligible. Based upon USGS data, the six leading producers of secondary aluminum in 2006 accounted for 79% of global production of secondary aluminum. The United States produced 3.54 Mt, China 2.35 Mt, Japan 1.07 Mt, Germany 0.8 Mt, Italy 0.66 Mt, and Mexico 0.6 Mt.

22. Data on global aluminum flows for 2006 are shown in Figure 1 which is modified from Martchek (2007). The main modification has been in the end-use classes; the classes used in Figure 1 correspond to USGS usage and contains the classes—construction, durable goods, electrical (power), machinery, packaging, transportation, and other. The classes used in Martchek (2007) follow European usage—building, engineering and cable, packaging, transportation, and other. Some countries keep a separate class for fabricated metal, which includes aluminum used in steel-making. The classes electrical and machinery are particularly important for accounting for aluminum use in countries that are building infrastructure and developing a manufacturing sector.

23. Figure 1 shows global bauxite production in flows in 2006 as 179.5 Mt, which is very similar to the USGS estimate of 183.5 Mt, and calculates alumina flows as 65.5 Mt compared with the 67 Mt estimated above. Figure 1 also shows primary metal production of 34 Mt—essentially the same as the production statistics in the MYB. Figure 1 also shows flows of 34.8 Mt of recovered metal, 18.4 Mt from metal recovered scrap from fabrication operations, 8.6 Mt recovered from losses during the process of manufacturing goods, and 7.8 Mt of material collected after use by consumers. The 18.4 Mt of material “recycled” within the smelter facilities does not get counted in government statistics, and many governments do not separately report material recycled from the processes of manufacturing goods and material recovered after its use by consumers. The total amount of material, identified as secondary aluminum in government statistics, recovered from both manufacturing and post-consumer use is estimated as 16.4 Mt by the IAI but 11.8 Mt by USGS. The IAI data suggest that almost half of secondary aluminum is from post-consumer material. Statistics on secondary aluminum production in the United States indicate that 35% of secondary aluminum comes from post-consumer material (Papp, 2009, p.61.2). All secondary aluminum reported for members of the European Union (EU27), the European Free Trade Association (EFTA), and Japan together

with the old scrap (post-consumer) portion of secondary aluminum for the United States amounts to only 5.4 Mt of material. Clearly, efforts to harmonize these data are warranted.

Table 3. Global production of primary and secondary aluminum in 2006.

	Primary	**Secondary**
	Metric tons	
Argentina	273,000	16,000
Brazil	1,605,000	253,000
Canada	3,051,000	47,000
Mexico		600,000
Venezuela	610,000	
United States	2,284,000	3,540,000
Total	7,823,000	4,456,000
Australia	1,932,000	130,000
China	9,360,000	2,350,000
India	1,104,000	
Indonesia	250,000	
Japan	57,000	1,070,000
New Zealand	337,000	22,000
Total	**13,040,000**	**3,572,000**
Austria		150,000
Azerbaijan	32,000	
Bosnia and Herzegovina	136,000	
Bulgaria		13,000
Croatia		2,000
Czech Republic		15,000
Denmark		25,000
Finland		36,000
France	442,000	222,000
Germany	516,000	796,000
Greece	165,000	3,000
Hungary	34,000	50,000
Iceland	328,000	
Italy	194,000	666,000
Montenegro	123,000	
Netherlands	312,000	25,000
Norway	1,422,000	349,000
Poland	58,000	19,000
Portugal		18,000
Romania	267,000	11,000
Russia	3,718,000	550,000
Serbia		1,000
Slovakia	161,000	
Slovenia	118,000	20,000
Spain	349,000	243,000
Sweden	101,000	32,000
Switzerland	40,000	190,000
Tajikistan	414,000	
Ukraine	113,000	130,000

United Kingdom	360,000	198,000
Uzbekistan		3,000
Total	**9,403,000**	**3,767,000**
Bahrain	860,000	
Cameroon	87,000	
Egypt	252,000	
Ghana	80,000	
Iran	205,000	
Kenya		2,400
Mozambique	564,000	
South Africa	895,000	
Turkey	60,000	
UAE	861,000	
Total	**3,864,000**	**2,400**
World total	**34,130,000**	**11,797,000**

3.1.2 Micro-Level Flows of Materials Associated with Aluminum Production[1]

24. The preceding section of the paper addressed macro flows of aluminum to understand the production of aluminum goods and associated manufacturing wastes (primary scrap) and the generation of post-consumer wastes or scrap. This section of the paper will focus on the materials required to produce aluminum and the wastes generated in the production process and is excerpted and modified from a draft manuscript by Goonan and Bleiwas (written communication) which presents models of the inputs to and outputs from the production of alumina from bauxite and of primary aluminum from alumina.

25. The IAI, the European Aluminium Association (EAA), and others have been developing information on part of the aluminum life cycle through an Aluminum Sector Addendum, which addresses a Greenhouse Gas Protocol (for accounting and reporting) developed by the World Business Council for Sustainable Development in concert with the World Resources Institute. The IAI and EAA reports are the primary data sources for the information presented here.

26. The materials flows presented below cover the primary production of aluminum, including bauxite mining (open pit), alumina production (Bayer process) and electrolytic smelting (Hall-Heroult process), and the production of secondary aluminum. Materials flow data, expressed in this report, are taken from a 2008 report by the EAA, which developed two models (one for Europe and another for the world) for the various process steps that produce aluminum from bauxite. This report provides information about the process steps for primary aluminum production, and is addressed to those interested in the generation of greenhouse gases, red mud, and other effluvia associated with primary aluminum production. The inclusion of two models allows for the comparison of reductions in wastes that may be achieved just from adopting currently available technologies on a wider basis. Other opportunities for reducing air emissions by adopting enhanced technologies are discussed later in this section.

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[1] By Thomas G. Goonan, Donald I. Bleiwas, and David Menzie

3.1.2.1 Bauxite Mining

27. The aluminum industry consumes nearly 90% of the bauxite mined; the remainder is used in abrasives, cement, ceramics, chemicals, metallurgical flux, refractory products, and miscellaneous products (Bray, 2010b). There are three main types of bauxite ore. They include trihydrate, which consists chiefly of gibbsite, $Al_2O_3•3H_2O$; monohydrate, which consists mainly of boehmite, $Al_2O_3•H_2O$; and mixed bauxite, which consists of gibbsite and boehmite. The proportion of trihydrate and monohydrate ores in this type of bauxite differs from deposit to deposit as do the type and amount of impurities like clay, iron oxide, silica, and titania. Free silica, clay, silt, and iron hydroxide are also common constituents of bauxite ore. The alumina content of bauxite ores ranges from 31to 52 percent, averaging about 41% on a production-weighted basis (International Aluminum Institute, 2009b). This study addresses the flow of metallurgical-grade bauxite, ores used to produce aluminum. These ores typically have a minimum Al_2O_3 content of 50 to 55% with a texture that ranges from powdery clay to indurated (hardened by cementation) masses.

28. Bauxite mining operations generally require a large support network, which often requires significant capital and operating costs. The great majority of the world's bauxite ores are extracted by open-cut methods. Before mining of the ores can commence, it is usually necessary to remove overburden and preservation of topsoil for post-mining rehabilitation. Most mines require the removal of 1 or 2 meters of overburden (International Aluminum Institute, 2009b; Royal Boskalis Westminster, 2010). Bauxite ore bodies vary from 2 to 20 meters in thickness (International Aluminium Institute, 2009b). Aerial extent can be highly variable.

29. Diesel-powered bulldozers, backhoes, front-end loaders, excavators, and haulage trucks are the principal tools used to remove and haul overburden and ore. The amount of equipment and size of the equipment is dictated to a large extent by the mining environment (wet or dry, for example), stripping ratio, scale of production or capacity, and distance to shipment points. Additional equipment and materials are required for the mining operation including roads, support vehicles and repair facilities, town site (houses, hospital, schools, etc.), energy and freshwater production and distribution, communication systems, parts and supplies. Rail and port facilities may be necessary depending upon the location of the mine.

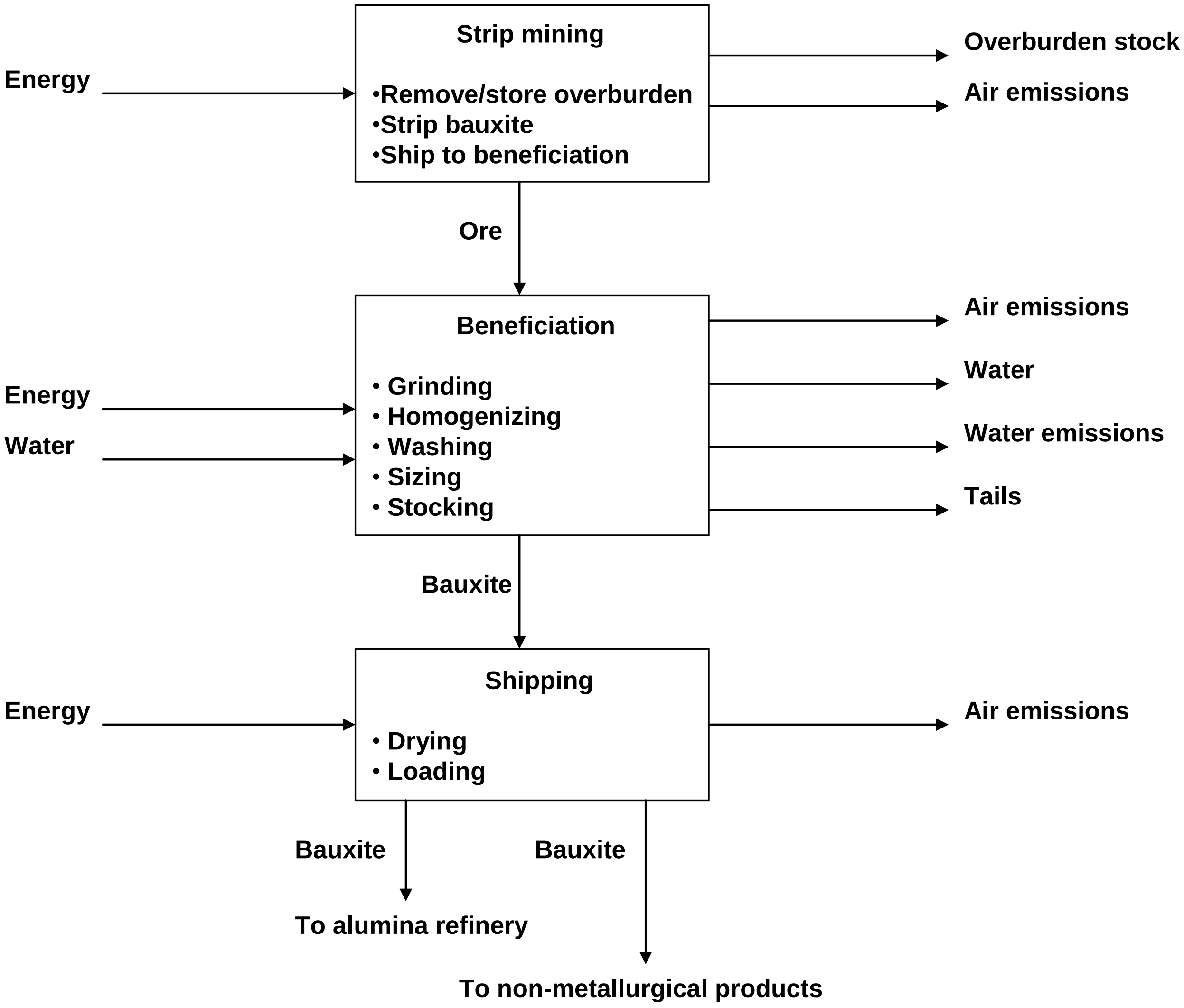
30. Some bauxite ores can be shipped directly to an alumina refinery without treatment because they are of sufficient grade and purity. Other ores may require added steps such as size reduction and moisture content reduction prior to shipping. At some sites the ore grade may be increased by removal of clays and other impurities by washing, wet screening, cycloning, and/or sorting. Flotation is sometimes used to reduce the silica content of an ore. Blending of ores may also be used to maintain grade uniformity to meet specifications. Wastes (mostly clays) produced from processing are transported to and stored in tailings ponds. Ore that is to be transported appreciable distances to refineries is often dried to reduce shipping costs.

31. A small open pit bauxite mine may have an annual capacity of roughly 500,000 t of ore, whereas the annual capacity of the largest mines approximates 23 Mt. Annual capacities of 3 Mt to 15 Mt of ore characterize most of the world's open pit bauxite operations. Bauxite mines operate for long periods of time, some as long as 100 years or more. Presently, the amount of land being opened for new or expanded bauxite mining equals the amount of post-mining land being rehabilitated, such that the total land use for bauxite mining worldwide would equal approximately one-half of the land area of Manhattan Island (New York City). The greatest difference between pre- and post-mining land use is a trade of farming (11 to 2 percent) for native forest (49 to 60 percent) (International Aluminum Institute, 2009b). Figure 2, which shows the bauxite mining process flow, is based on a description of bauxite mining at the Alcoa-owned Juruti Mine in Brazil (Alcoa, 2009).

32. The EAA has modeled the typical world bauxite mine. Figure 3 shows the generalized materials flows associated with world bauxite mining (European Aluminium Association, 2008). Inputs and outputs

per metric ton of bauxite mined are measured in kilograms (gross), metric tons (gross), and cubic meters. The model presented in Figure 3 does not include materials included in overburden or mine waste.

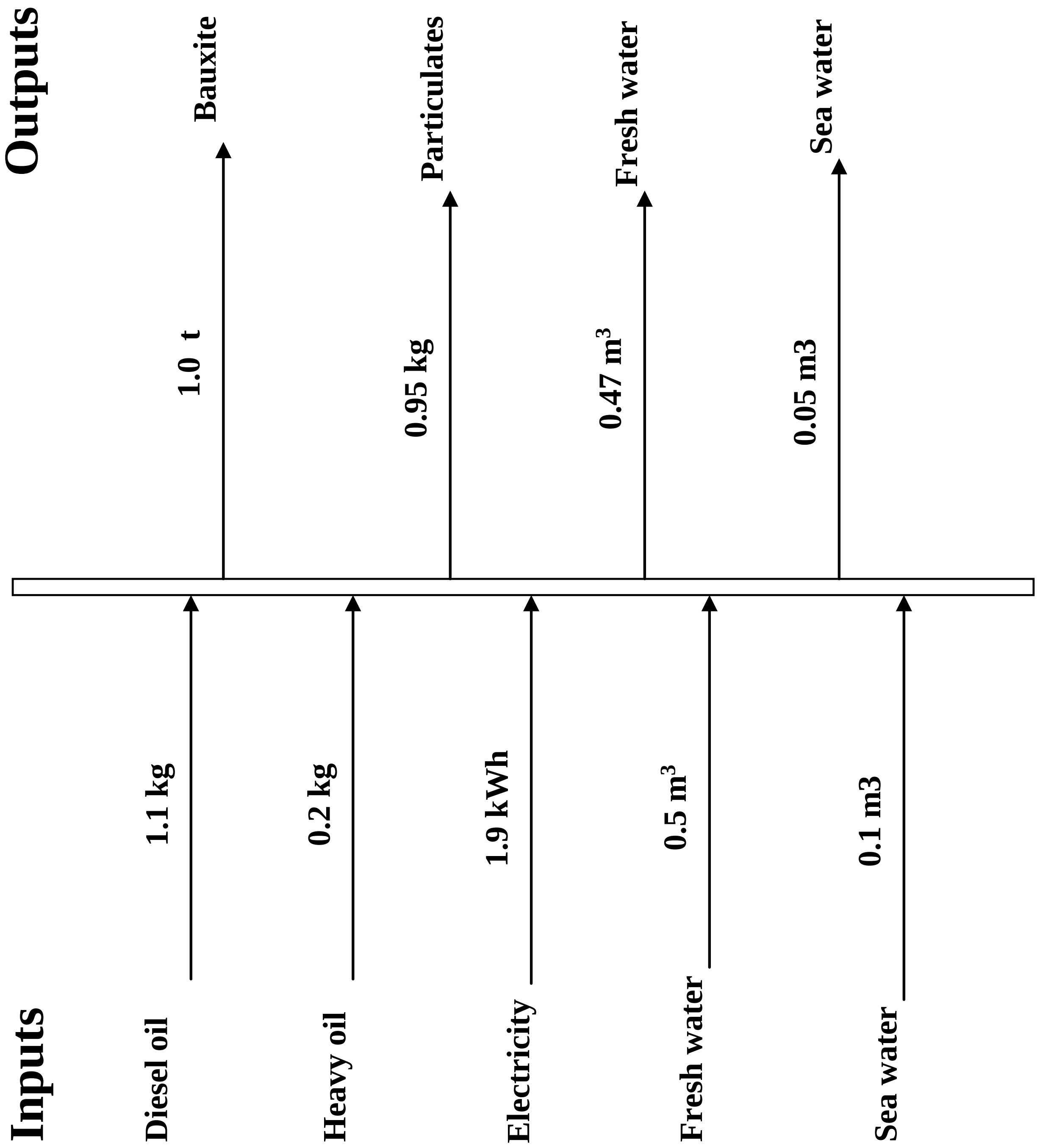
Figure 2. Diagram showing a typical process flow for bauxite mining.



Source: Alcoa Inc., 2009.

Figure 3. Diagram showing selected materials flows for a model "world" bauxite mine.

Source European Aluminum Association, 2008, p. 23.



3.1.2.2 Alumina Production (refining)

33. Virtually all alumina commercially produced from bauxite is obtained by a process patented by Karl Josef Bayer (Austria) in 1888. The Bayer process involves the following steps:

- *Digestion*—bauxite is ground and slurried into a caustic soda (NaOH), which is then pumped into large pressure tanks called digesters. The sodium hydroxide reacts with the alumina minerals to form soluble sodium aluminate (NaAlOH).

- *Clarification*—the solution from the digestion step is depressurized and processed through cyclones to remove coarse sand. The remaining fluid is processed in thickeners where flocculants are added to agglomerate solids, which are removed by cloth filters. These residues (red mud) are washed, combined, and discarded, and the clarified solution (containing the NaAlOH) is passed to the next step.

- *Precipitation*—the solution from the clarification step is seeded with alumina seed (very small) crystals to aid precipitation of larger agglomerated alumina crystals. The product-sized crystals are separated from the small crystals (recycled as seed) and are washed to remove entrained caustic residue. The agglomerates are moved to the next step.

- *Calcination*—The agglomerates of NaAlOH are placed in rotary kilns or stationary fluidized-bed calciners at temperatures that can exceed 960ºC (1,750 ºF), which drives off the chemically combined water leaving a residue of commercial-grade alumina (Plunkert, 2006, Red Mud Project 2010a).

Figure 4 shows the process flows for alumina refining (CiDRA, 2010).

34. Materials flows within the Bayer process are dependent on the grade of the bauxite being processed and the amount and character of the non-alumina minerals contained in the bauxite. Figure 5 shows selected materials flows for a model “European” and “World” alumina refinery, in 2005 (European Aluminium Association, 2008).

35. Figure 5 presents the inputs to and outputs from alumina production per metric ton alumina as kilograms (gross), metric tons (gross), and cubic meters of the various materials. In 2005, the amount of bauxite required, for a model “Europe” and the “World” alumina refinery, to produce one t of alumina was 2.2 t and 2.7 t respectively, which indicates that on average European smelters were processing higher grade bauxite than the rest of the world. Red mud production from these models followed this trend reciprocally—that is, 706 kg/t for the European model, and 1,142 kg/t for the worldwide model (European Aluminium Association, 2008). Reduction of red mud waste by processing higher grade bauxite is not likely to represent a strategy for long-term sustainable production of aluminum because average grades of metals produced typically decline with time as higher grade deposits are produced before lower grade ones.

36. The most important output from the Bayer process after alumina is red mud. The composition of red mud worldwide varies as follows: Fe_2O_3, 30 to 60 percent; Al_2O_3, 10 to 20 percent; SiO_2, 3 to 50 percent; Na_2O, 2 to 10 percent; CaO, 2 to 8 percent; and TiO_2, trace to 25 percent. Red mud is a highly complex material, and its ultimate chemistry depends on the nature of the original bauxite ore. It is highly alkaline and contains a variety of elements and mineral species in small sizes and contains as much as 50% water (Red Mud Project, 2010b).

37. In the past, red mud has been disposed of at sea, or contained in lined lake-size containment compounds (Red Mud Project, 2010c). While these practices still are used, research is ongoing to find better ways to recycle and reuse red mud—for example, as building materials (bricks, roofing and flooring tiles), catalysts, ceramics, fillers, fertilizers, light-weight aggregates, metallurgical fluxes, and recovery of other metals (Red Mud Project, 2010d–e). In 2008, alumina refining worldwide produced about 93.2 Mt of red mud (roughly 40% water), of which 83.9 Mt was attributable to aluminum production. The reuse of red mud offers an opportunity to develop new industries based upon the wastes from alumina production.

3.1.2.3 Aluminum Smelting and Electrolysis

38. Primary aluminum is produced by the electrolysis of alumina dissolved in molten fluoride salt. The process was independently invented in 1886 by Charles Martin Hall (United States) and Paul Louis Toussaint Héroult (France) and underwent continual improvement over the years. In the Hall-Heroult electrolytic reduction cell, alumina and aluminum fluoride are the material feedstocks. The carbon in anodes, which are either prebaked (90% of operations) or Söderberg-type (10% of operations), are consumed by reaction with the oxygen in the alumina to form carbon dioxide, which is ultimately released to the atmosphere. Figure 6 shows the process flows for aluminum smelting (Beck, 2008, and European Aluminium Association, 2008). Ancillary to the aluminum reduction cell process is anode manufacturing, which generates additional emissions of concern.

39. Anodes are critical to aluminum reduction. They carry the electric charge (which drives the reaction) to the cryolite (the alumina solvent) in the reduction cell, and they provide the carbon (which causes the anode to be continuously consumed) for the reduction reaction that strips the oxygen from the alumina and removes it to the atmosphere as carbon dioxide. There are two primary technologies used to produce anodes for the Hall-Héroult process—Söderberg and prebake. Söderberg anodes begin as semi-liquid constructions that are continuously fed into the molten cryolite bath. Prebaked anodes are preformed and hardened in gas-fired ovens at high temperatures. Prebaked anodes are then fed into the cryolite bath. The major difference is that the Söderberg anode hardens with heat generated from the electrolytic process as it descends into the cryolite bath and the prebaked anode is hardened before use in the electrolytic cell. The newest and largest aluminum smelters generally use prebaked anodes, which are more efficient. To produce a prebaked anode, petroleum coke and pitch are blended together and baked in ovens. Anode manufacturing generates additional materials flows.

Figure 4. Diagram showing a typical process flow for alumina refining.

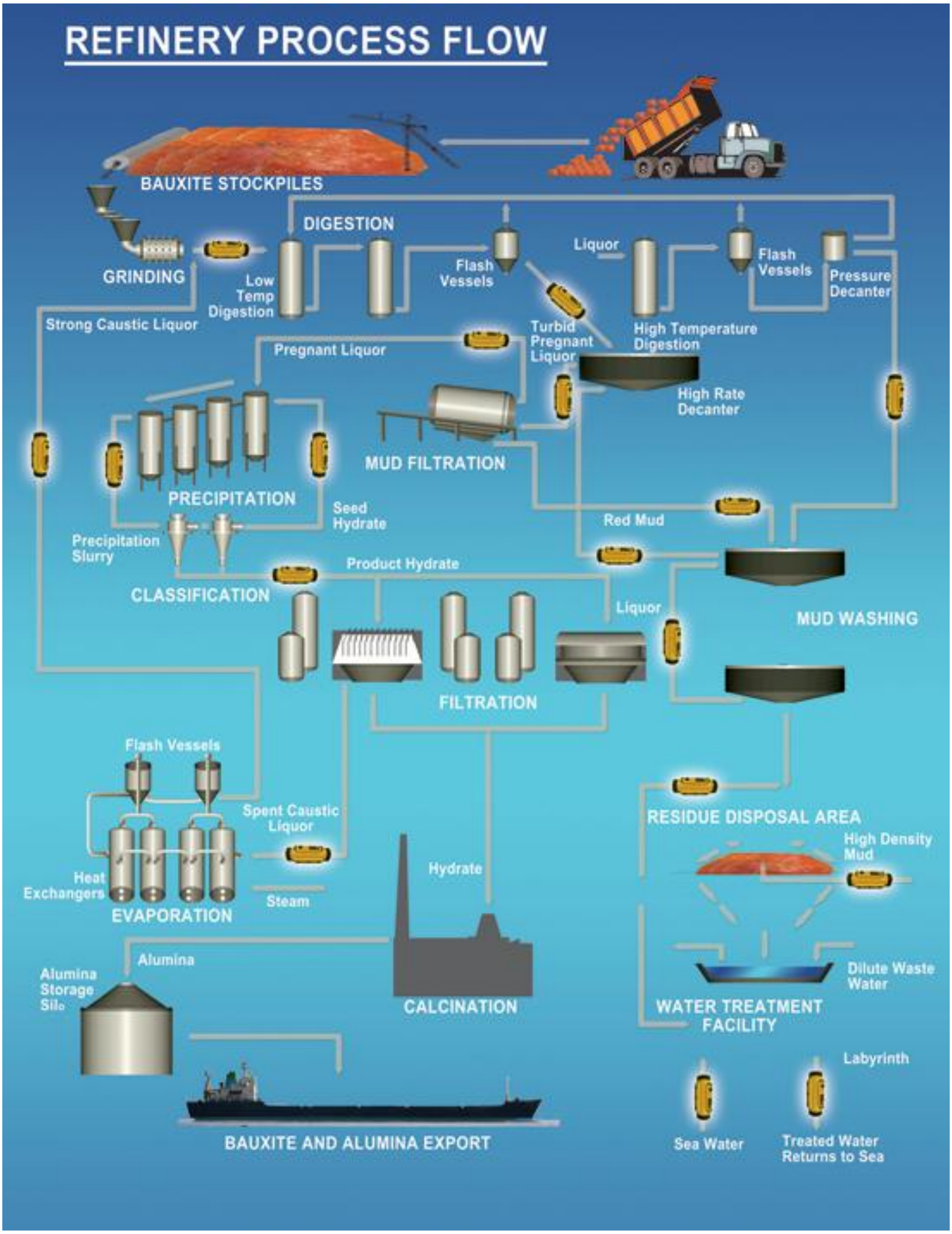


Figure 5. Diagram showing selected materials flows for a model "European" and "world" alumina refinery. Source European Aluminium Association, 2008, p. 24.

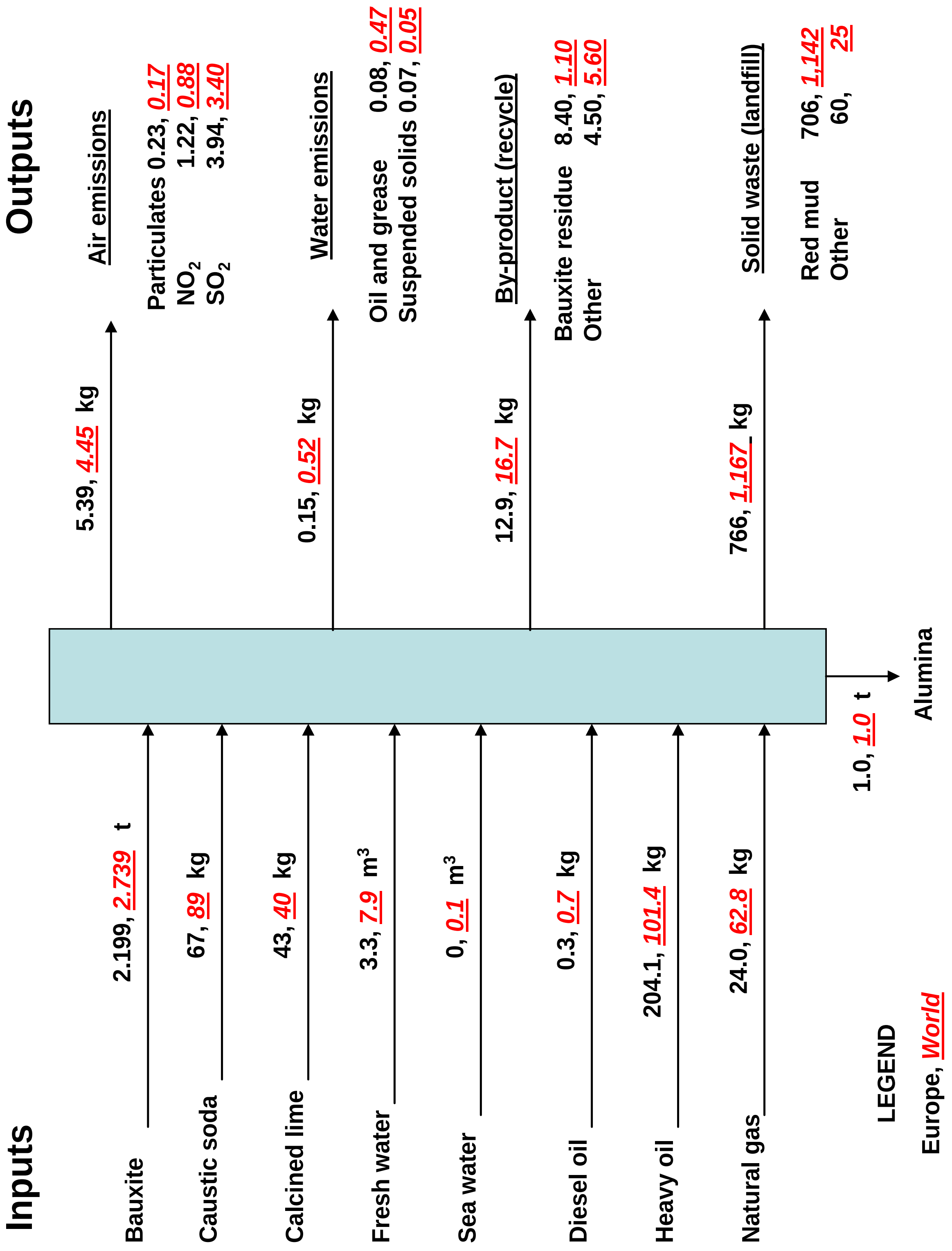
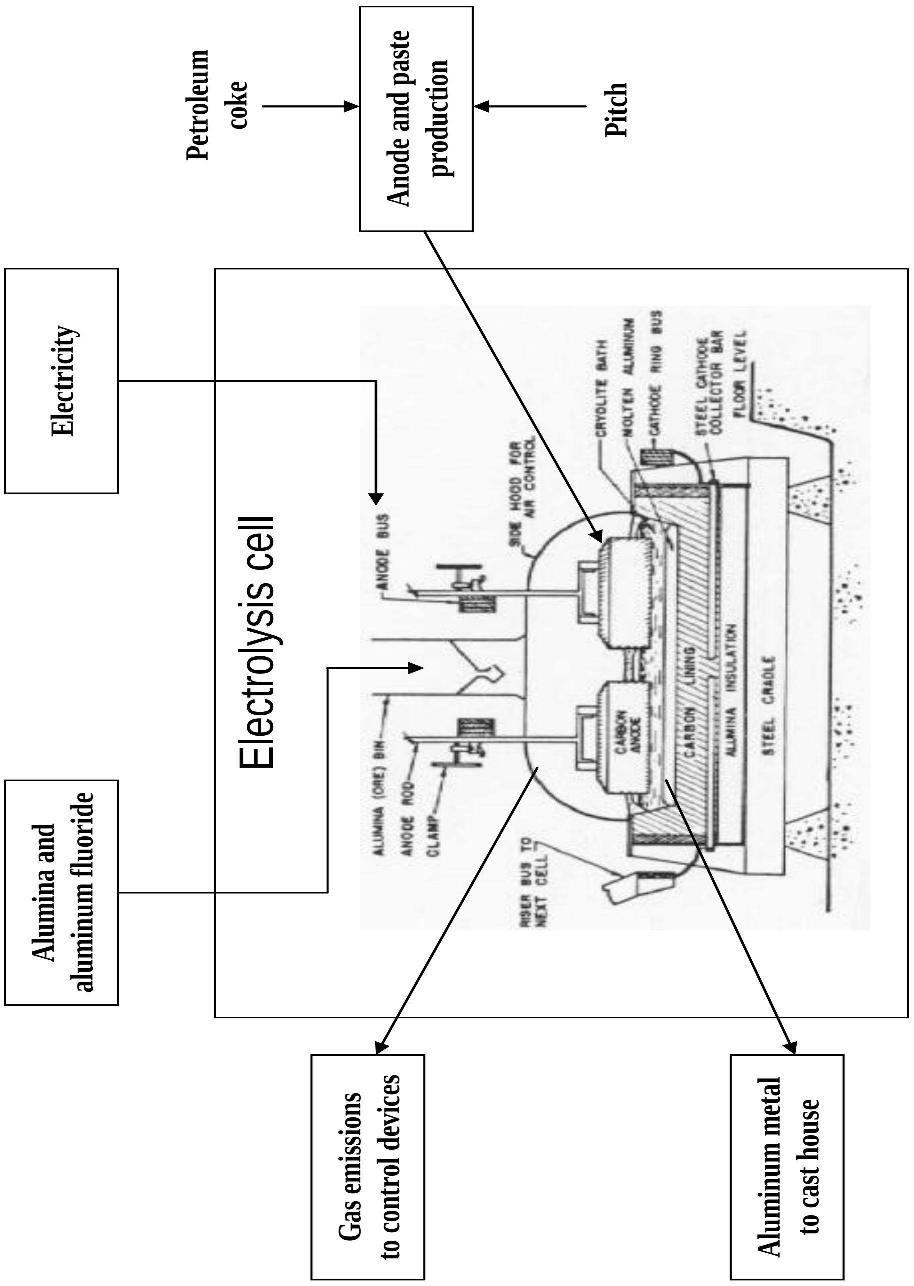
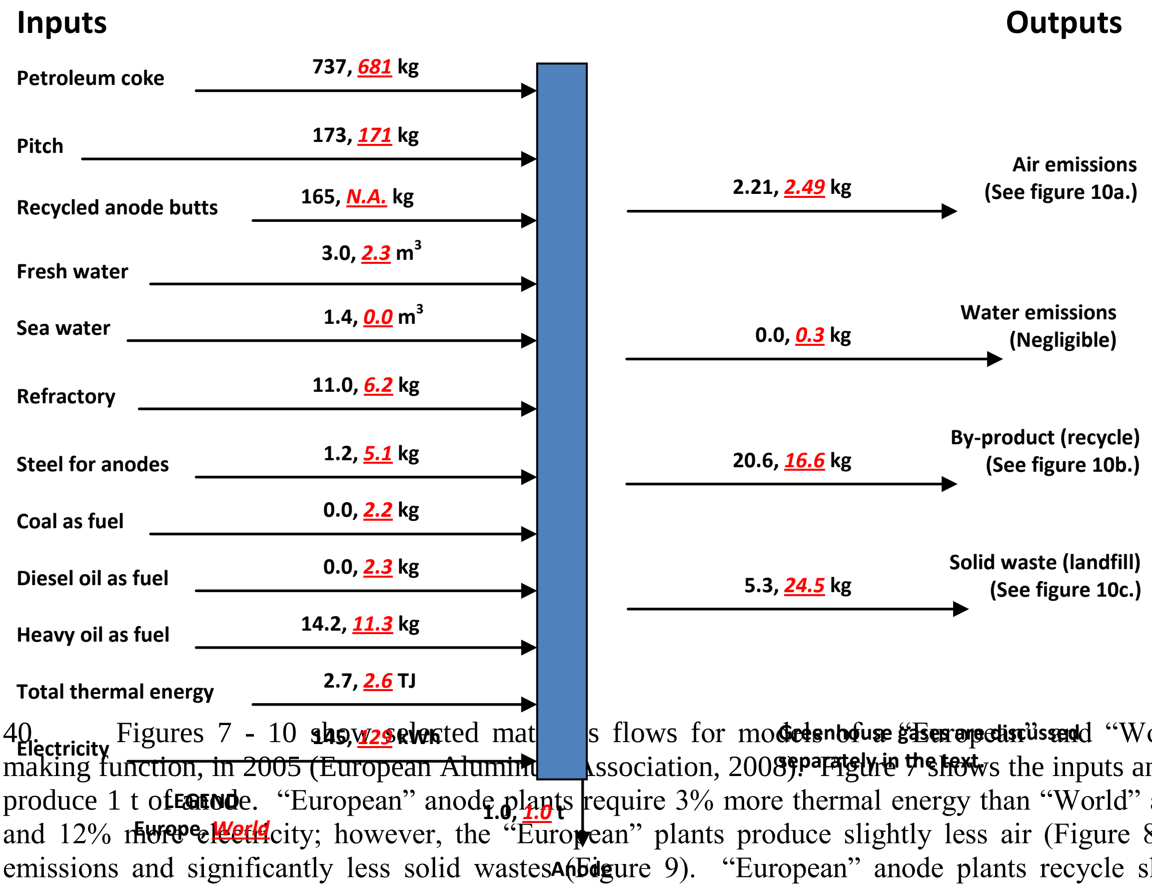


Figure 6. Diagram showing a typical process flow for aluminum smelting.



Obtain permission to use cell drawing from http://electrochem.cwru.edu/encycl/art-a01-al-prod.htm

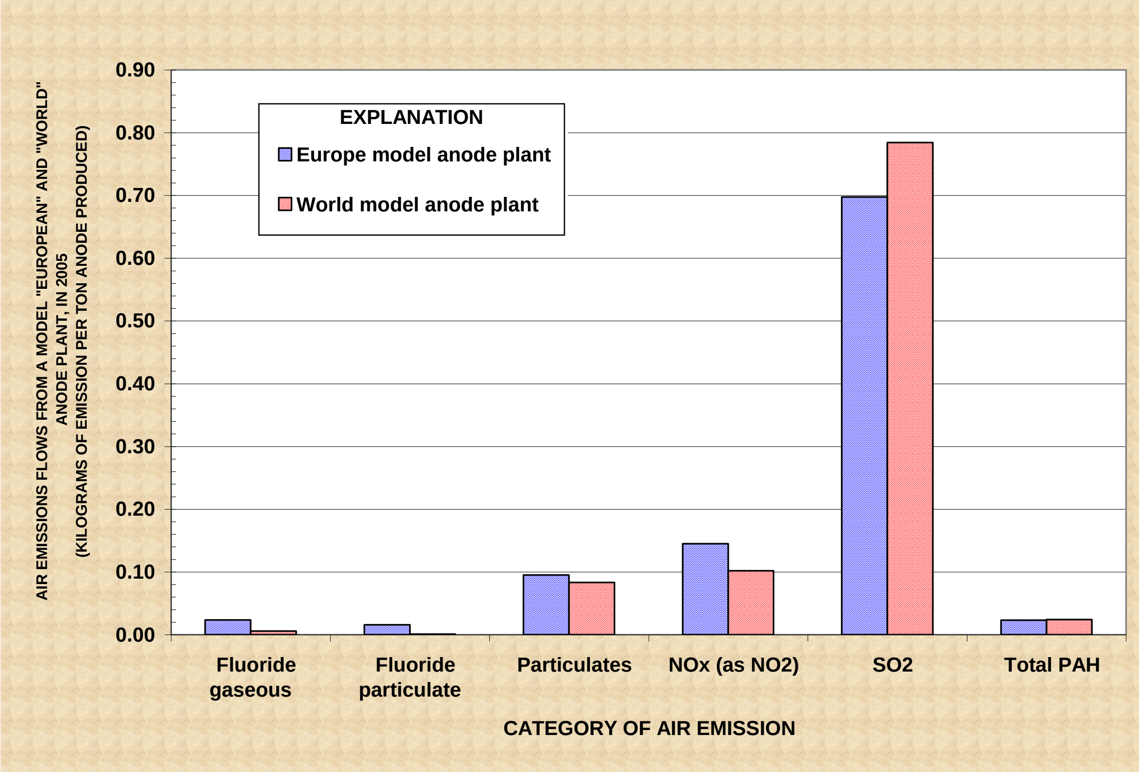
Figure 7. Diagram showing selected materials flows for a model "European" and "World" anode-making function. Source European Aluminium Association 2008, p. 25.



40. Figures 7 - 10 show selected materials flows for models of "European" and "World" anode-making function, in 2005 (European Aluminium Association, 2008). Figure 7 shows the inputs and outputs to produce 1 t of anode. "European" anode plants require 3% more thermal energy than "World" anode plants and 12% more electricity; however, the "European" plants produce slightly less air (Figure 8) and water emissions and significantly less solid wastes (Figure 9). "European" anode plants recycle slightly more refractory materials and slightly less steel than "World" plants but significantly more other solid wastes (Figure 10).

41. Salient input flows to produce 1 t of anode in the "European" and "World" models of the aluminum smelting process, as shown in Figures 7 - 10 are respectively, 737 and 681 kg of petroleum coke, 173 and 171 kg of pitch, 2.7 and 2.6 terrajoules of fuel energy, and about 145 and 129 kWh of electricity. The corresponding output flows (exclusive of greenhouse gases) of significance are, respectively, 1.5 and 2.0 kg of SO_2 and 5.3 and 24.5 kg of various materials to landfill storage. Of primary environmental concern is the generation of greenhouse gas (CO_2).

Figure 8. Bar chart showing air emissions for a model “European” and “World” anode-making function. Gaseous fluoride and fluoride particles are expressed as contained fluorine. PAH is polycyclic hydrocarbons.



42. The principal inputs to the aluminum smelting process are alumina, aluminum fluoride, carbon (as anodes) and electricity. The principal outputs are aluminum metal, CO_2, and some solid wastes. Figures 11-15 show selected materials flows for models of "World" and "European" aluminum smelters (Hall-Heroult process). Salient input flows to produce one t of aluminum metal for the model "European" and "World" smelters, as shown in Figures 11 - 15 are, respectively, 1.93 and 1.92 t of alumina, about 428 and 435 kg of anode paste, and about 14.9 and 15.3 MWh of electricity. In 1930, about 25 MWh per t aluminum was required (Rosenqvist, 2004, p. 449). The corresponding output flows (exclusive of greenhouse gases) of significance are, respectively, 8.2 and 14.9 kg of SO_2, about 1.1 and 3.4 kg of fluorine to air (0.6 and 0.3 kg to water), and 28.5 and 32.2 kg of various materials to landfill storage.

Figure 9. Bar chart showing solid waste (landfill) for a model "European" and "World" anode-making function.

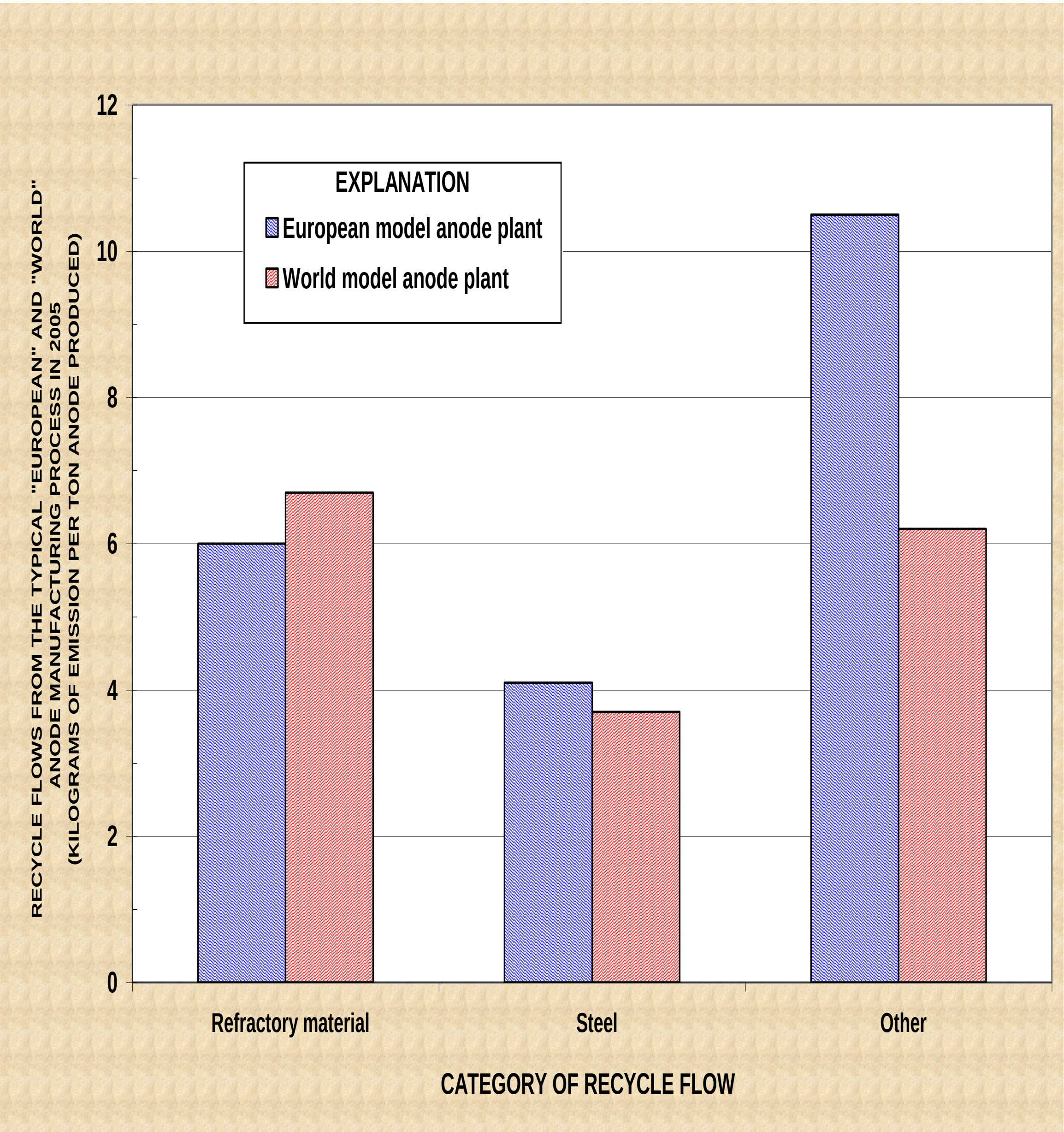


Figure 10. Bar chart showing externally-recycled waste products for a model “European” and “World” anode-making function.

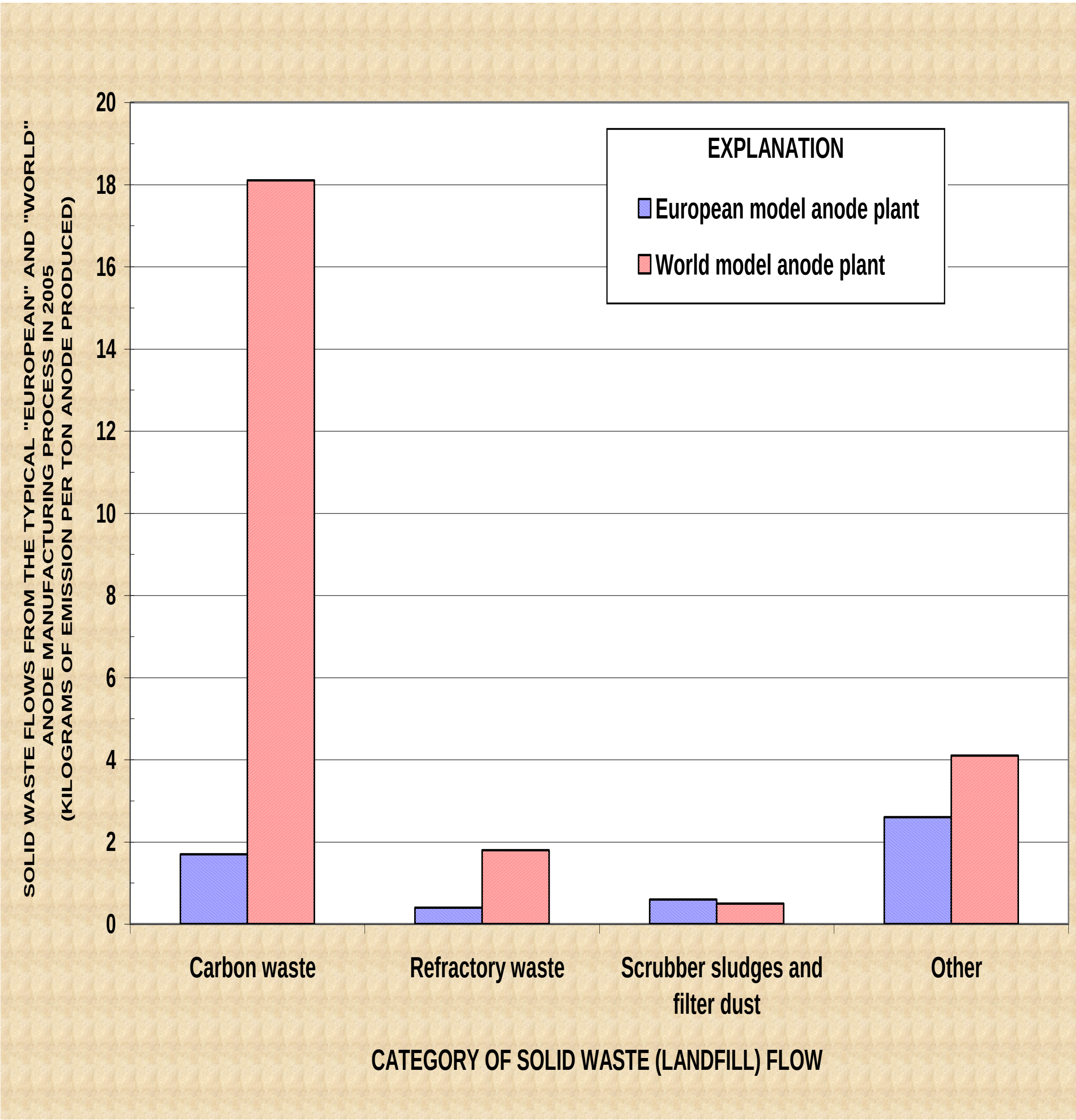


Figure 11. Diagram showing selected materials flows for models of "European" and "World" aluminum smelters. Source EAA, 2008, p. 27.

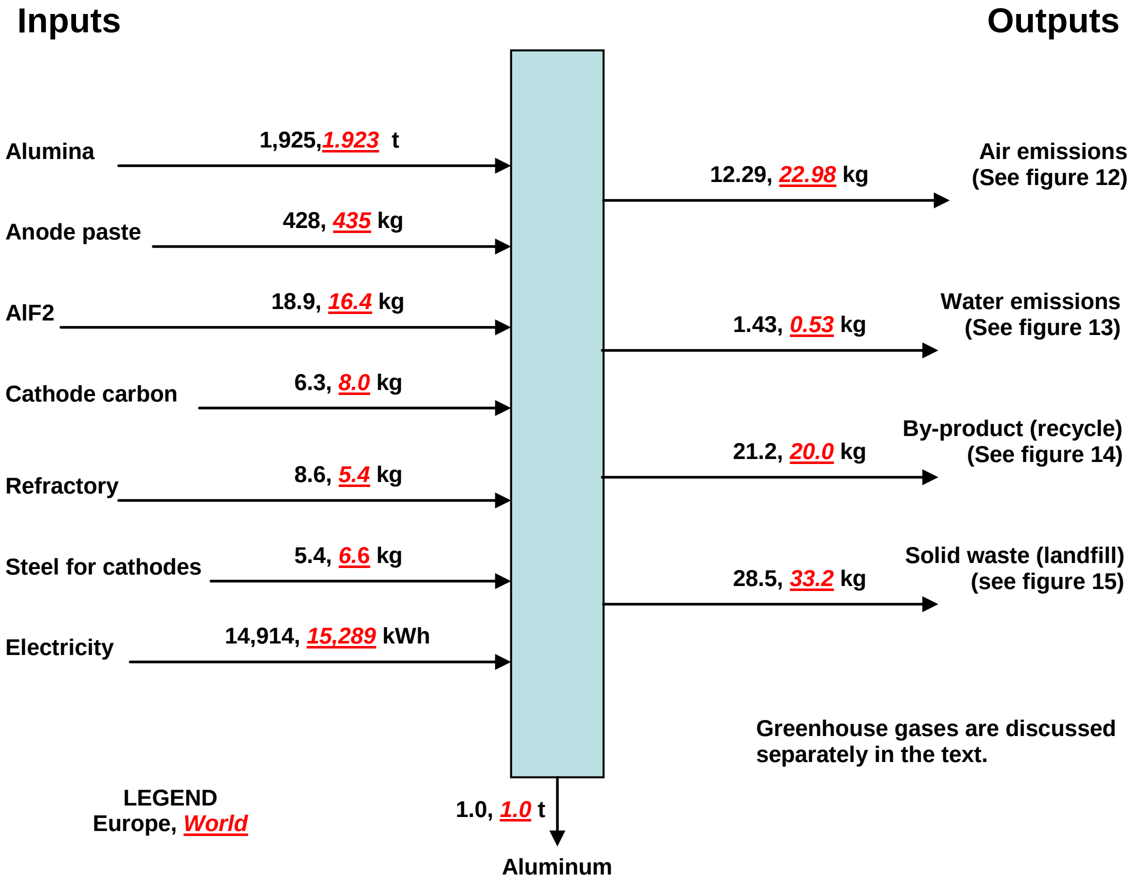


Figure 12. Bar chart showing air emissions for models of “European” and “World” aluminum smelters.

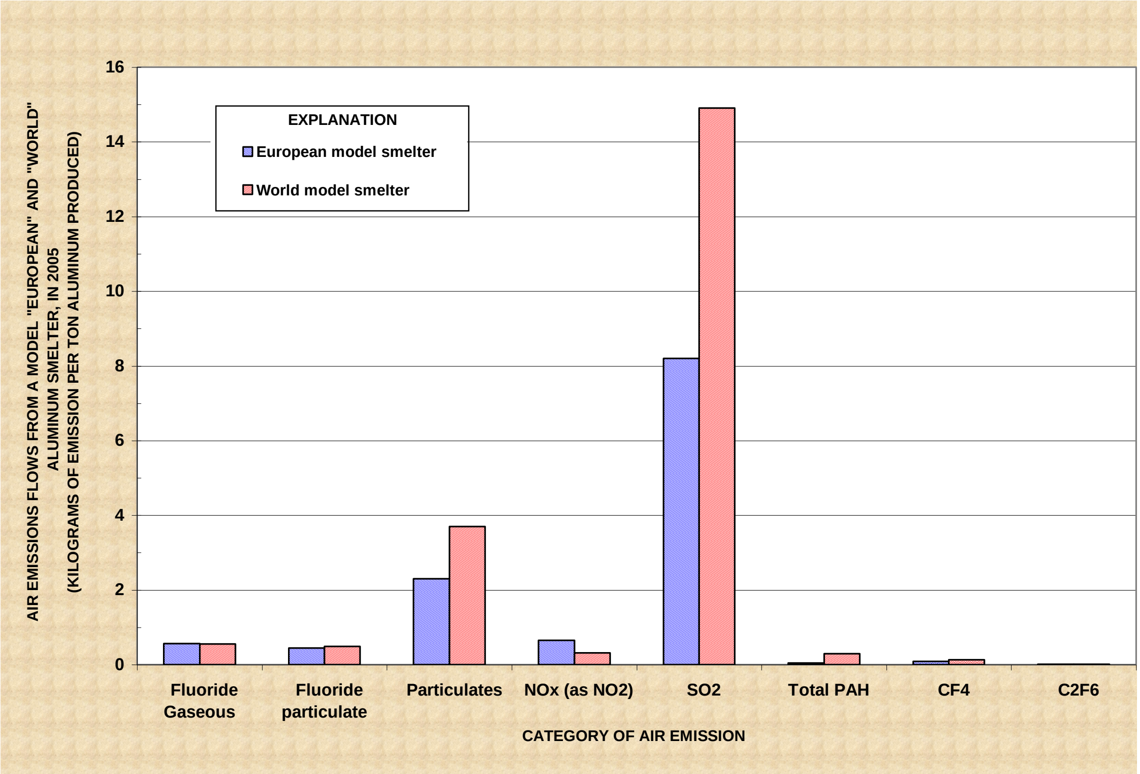


Figure 13. Bar chart showing emissions to water for models of "European" and "World" aluminum smelters.

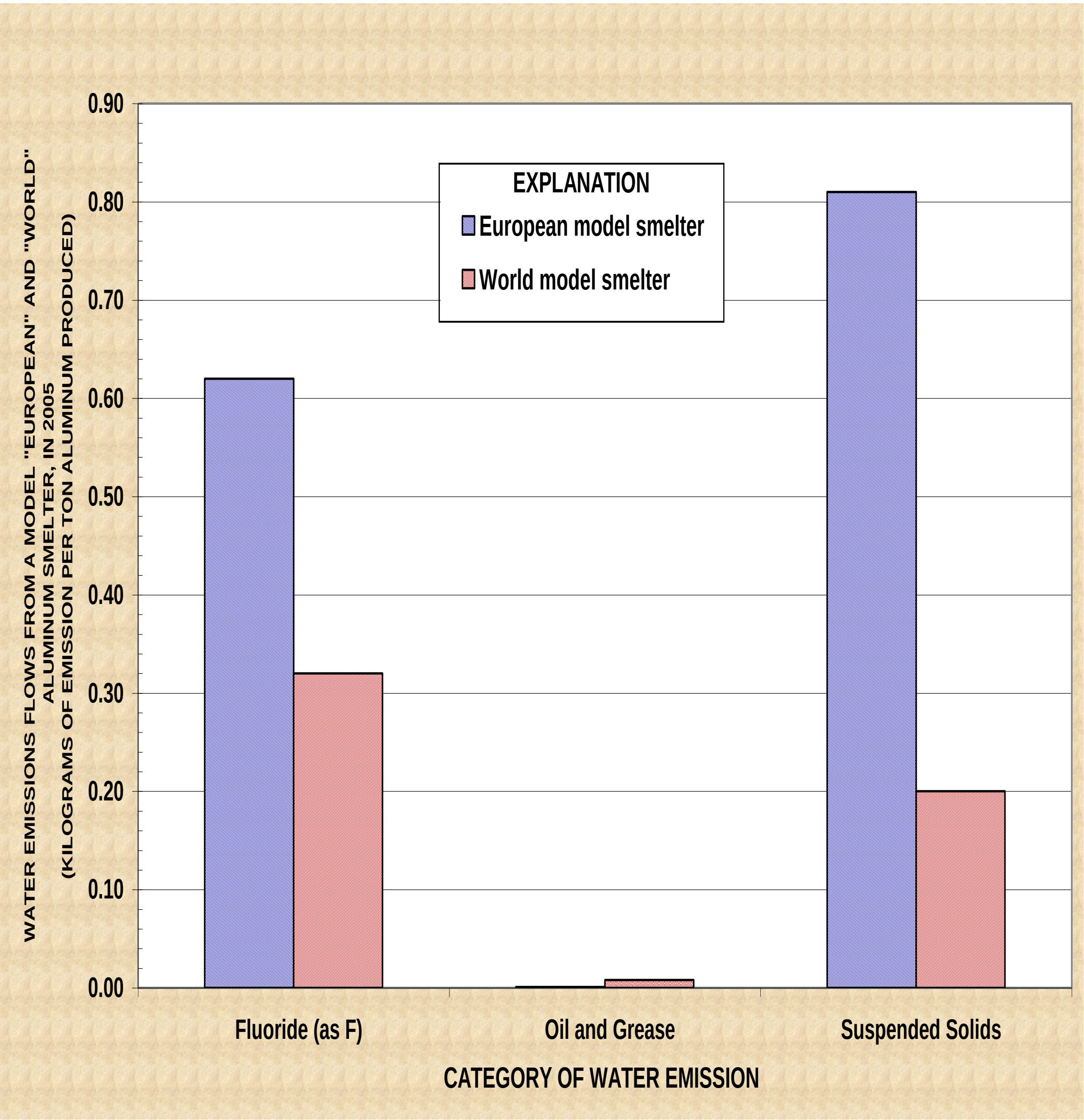


Figure 14. Bar chart showing externally recycled waste from “European” and “World” aluminum smelters.

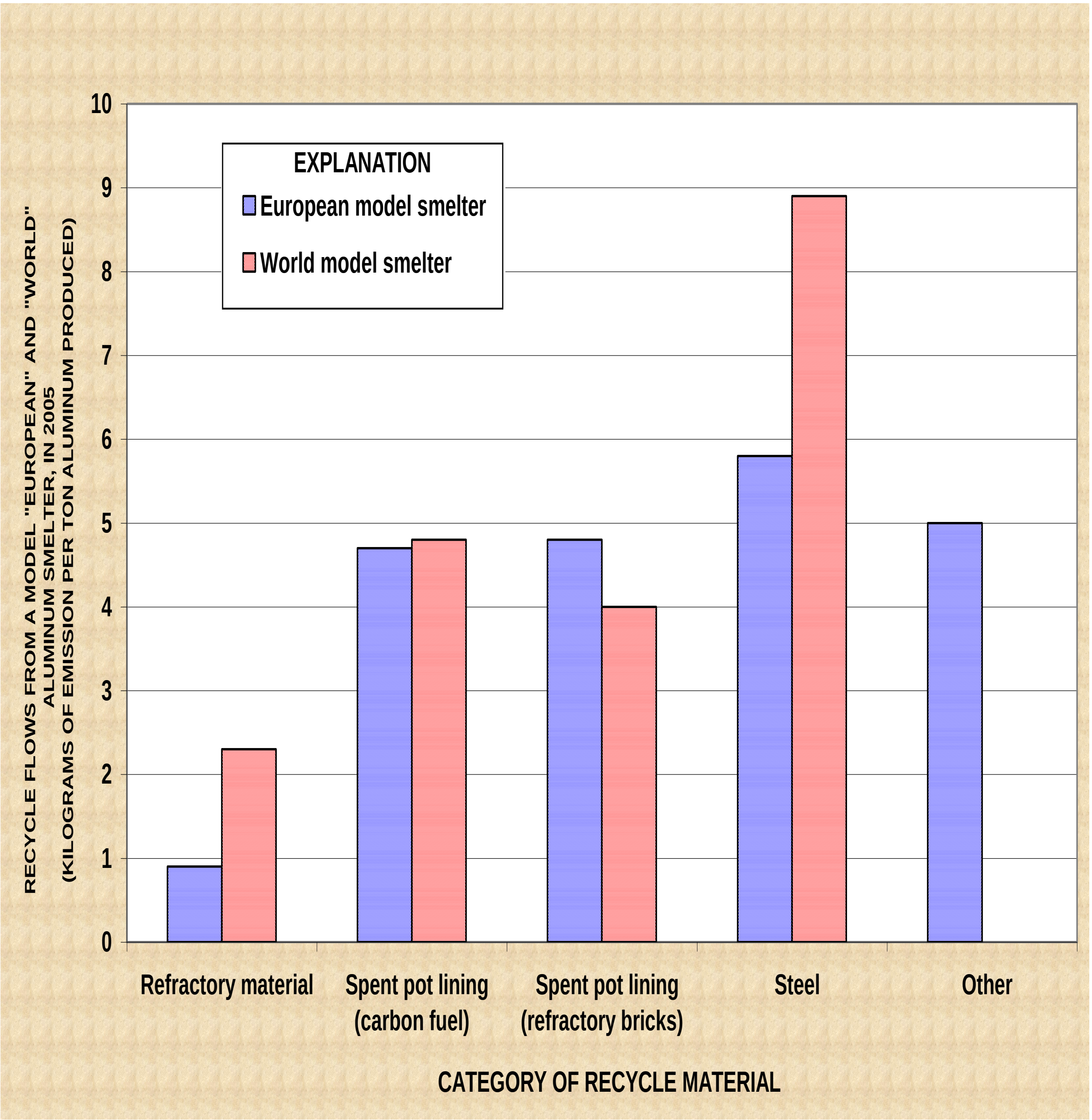
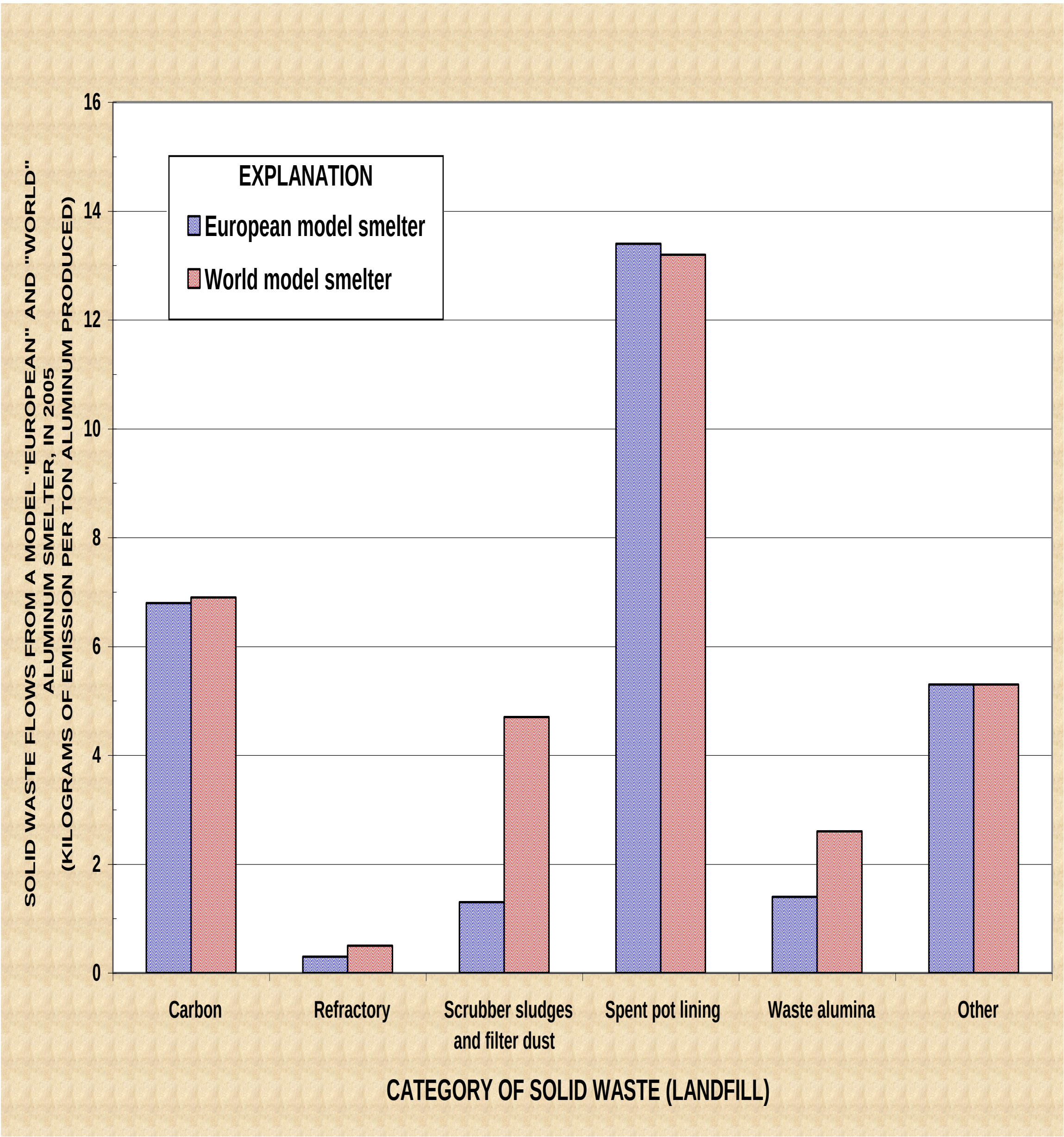


Figure 15. Bar chart showing solid waste from "European" and "World" aluminum smelters.



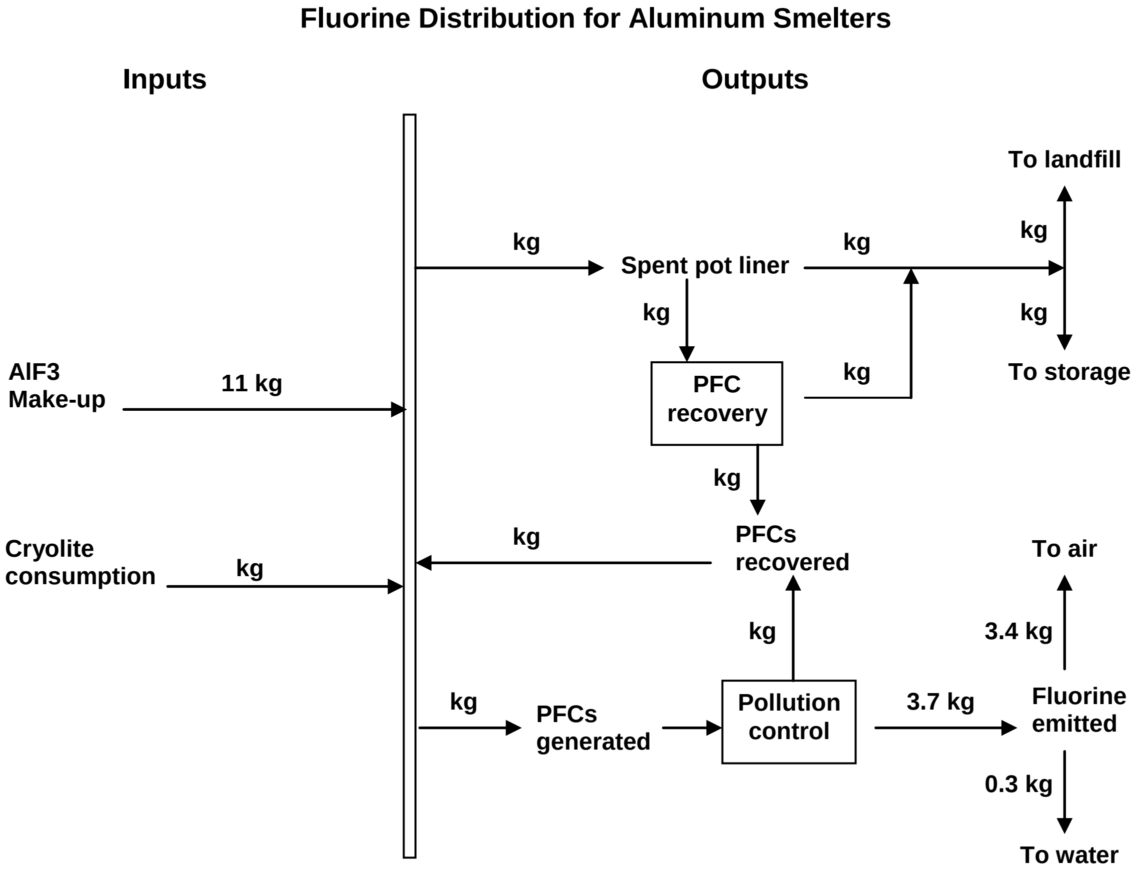
3.1.2.3.1 Aluminum Smelting and Electrolysis—Greenhouse Gas (GHG) Emissions

43. A greenhouse gas (GHG) is an atmospheric gas that is believed to contribute to climate change by increasing the ability of the atmosphere to trap heat. Different species of such gases have differing abilities to trap heat. Global warming potential (GWP) is a measure of the relative effectiveness of a GHG to affect climate. The heat-trapping ability of 1 ton of CO_2 is the common standard, and emissions are expressed in terms of CO_2 equivalent.

44. The burning of fossil fuels for energy production, transportation, and industrial activities is among the human activities that can contribute carbon dioxide and other GHG emissions to the atmosphere. Aluminum smelting is one of the industrial activities under study because the process emits significant quantities of carbon dioxide and some perfluorocarbon (PFC) gases.

45. Although PFCs emitted from aluminum smelters are not considered toxins or ozone-depleting gases (Simmonds and others, 2002), they are considered to be GHGs. PFCs are of particular concern because they have a greater global warming potential (GWP) per unit of emission than carbon dioxide. It has been estimated that 1 t of CF_4 has the equivalent GWP of 6,500 t of CO_2 and that 1 t of C_2F_6 has the equivalent GWP of 9,200 t of CO_2 (U.S. Environmental Protection Agency, 2006; International Aluminium Institute, 2009c). Aluminum smelting and the manufacturing of electronic chips are the largest known anthropogenic sources of PFCs (Aslam and others, 2003; U.S. Environmental Protection Agency, 2006). Figure 16 shows the flows of fluorine within the aluminum smelting process step. There is insufficient information to calculate all of the flow quantities; however, they are represented in the diagram as either a number reported for the World model smelter, or as "kg", indicating a flow of "unknown" kg of fluorine per ton of aluminum produced (European Aluminium Association, 2008).

Figure 16. Diagram of sources and distribution of fluorine during aluminum smelting.



46. PFCs have extremely stable molecular structure relative to other anthropogenic gases in the atmosphere and are largely immune to the chemical processes that break down most atmospheric pollutants in the lower atmosphere. Not until the PFCs reach the mesosphere, about 60 kilometers above Earth do very high-energy ultraviolet rays from the sun destroy them. This removal mechanism is extremely slow and as a result PFCs accumulate in the atmosphere and possibly remain there for several thousand years (U.S. Environmental Protection Agency, 2006).

47. In 2006, GHG emissions worldwide totaled about 51 gigatonnes (Gt). Taken together, the steel, copper, aluminum, and nickel industries accounted for 2.62 Gt, or about 5.2% of total GHG emissions. The USGS estimates, based on the relative production levels of aluminum, copper, nickel, and steel in 2008, that the aluminum industry contributed 0.45 GT of CO_2 equivalents of GHG.

48. Significant amounts of greenhouse gases are emitted while mining, concentrating, smelting, and refining metals. Table 4 provides a perspective on how the process of producing aluminum from bauxite compares with processes for the production of other metals with regard to the generation of greenhouse gases (Carbon Emitters, 2009).

49. Aluminum production generates not only PFCs during anode events (discussed separately below) but also large quantities of CO_2 from electricity (generated from combustion of hydrocarbons) use, fuel use, and process-generated reduction reactions. The World Business Council and World Resource Institute have suggested a GHG reporting protocol that accounts for GHG generation on a corporate basis. GHGs attributable to imported materials and energy flows are accounted to the ex-corporate generator—for example, the GHG generated by hydrocarbon-originated electricity that is imported (across the corporate fence) would be considered as “indirect” with respect to the subject corporation (International Aluminium Institute, 2003).

50. Martchek (2007) has calculated CO_2-equivalent emissions for several steps of global aluminum production. Table 5 presents those results. Martchek further demonstrates (based on model results) that the intensity of GHG emissions for the worldwide aluminum industry (mining through semifabricated shipments) decreased to 8.2 in 2005 from 11.0 in 1990 Mt CO_2e/Mt_shipments, and projects the level to be 6.1 Mt CO_2e/Mt_shipments in 2032. Drivers for this actual and expected improvement are both increased recycling and lower emissions from primary aluminum smelters (Martchek, 2007).

Table 4. Selected metals industry contributions to greenhouse gas (GHG) emissions, in 2006.

Metal industry	Production	GHG	World GHG share	Fossil fuel GHG share
	(Mt)	Gt CO_2-e	Percent	Percent
Steel	1,250	2.13	4.2	6.3
Copper	13.5	0.04	0.1	0.1
Aluminum	33	0.41	0.8	1.2
Nickel	1.4	0.04	0.1	0.1

Source: Carbon Emitters (2009).

Table 5. Greenhouse gas emissions intensity of primary aluminum operations, in 2005.

Production step:	Mining	Refining	Anodes	Smelting	Mining through smelting
Contributor	CO_2e/t_Al	CO_2e/t_Al	CO_2e/t_Al	CO_2e/t_Al	CO_2e/t_Al, (%)[1]
Process			388	1,582	1,970, (21.3)
Fuels	16	754	135	133	1,038, (11.2)
Perflurocarbons (PFC)				960	960, (10.4)
Electricity		58	63	5,147	5,268, (57.0)
Sub-total (*total)*	16	812	586	7,822	*9,236*
Percent of *total*	0.17	8.79	6.34	84.69	

[1] Percent of total CO_2e/t_Al (9,236)for mining through smelting.

Units, unless specified otherwise, are in kg CO_2 equivalents/t_aluminum, where CO_2e is the nomenclature for a CO_2 equivalent. PFCs (perfluorocarbons) are weighted higher than CO_2 for global warming potential (GWP); one t of CF_4 has the equivalent GWP as 6,500 t of CO_2, and that 1t of C_2F_6 has the equivalent GWP as 9,200 t of CO_2.

Source: Martchek (2007).

3.1.2.3.2 Aluminum Smelting and Electrolysis—Generation of PFCs (Anode Events)

51. The normal reduction process is represented by the following chemical equation:

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

52. On occasion, there is an overvoltage disturbance in the cell. These episodes, termed “anode events,” are triggered by an insufficient amount of alumina in the cell. The anode event causes the fluorine contained in the cryolite and aluminum fluoride to react with the carbon anodes to form the gases tetrafluoromethane (CF_4) and hexafluorethane (C_2F_6), often referred to as perfluorocarbons (PFCs). An anode event is represented by the following chemical equation:

$Na_3AlF_6 + nC \rightarrow (CF_2)n \rightarrow CF_4, C_2F_6$.

53. A typical anode event may have duration of approximately 2 minutes and have a frequency of 0.2–1.5 cells per day for a smelter with 150–300 cells (Fraser and others, 2009). The frequency and duration of anode events have been reduced considerably since the late 20th century as old plants are phased out and new plants are constructed with improved monitoring of the cell conditions in the molten “bath” and advances in plant design.

3.1.2.3.3 Industry Performance Goals

54. The IAI and its member companies have adopted through the Alumina for Future Generations program a number of performance targets related to the release of certain production wastes. Among these goals is the reduction of PFC emissions by 2020 to 50% of 2006 levels. This corresponds to a level of emissions of .5 t of CO_2 equivalent per ton of aluminum. The IAI has adopted a goal of achieving a 33% reduction from the 1990 level of 2.4 kg of fluorine per ton of aluminum produced by 2010. IAI also adopted a goal to reduce the amount of electrical energy used in aluminum smelting by 10% to 14.5 mega watt hours from 1990 levels by 2010. Finally, IAI adopted a goal of reducing energy use per ton of alumina refined by 10% from 2006 levels to 14.4 Giga joules per ton of aluminum by 2020 (IAI, 2009a).

3.1.2.4 Materials Inputs to and Outputs from Secondary Aluminum Production[2]

55. Goonan (written communication) presents models of the inputs to and outputs from the production of secondary aluminum from aluminum scrap. The following section is excerpted and modified from that report.

56. Secondary aluminum is recovered from the processing of various kinds of aluminum scrap including wire and cable, wrought alloys, casting alloys, used beverage cans, turnings, packaging, and dross (a mixture of metal, alumina, and other materials). Alumina (Al_2O_3) that comes into the remelting system or that is generated within the system cannot be thermodynamically reduced to aluminum and therefore leaves the system as a nonmetallic residue, which ultimately is sold to the cement industry or used as backfill for mine recovery.

57. For primary aluminum production, there are environmental concerns about greenhouse gases (CO_2, CF_4, and C_2F_6) and land use for mining and disposal of red mud (Bayer process residue) and smelter wastes (spent pot liner and other). Recovering aluminum from scrap to produce secondary aluminum ingot consumes about 6% of the energy required to produce primary aluminum. This significant energy difference

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[2] By Thomas G. Goonan

is responsible for the emphasis placed on aluminum recycling in today's society and in the aluminum industry. Furthermore, to achieve a given output of ingot, recycled aluminum requires only about 10% of the capital equipment costs compared with those required for the production of primary aluminum (U.S. Department of Energy, 2007, p. 64). Fluorocarbon gases are not produced with secondary smelting. The principal greenhouse gas is CO_2 and, because of the lower energy consumption, very much less is generated than that produced in primary smelting.

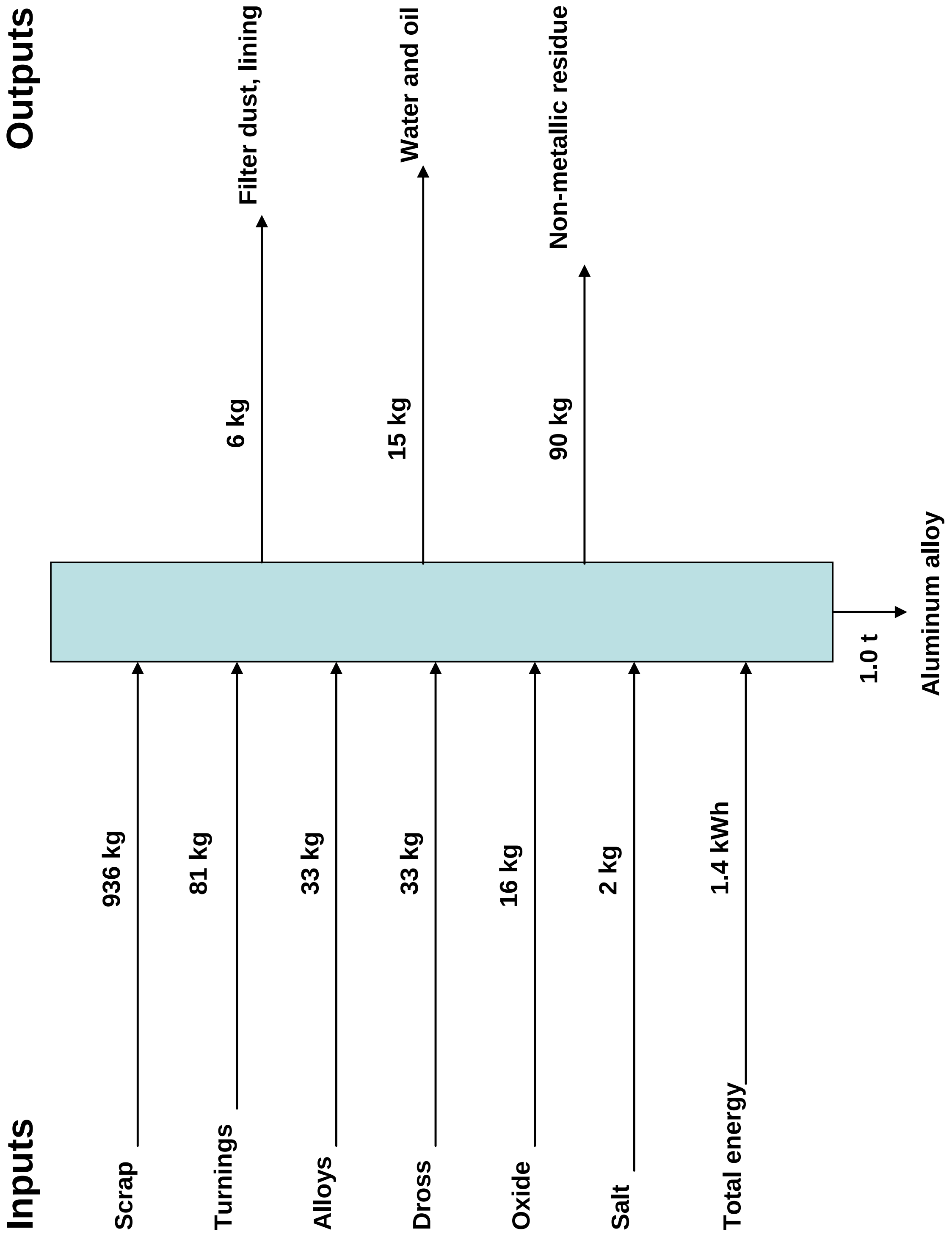
58. Boin and Bertram (2005) reported on the efforts of 15 European Union members to construct a model for secondary aluminum in Europe—European Scrap Smelting Unit Model (ESSUM). In 2002, ESSUM showed that producing 1 t of aluminum metal alloy produced required 936 kg of scrap, 81 kg of turnings, 33 kg of alloys, 33 t of dross, 16 t of oxide, and 2 t of salt (Figure 17).

59. Scrap for processing in secondary smelters can come from many sources and can be of various types. One convenient means to categorize scrap generation is by life-cycle stage, which would include production (smelting), fabrication (making usable shapes of various alloys for further processing), manufacturing (machining shapes to make parts for assemblies), and end-of-life (recovery of old scrap from economic sectors). Scrap can also be assigned to different processing modes. Remelters usually operate flux-free furnaces that treat clean, identified, and essentially new scrap generated from fabrication and manufacturing operations. Remelters make specific alloys, usually for wrought products. Refiners deal with dross (skimmings) foundry scrap, and much of the end-of-life scrap. Refiners make foundry alloys and deoxidation alloys for the steel industry.

60. The greenhouse gas generation difference between primary and secondary aluminum smelting is significant. One investigator estimated GHG emissions (alumina through casting of primary aluminum) within the EU27 at about 11 Mt CO_2-equivalent, whereas secondary remelting and refining generated 0.88 and 0.96 Mt of CO_2-equivalent respectively. The substitution of secondary for primary aluminum product can significantly reduce greenhouse gas emissions [Fraunhofer Institute for Systems and Innovations Research (ISI), 2009].

61. Secondary aluminum processing is heavily dependent on natural gas consumption. Furnaces that use natural gas can generate NOx, a precursor to ozone (Metals Advisor, 2010). Life-cycle analysis could be used to measure NOx and to develop strategies to reduce emissions.

Figure 17. Diagram showing selected material flows for a model "European" secondary aluminum smelter, in 2002.



3.1.3 Global Mass Flows of Aluminum—Consumption

3.1.3.1 Consumption—Overview

62. IAI has summarized the disposition of aluminum as a total in finished products (40.4 Mt in 2006) and as net additions to products in use (24.4 Mt in 2006), which are distributed in among the following end-uses:

buildings (32%)

engineering and cable (28%)

packaging (1%)

transportation (28%) including automobiles (16%)

other (11%).

63. This report first examines the apparent consumption of aluminum for the 20 most populous countries to show how aluminum consumption varies among countries. The next section will examine consumption by end-use.

64. Consumption of aluminum can be measured at different points in the cycle of material use. Consumption can be measured either as quantity of material that goes into goods manufactured within the country (industrial consumption) or as the quantity of material in goods consumed by inhabitants of the country (final consumption). Industrial consumption can be easily estimated as the amount of aluminum produced in the country plus imports of aluminum less exports of aluminum. Final consumption is much more difficult to measure as it requires at a minimum knowledge of the goods consumed and their aluminum contents.

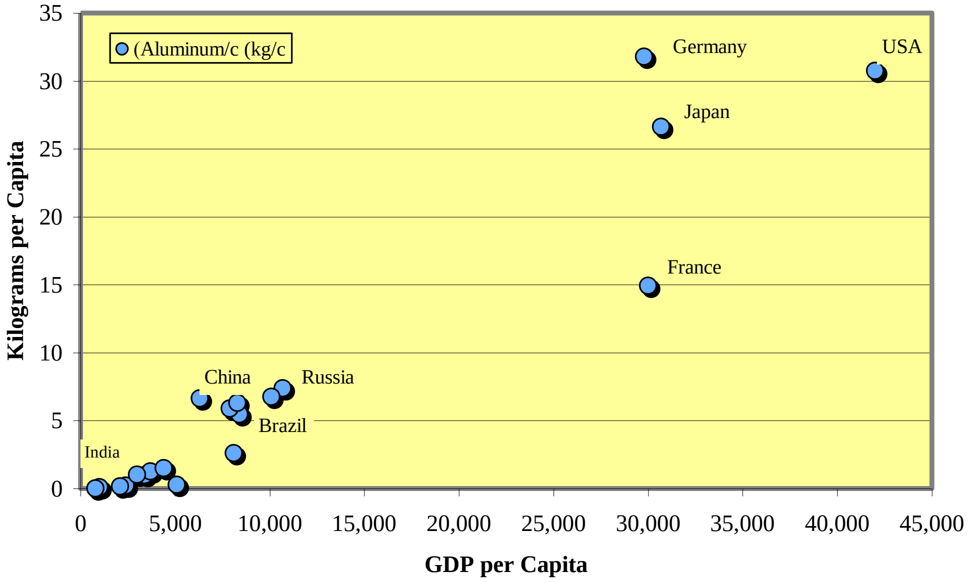
65. Previous studies (DeYoung and Menzie, 1999; Menzie, DeYoung, and Steblez, 2001) have shown that industrial consumption per-capita in countries is related to the average national income level of the country as measured by GDP per-capita. Table 6 presents data on and Figure 18 is a plot of the aluminum consumption per-capita versus GDP per-capita in 2006 for the 20 most populous countries (China, India, United States, Indonesia, Brazil, Pakistan, Bangladesh, Russia, Nigeria, Japan, Mexico, Philippines, Vietnam, Germany, Ethiopia, Egypt, Turkey, Iran, Thailand, and France). Together these countries consumed 30.3 Mt of aluminum in 2006 or about two-thirds of global production. In general, countries with a GDP per-capita less than $5,000 consume less than 5 kilograms (kg) of aluminum per-capita; countries with a GDP per-capita between $5,000 and $15,000 consume between 5 and 10 kg of aluminum per-capita; and countries with incomes per-capita greater than $25,000 consume between 15 and 35 kg of aluminum per-capita. The change in per-capita consumption that accompanies an increase in income is dramatic and is an important factor in understanding the likely future consumption of aluminum both at a country level and globally.

Table 6. Population, gross domestic product (gdp), aluminum consumption, gdp per-capita, and aluminum consumption per-capita for the 20 most populous countries in 2006.

Country	Popn (M)	GDPpp (B$)	Aluminum (kt)	GDP/c pp ($)	Aluminum/c (kg/c)
China	1,304	8,220	8,648	6,300	6.63
India	1,108	3,770	1,080	3,400	0.97
USA	298	12,500	9,173	42,000	30.74
Indonesia	232	858	288	3,700	1.24
Brazil	192	1,610	1,044	8,400	5.45
Pakistan	166	399	34	2,400	0.21
Bangladesh	150	315	24	2,100	0.16
Russia	142	1,520	1,047	10,700	7.37
Nigeria	140	140	11	1,000	0.08
Japan	128	3,910	3,393	30,700	26.61
Mexico	107	1,080	725	10,100	6.75
Philippines	95	486	26	5,100	0.28
Vietnam	85	256	88	3,000	1.03
Germany	82	2,460	2,619	29,800	31.78
Ethiopia	77	62	0	800	0.00
Egypt	74	326	110	4,400	1.48
Turkey	74	582	433	7,900	5.88
Iran	65	526	168	8,100	2.59
Thailand	65	537	407	8,300	6.29
France	63	1,900	945	30,000	14.92
Congo-K	62	50	0	800	0.00
UK	61	1,870	567	30,900	9.35
Italy	58	1,650	1,686	28,400	29.02
Korea, Rep	49	1,000	1,153	20,400	23.53
South Africa	48	580	264	12,100	5.51
Burma	47	76	0	1,600	0.00
Ukraine	47	317	39	6,800	0.84
Colombia	42	298	77	7,100	1.83
Spain	40	1,020	863	25,200	21.36
Argentina	40	543	146	13,700	3.68
Sudan	39	81	1	2,100	0.02
Tanzania	39	27	0	700	0.00
Poland	39	490	227	12,700	5.88
Kenya	36	43	13	1,200	0.36
Algeria	33	238	6	7,200	0.18
Canada	33	1,080	1,031	32,900	31.52
Morocco	30	130	12	4,300	0.40
Uganda	29	50	0	1,700	0.01
Peru	28	173	2	6,100	0.07

Nepal	28	41	0	1,500	0.00

Figure 18. Aluminum consumption per capita versus gross domestic product per capita for the 20 most populous countries in 2006.



3.1.3.2 Consumption—End-Uses

66. This study also presents statistics on end-use of aluminum for selected populous countries including Argentina, Brazil, China, France, Germany, India, Japan, Mexico, Russia, the United Kingdom, and the United States. Table 7 presents data on the percentage of aluminum consumption for various end uses in these countries. The data are available for different years and use somewhat different end-use classifications, which limit the conclusions that can be drawn from the data.

67. Nevertheless, the data when combined with data on GDP per-capita do suggest that several important changes in the consumption of aluminum occur as income increases. First, the data show that aluminum consumption for electrical end uses fall with increasing income (Figure 19). Second, the data show that aluminum consumption for transportation end-uses increases with rising income (Figure 20).

Table 7. Aluminum end use data for select high-income countries and populous countries with growing economies.

Selected Populous Countries with Growing Economies

	2008	2008	2009	2007		
	Argentina	Brazil	China	India	Mexico	Russia
Construction	21.4	11.3	40	13	6	7
Transportation	22	25.8	18	18	38	19
Electrical (Power)	15.7	11.6	12	31	21	18
Durable Goods	6.9	8.7	11	12	9	10
Packaging	19.3	28.7	9	11	6	3
Machinery and equipment	4.7	4	8	6	12	40
Fabricated metal	6.3					
Others	4.1	9.9	2	9	8	3
	100	100	100	100	100	100

Sources:

Associacao Brasileira do Aluminio http:www.abal.org.br/english/industria/estatisticas_consdomsetor.asp

Indian Minerals Yearbook 2007

Boltramovich, Dudarev, and Gorelov (2003, p. 126)

High-Income Countries

	2004	2006				2006
	France	Germany	United Kingdom	Western Europe	Japan	United States
Construction	21	16.0	30	25	13.2	13.0
Transportation	36	44.1	21	36	40.5	38.0
Electrical		6.0			4.5	5.0
Durables		4.6				7.0
Packaging	10	9.3	21	17	10.2	26.0
Machinery		8.4			3.9	7.0
Engineering	31		28	14		
Fabricated metal		5.6			11.6	
Other	2	6.0		8	16.1	4.0
Total	100	100.0	100	100	100.0	100.0

Figure 19. Percentage of aluminum consumption in electrical end uses versus gdp per capita.

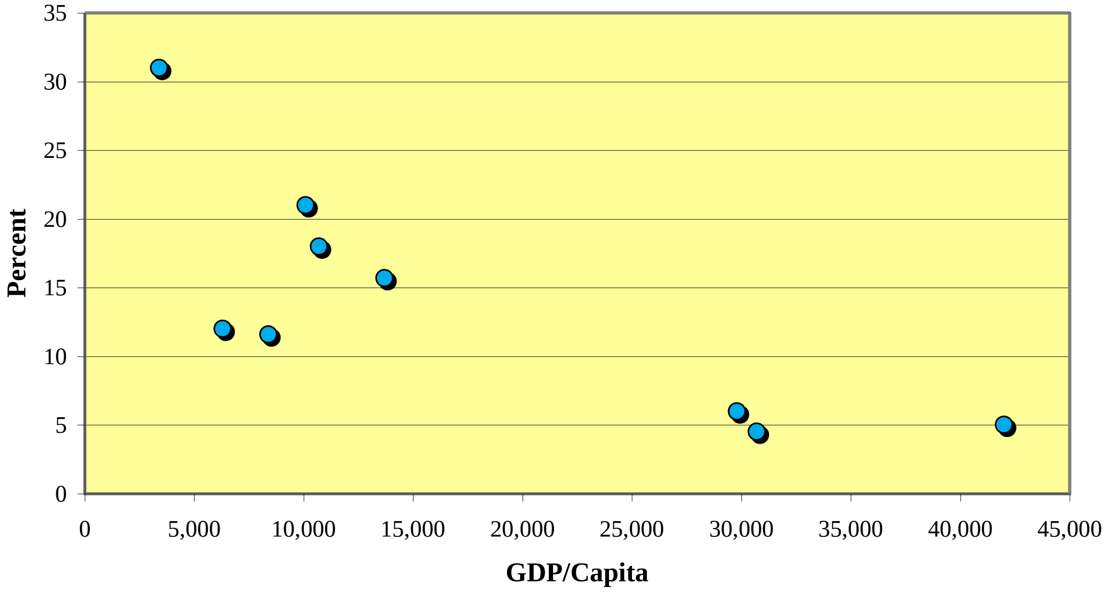
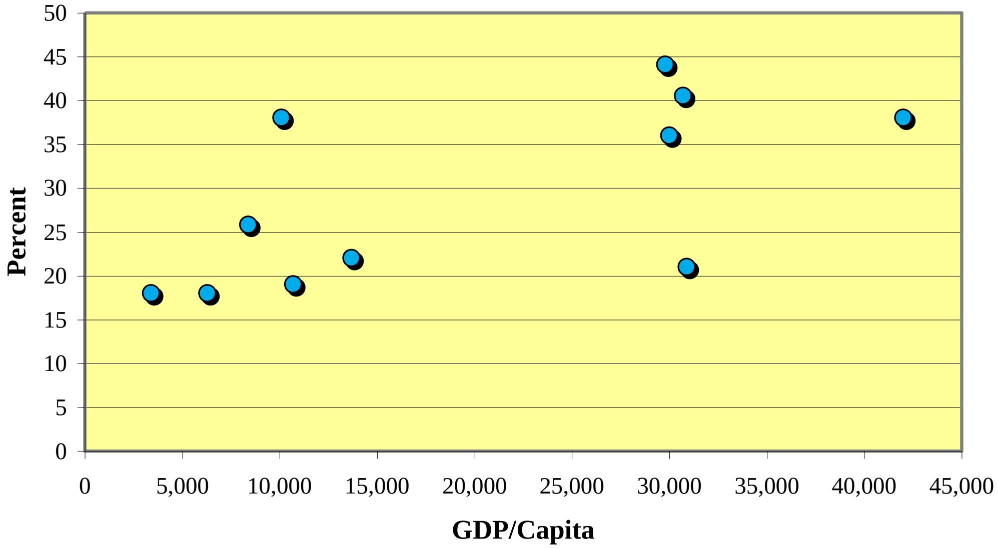


Figure 20. Percentage of aluminum consumption in transportation end use versus gdp per capita.



68. These changes in the use of aluminum with income have important implications for aluminum recycling. Because aluminum in electrical systems is typically in service for long periods of time, the amount of aluminum available for recycling in countries with lower but rapidly growing incomes is likely to be delayed relative to countries with higher incomes. Transportation is the largest end use of aluminum in high-income countries and automobiles are typically the largest use of aluminum in transportation. Because automobiles typically have in-service time periods of about 10 years, higher income countries have a larger supply of aluminum scrap available for trade or recycling than do countries that do not use automobiles for transportation or are only beginning to use automobiles as a primary mode of transportation. The transition from lower to higher incomes thus is accompanied by an increased availability of relatively easily recoverable aluminum. Of course, in-service times will create delays in the availability of this material.

69. Packaging is another end use that has a short in-service lifespan. Packaging such as used beverage cans (UBCs) can be easily collected, crushed, packaged, and recycled, and where widely used they represent a ready source of post-consumer aluminum scrap. Use of aluminum packaging varies considerably, but inconsistently, with income. Factors other than income appear to play an important role in determining the proportion of aluminum used in packaging.

70. Because transportation becomes a more important component of aluminum end use as incomes rise, this study has examined several components of the transportation end-use in some detail.

3.1.3.2.1 Consumption for Transportation—Light Vehicles

71. The production and use of automobiles and light commercial vehicles is a major component of transportation and one that grows rapidly with rising income. Estimates of the amount of aluminum in light vehicles can be calculated using statistics on vehicle production published by the International Organization of Motor Vehicle Manufacturers (OICA, undated) and data on the intensity of use of aluminum in vehicles (Ducker Worldwide LLC, 2008). Data on the aluminum content of vehicles by region for North America, the European Union, Japan, a world average, South Korea, China, India and other Asia, Russia and other Europe, South America, and the Middle East and Africa is presented for 2009 in Ducker Worldwide LLC (2008, p.10). Data for both 2006 and 2009 are presented for North America, the European Union, and Japan.

72. These data suggest that in 2006 aluminum use per vehicle was about 4% lower than in 2009. Therefore, the 2009 regional aluminum intensities were adjusted and the adjusted data are presented with vehicle production data, calculated aluminum intensity data, estimated aluminum in light vehicles, aluminum consumption in 2006, and estimated aluminum consumption in transportation end-uses in Table 8. The calculated aluminum content of vehicles is the product of the number of vehicles and the estimate of the aluminum intensity of vehicles; the estimated consumption of aluminum is from the World Bureau of Metal Statistics. The estimated aluminum consumption in transportation end-uses is based on World Bureau of Metal Statistics data and the transportation end-use percentages were presented in Table 8. About 69 million light vehicles were manufactured in 2006 containing approximately 7.8 million tons of aluminum for an average content of 113 kg per vehicle. Vehicles manufactured in North America contained the most aluminum, averaging 143 kg per vehicle, and vehicles manufactured in Africa and the Middle East contained the least aluminum, averaging 66 kg per vehicle.

Table 8. Vehicle production, aluminum intensity, aluminum in vehicles, aluminum consumption, and selected data on aluminum consumption in transportation.

Country	Total Vehicles	Aluminum Intensity (kg/vehicle)	Aluminum in vehicles (t)	Aluminum Consumption in 2006 (t)	Aluminum Consumption in Transportation End-Uses (est)
Argentina	432,101	67	28,951	145,600	32,032
Australia	330,900	78	25,810	439,600	
Austria	274,932	118	32,442	419,700	
Belgium	918,056	118	108,331	466,900	
Brazil	2,611,034	67	174,939	1,044,400	269,455
Canada	2,572,292	143	367,838	1,030,800	
China	7,188,708	96	690,116	8,648,100	1,556,658
Czech Rep.	854,907	118	100,879	129,600	
Egypt	91,518	66	6,040	109,500	
Finland	32,770	76	2,491	72,500	
France	3,169,219	118	373,968	944,700	340,092
Germany	5,819,614	118	686,714	2,619,000	1,154,979
Hungary	190,823	118	22,517	224,800	
India	2,019,808	78	157,545	1,079,500	194,310
Indonesia	297,062	78	23,171	288,000	
Iran	904,500	66	59,697	168,400	
Italy	1,211,594	118	142,968	1,686,100	
Japan	11,484,233	110	1,263,266	3,392,600	1,374,003
Malaysia	502,973	78	39,232	193,400	
Mexico	2,045,518	143	292,509	724,700	275,386
Netherlands	159,454	118	18,816	146,400	
Poland	714,600	118	84,323	227,000	
Portugal	227,325	118	26,824	111,500	
Romania	213,597	118	25,204	246,500	
Russia	1,508,358	76	114,635	1,047,000	198,930
Serbia	11,182	76	850	109,500	
Slovakia	295,391	118	34,856	25,500	
Slovenia	150,320	118	17,738	112,200	
South Africa	587,719	66	38,789	264,000	
South Korea	3,840,102	104	399,371	1,153,200	
Spain	2,777,435	118	327,737	862,800	
Sweden	333,168	118	39,314	138,400	
Taiwan	303,221	78	23,651	561,700	
Thailand	1,194,426	78	93,165	407,000	
Turkey	987,780	66	65,193	433,000	
Ukraine	295,260	76	22,440	39,500	
UK	1,648,388	118	194,510	566,500	118,965

USA	11,263,986	143	1,610,750	9,173,000	3,485,740
Uzbekistan	110,000	78	8,580		
Others	531,606	108	57,413		
Total	69,222,975		7,803,584		

Source: International organization of Motor Vehicle Manufacturers
http://oica.net/category/production-sttistics/2006-statistics/

73. The data on the aluminum content of vehicles give an estimate of the amount of material from this source that was added to total aluminum in use in 2006. When compared to the IAI global flow for 2006, these data indicate that light vehicles accounted for almost 20% of the aluminum in finished products. This can be compared to the percentage of aluminum in total products stored in automotive uses, 16% (Martchek, undated). An estimate of the amount of aluminum that was used to manufacture the vehicles can be made by comparing North American shipments of aluminum to manufacturers of vehicles to the amount of aluminum in light vehicles manufactured in North America (Table 9). These data indicate that, for every ton of aluminum in the vehicle, 1.046 tons of aluminum were used to make the vehicles.

74. When the estimated aluminum content in light vehicles is compared to aluminum consumption and to estimates of aluminum consumption in the transportation end-use (Table 8), some inconsistencies are apparent. For example, the calculated aluminum content of vehicles for Slovakia exceeds the estimated aluminum consumption of the country in 2006. Also, the calculated aluminum content of vehicles exceeds the estimated aluminum content of transportation end uses for France and Mexico by about 6.5% and for the United Kingdom (UK) by 64% (Table 10). Because Mexico is not a major manufacturer of aircraft, ships, or rail transportation, the difference may not indicate a major estimation problem. The large differences for France and the UK, however, are more serious. France manufactures aircraft in addition to vehicles which would add to the size of the difference between aluminum reported in the end-use statistics versus aluminum calculated by estimating aluminum use by different modes of transportation. The estimated percent of aluminum in transportation end uses for France is not unusual compared to the other high-income countries. The UK manufactures aircraft and builds ships in addition to light vehicles. The estimated percent of aluminum consumption in transportation end uses for the UK (21 percent) is the lowest for high-income countries by a significant amount. When compared with the amount of aluminum calculated for light vehicles and not estimated for other modes of transportation, the low estimate for the transportation end use in the UK appears to be in error.

Table 9. Comparison of shipments of aluminum for passanger cars and light trucks with estimated aluminum in automobiles and light commercial vehicles in North America.

Aluminum shipments for passenger vehicles and light trucks in North America (t)	2,375,000
Aluminum in automobiles and light commercial vehicles manufactured in North America (t):	2,271,100
Canada	367,838
Mexico	292,509
United States	1,610,750
Estimate of scrap generate in manufacture	103,900
Percent of shipments to scrap	4.4
Factor to estimate scrap from aluminum in vehicles	0.046

75. Comparison of aluminum used in the manufacture of vehicles with aluminum in transportation end uses in countries where vehicles are the main mode of transportation manufactured are in closer agreement (Table 10). For example, transportation end-use data (about 32,000 t) for Argentina, which manufactures vehicles but not aircraft or ships, agree closely with the amount of aluminum that would be used in the manufacture of vehicles (about 30,000t). Light vehicles account for 85% of the aluminum in transportation end-uses in India, which has a small shipbuilding sector. Because the other countries with estimated aluminum consumption for transportation end uses have more complex transportation manufacturing sectors, analysis of the aluminum used in the manufacture of other modes of transportation will be necessary to further test the validity of the end-use data.

Table 10. Estimate of aluminum used to manufacture other forms of transportation.

Country	Estimated aluminum shipments for vehicles	Estimated aluminum in transportation	Estimated aluminum for other forms of transportation
Argentina	30,300	32,000	1,700
Brazil	183,000	269,000	86,000
China	722,000	1,560,000	838,000
France	391,000	340,000	-51,000
Germany	718,000	1,155,000	437,000
India	165,000	194,000	29,000
Japan	1,320,000	1,374,000	54,000
Mexico	306,000	275,000	-31,000
Russia	120,000	199,000	79,000
United Kingdom	203,000	119,000	-84,000
United States	1,680,000	3,490,000	1,810,000

76. The limited end-use data available and the inconsistencies in data classes point to a need for consistent end-use classes, data for additional countries and for more accurate data on aluminum end uses. Historical data for countries that have recently experienced rapid economic growth and transformation could improve estimates of future aluminum flows.

3.1.3.2.2 Consumption for Transportation—Aircraft

77. A second use of aluminum is in aircraft. IAI (undated) estimated that 80% of an aircraft's weight is aluminum. Tables 11- 14 present estimates of the aluminum content of aircraft delivered in 2006 by Airbus, Boeing, Bombardier, and Embraer respectively. Airbus has manufacturing and assembly facilities in France, Germany, Spain and the UK. Thus, it is difficult to assign the almost 19,000 t of aluminum in the aircraft delivered in 2006 to individual countries for comparison with country-level consumption data.

Table 11. Estimate of aluminum content of Airbus aircraft delivered in 2006.

Aircraft	Number	Weight of 1 aircraft (kg)	Estimated aluminum content (t)
Single aisle	339	42000	11,390
Widebody	86	99000	6,811
Freighters	9	93000	670
		Total	18,871
Average aluminum content per aircraft			43

Sources: Airbus (2007) and Airlines.net (undated)

78. Boeing's principal manufacturing and assembly facilities are in the United States. The majority of Bombardier's facilities are located in Canada, but some are in the United States. The principal manufacturing facilities of Embraer are in Brazil. Boeing delivered aircraft containing about 20,500 t of aluminum. Bombardier's aircraft contained almost 3,500 t of aluminum; the proportion of aircraft built in the United States is unstated. Embraer delivered aircraft containing 2,200 t of aluminum in 2006.

Table 12. Estimate of aluminum content of Boeing aircraft delivered in 2006.

Aircraft	Number	Weight of 1 aircraft (kg)	Estimated aluminum content (t)
717-200	5	31,892	128
737-600	10	37,104	297
737-700BBJ	10	42895	343
737-700	108	38,147	3,296
737-800BBJ2	2	45,730	73
737-800	172	41,145	5,662
747-400	14	180,985	2,027
767-200	2	74,752	120
767-300	10	80,467	644
777-200	25	139,025	2,781
777-300	40	160120	5,124
		Total	20,493
Average aluminum content per aircraft			51

Sources: Boeing (undated) and Airlines.com (undated)

Table 13. Estimate of aluminum content of Bombardier aircraft delivered in 2006.

Aircraft	Number	Weight of 1 aircraft (kg)	Estimated aluminum content (t)
Regional Airlines	112		
CRJ700/CRJ900	63	19,595	988
CRJ100/200 CL601/604	49	11,500	451
Business Aircraft	212		
Challenger 300	55	10140	446
Global Jets	63	22135	1,116
Lear 55/60	94	6282	472
		Total	3,473
Average aluminum content per aircraft			11

Sources: Anon (2007) and Airlines.com (undated)

Table 14. Estimate of aluminum content of Embraer aircraft delivered in 2006

Aircraft	Number	Weight of 1 aircraft (kg)	Estimated aluminum content (t)
Commercial Aviation	98		
ERJ 145	12	11800	113
EMBRAER 170	35	20150	564
EMBRAER 175	12	20150	193
EMBRAER 190	40	27100	867
EMBRAER 195	3	27100	65
Executive Aviation	27		
Legacy 600	26	16000	333
Legacy Shuttle	1	16000	13
Defense and Government	5		
EMBRAER 170	4	20150	64
EMBRAER 190	1	27100	22
		Total	2,235
Average aluminum content per aircraft			17

Sources: Empresa Brasileira de Aeronautica SA, (Embraer) (2007) and Airlines.com (undated)

79. It is not clear how much aluminum was used to build the aircraft as no data on shipments to aircraft manufacturers were available for the study. However, data from Boeing (undated) indicate that the company offered 18,700 t of aluminum scrap for sale in 2006. If the Boeing's ratio of scrap plus aluminum in product to aluminum in product (approximately 2) is typical of other aircraft manufacturers, it suggests that 2 tons of aluminum must be purchased for every ton of aluminum in the final product. Thus, vehicles and aircraft only account for 1.8 Mt of the 3.5 Mt of aluminum used to build transportation in the United States. In Brazil, about 4,400 t of aluminum were used to manufacture aircraft. Together vehicles and aircraft account for 187,000 t of the 269,000 t of aluminum used in transportation end-uses in Brazil.

3.1.3.2.3 Consumption for Transportation—Railcars

80. Based on data from Freight Car America Inc (2007, undated), we estimate that about 410,000 t of aluminum were contained in railcars manufactured in the United States in 2006. Again, the amount of aluminum required to manufacture the rail cars is unknown, but if the ratio is similar to that calculated for aircraft, the amount of aluminum accounted for by light vehicles, civilian aircraft, and railcars in the United States would be about 2.5 Mt of the 3.5 Mt calculated from the transportation end-use.

3.1.3.2.4 Consumption for Transportation—Final Thoughts

81. The data on the aluminum content of manufactured products seems to be reasonably accurate. However, for some of the products considered above, part of the aluminum could be aluminum alloy containing up to 10% alloying metals, such as zinc and copper. The amount of alloy used is unknown, and therefore no adjustment has been made to the calculated aluminum contents of products. If the aluminum contents are accurate, scrap ratios calculated for vehicles and aircraft could be conservative. Shipment data would be useful in resolving these issues.

82. Finally, data on the in-service times for the transportation systems would be useful for estimating the volumes of post-consumer scrap that are likely generated. Vehicles appear to have in-service times of 10 to 15 years. Based upon data from Jet Information Services (undated), aircraft appear to have in-service times of about 25 years. Jet Information Services (undated) also contains information on the number of aircraft removed from active inventory from 1965 to 2000 for aircraft manufactured by western firms. In 2000, about 225 aircraft were removed from active inventory. Not all aircraft removed from active inventory are scrapped, but it appears that most are. If 75% of the aircraft were scrapped, then aluminum from about 170 aircraft was added to post-consumer scrap. Using the per aircraft aluminum content for Airbus (Table 9) and Boeing (Table 10), the two largest western aircraft manufacturers, this would generate between 7,300 t and 8,700 t of post-consumer aluminum scrap.

3.2 Future Global Mass Flows of Aluminum

83. This section of the report examines future mass flows of aluminum for the short and medium term (to 2015) and for the longer term (2015 to 2025).

3.2.1 Short- to Medium-Term Production Forecasts

84. For the short- to medium-term (from the present to 5 years), outlooks have been developed based upon projected trends that could affect existing production facilities, planned expansions of existing facilities, and planned new facilities that operating companies, consortia, or governments have projected to come online within indicated timeframes. The outlooks are not forecasts of what production will be but rather what the industry is likely to be able to produce given announced industry intentions.

3.2.1.1 Bauxite

85. The outlooks for the production of bauxite in Africa, the Middle East, the Americas, Asia, and Europe and Eurasia presented in Table 15 are based on those in the summary chapters of MYB 2007 (Anderson and others, 2010; Fong-Sam and others, 2009; Levine and others, 2010; Mobbs and others, 2010; Yager and others, 2010). The summary chapters contain outlooks for individual bauxite-producing countries. African production is forecast to increase to 24 Mt in 2015 from 20 Mt in 2006; production from the Middle East is forecast to increase almost 29% per year to 4.9 Mt in 2015 from 0.5 Mt in 2006. Aluminum production in the Americas is expected to reach 60 Mt in 2015, which is up from 50 Mt in 2006. Asia is expected to produce 160 Mt of bauxite, which represents an increase of almost 5% per year from 104 Mt. Bauxite production in Europe and Eurasia is expected to increase to 18 Mt. in 2015 from 8.7 Mt in 2006. In total, global bauxite production is expected to increase 4.4% per year to 270 Mt in 2015 from 183 Mt in 2006.

Table 15. Short to medium term (1 to 5 year) outlook for bauxite production (totals may not add owing to independent rounding).

	2011	2013	2015
		in thousands of tons	
Africa	18,000	21,000	24,000
Middle East	1,600	4,900	4,900
Americas	59,000	58,000	60,000
Asia and the Pacific	140,000	150,000	160,000
Europe and Eurasia	16,000	17,000	18,000
World	235,000	250,000	270,000

3.2.1.2 Aluminum

86. The outlooks for the production of aluminum in Africa, the Middle East, Asia, and Europe and Eurasia presented in Table 16 are taken directly from four summary chapters of MYB 2007 (Fong-Sam and others, 2009; Levine and others, 2010; Mobbs and others, 2010; Yager and others, 2010); the outlooks for the Americas are based upon those presented in Anderson and others (2010) but have been modified to include data for the United States. If economic conditions warrant, there should be sufficient industry capacity to produce 55 Mt of aluminum in 2011, 60 Mt in 2013, and 61 Mt in 2015. This represents an average rate of increase of 2.6% per year. The regions with the largest projected rates of increase are Africa (8.4%) and the Middle East (2.8%). The increase in Africa is mainly scheduled to take place in South Africa. The increase will be contingent upon availability of sufficient power; South Africa has experienced power shortages in recent years. The increases in the Middle East are projected to spread across more countries with the United Arab Emirates, Saudi Arabia, and Iran all slated for increases in aluminum production capacity. Bauxite production is slated to increase by almost 3% from 2011 to 2015 with production increases scheduled for Australia, Brazil, China, Guinea, India, Saudi Arabia, Sierra Leone, and Vietnam.

Table 16. Short to medium term (1 to 5 year) outlook for aluminum production.

	2011	2013	2015
Region		in thousands of tons	
Africa	2,100	2,800	2,900
Middle East	4,270	5,395	5,395
Americas	16,500	18,500	18,000
Asia	24,200	26,000	27,000
Europe and Eurasia	12,000	13,000	13,000
World	55,000	60,000	61,000

3.2.2 Long-Term Production Forecasts

87. Long-term forecasts of aluminum are made using a logistic regression model that relates aluminum consumption per-capita to the average income in the country as measured by GDP per-capita. The model estimates future consumption; assuming that the market for aluminum is in balance or nearly so, the production of aluminum can be inferred. Studies by DeYoung and Menzie (1999) and Menzie, DeYoung, and Steblez (2001) investigated the relationship of industrial consumption of metals such as aluminum and copper and noted that consumption was low when the average income was low but grew rapidly with increasing income until a threshold level of per-capita consumption was reached. Menzie, Singer and DeYoung (2005) and Singer and Menzie (2009) used a logistic regression, which captures the relationship between GDP per-capita and metal consumption that was noted by DeYoung and Menzie (1999) and Menzie, DeYoung, and Steblez (2001), to estimate the per-capita consumption of copper as a function of GDP per-capita. They used projected economic growth rates and projected rates of population growth to estimate future GDP per-capita.

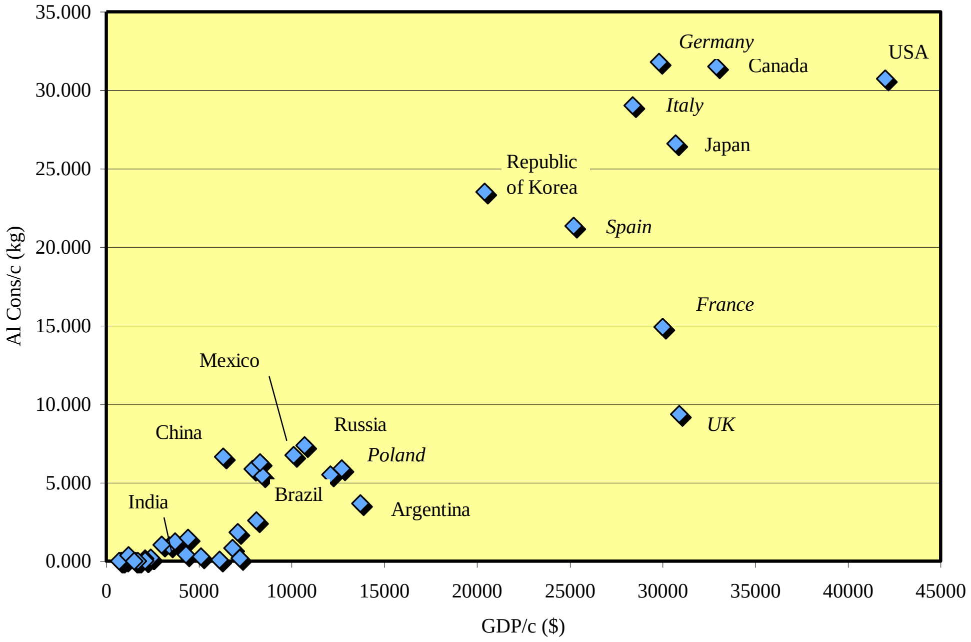
3.2.2.1 The Model for Forecasting Long-Term Aluminum Consumption

88. Initial models of GDP per-capita and aluminum consumption per-capita were fit for the 40 most populous countries in the world (Table 17). Figure 21 is a plot of those data. The initial model was not very satisfactory because France and the UK consume aluminum per-capita at lower rates than is typical for other high-income countries. France and especially the UK have had falling rates of industrial consumption of metals in recent years as economic integration has increased among EU member states and as manufacturing has moved to other EU countries. Consumption in Italy and Spain has increased as it has declined in France and the UK. Therefore, the six large countries that were members of the EU were combined into one entity (EU6) for purposes of fitting a logistic model to GDP per-capita and aluminum consumption.

Table 17. Gross domestic product (GDP), population, aluminum consumption, GDP per capita, and aluminum consumption per capita for the 40 most populous countries in 2006.

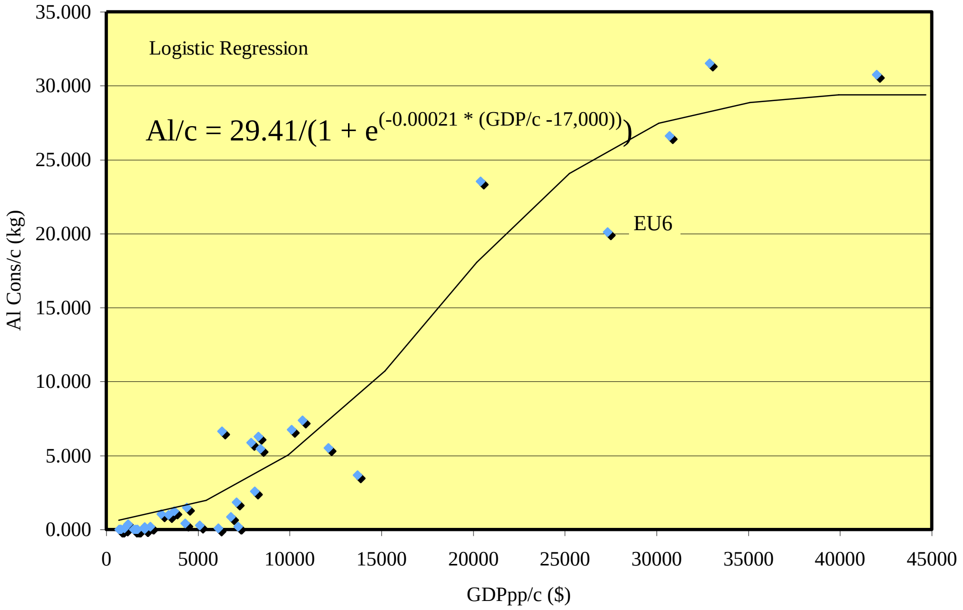
China	2630.11	1304.3	8648.1	2016	6300	6.630
India	886.867	1107.6	1079.5	801	3400	0.975
USA	13244.55	298.4	9173	44385	42000	30.741
Indonesia	364.239	231.8	288	1571	3700	1.242
Brazil	1067.71	191.5	1044.4	5576	8400	5.454
Pakistan	128.996	166.2	34.1	776	2400	0.205
Bangladesh	65.216	150	23.6	435	2100	0.157
Russia	979.048	142.1	1047	6890	10700	7.368
Nigeria	115.35	140.4	11	822	1000	0.078
Japan	4367.46	127.5	3392.6	34255	30700	26.609
Mexico	840.012	107.4	724.7	7821	10100	6.748
Philippines	116.931	95.3	26.4	1227	5100	0.277
Vietnam	60.995	85.4	87.9	714	3000	1.029
Germany	2897.03	82.4	2619	35158	29800	31.784
Ethiopia	73.79	77.4	0.13	953	800	0.002
Egypt	107.375	74.1	109.5	1449	4400	1.478
Turkey	392.424	73.7	433	5325	7900	5.875
Iran	212.492	65	168.4	3269	8100	2.591
Thailand	206.258	64.7	407	3188	8300	6.291
France	2231.63	63.3	944.7	35255	30000	14.924
Congo-K	19	62.4	0	304	800	0.001
UK	2373	60.6	566.5	39158	30900	9.348
Italy	1852.59	58.1	1686.1	31886	28400	29.021
Korea, Rep	888.267	49	1153.2	18128	20400	23.535
South Africa	257.279	47.9	264	5371	12100	5.511
Burma	13.123	47.4	0	277	1600	0.001
Ukraine	106.469	46.6	39	2285	6800	0.837
Colombia	136.132	42	76.8	3241	7100	1.829
Spain	1231.73	40.4	862.8	30488	25200	21.356
Argentina	212.71	39.6	145.6	5371	13700	3.677
Sudan	36.401	38.6	0.68	943	2100	0.018
Tanzania	14.198	38.6	0.04	368	700	0.001
Poland	341.724	38.6	227	8853	12700	5.881
Kenya	22.819	35.9	13	636	1200	0.362
Algeria	114.831	33	6	3480	7200	0.182
Canada	1275.28	32.7	1030.8	38999	32900	31.523
Morocco	65.405	30.2	12.2	2166	4300	0.404
Uganda	9.495	29.2	0.2	325	1700	0.007
Peru	93.027	28.4	2.1	3276	6100	0.074
Nepal	8.865	27.5	0	322	1500	0.001

Figure 21. Aluminum consumption per capita versus GDPpp per capita in 2006



89. Figure 22 shows a plot of the EU6 and the other 34 populous countries’ aluminum consumption per-capita versus GDP per-capita and the logistic equation and curve fit to the data. All of the parameters of the equation are significantly different from zero at a 5% confidence level and the curve provides a reasonable approximation of the data albeit with significant error. The error indicates that items beyond income affect aluminum consumption per-capita. The model of consumption is essentially projective based upon assumed rates of economic growth. Nevertheless, the model is likely to give a reasonable status quo projection of aluminum consumption into the future.

Figure 22. Aluminum consumption per capita versus GDPpp per capita in 2006 (includes EU6).



3.2.2.2 Forecasts

90. Table 18 presents data for 2006 and forecasts for 2015, 2020, and 2025 for GDP, population, GDP per-capita, aluminum consumption per-capita and aluminum consumption for the 20 most populous countries in 2006. Growth rates are based on the average of the last 10 years. The table also uses the ratio of the aluminum consumption in the 20 most populous countries to global aluminum production to estimate world aluminum consumption. If it is assumed that aluminum production is equal to aluminum consumption, then the estimates can be used to examine a number of implications of the model.

91. The model is quite simple and does not provide associated confidence limits or address possible affects of important variables such as price and substitution. Errors associated with long-term are necessarily large as errors are typically multiplicative, enlarging upon previous errors. Prices are a nonlinear function of the balance between the supply and demand for a commodity. Because mine and plant capacities at the various steps in the aluminum production process are capital intensive and benefit from economies of scale, mine and plant capacities are typically added, or enlarged, in large increments that require time to build. As a result, supply is relatively inelastic with regards to increases in demand beyond the point of installed capacity. Therefore, forecasting prices is very difficult even for the near-term. Evaluation of substitution requires comparison of price and performance measures for competing materials such as composite materials. An evaluation of such materials is beyond the scope of this study.

Table 18. Estimated population, GDP per capita, aluminum consumption per capita, and aluminum consumption for 2015, 2020, and 2025.

		2015				2020				2025			
		Popn M	**GDPpp/c**	**Al/c(kg/c)**	**Al cons.**	**Popn M**	**GDPpp/C**	**Al/c(kg/c)**	**Al cons.**	**Popn M**	**GDPpp/C**	**Al/c(kg/c)**	**Al cons.**
					(t) x 103				(t) x 103				(t) x 103
1	**China**	1,396	13,879	8.86	12,371	1,431	21,806	20.92	29,939	1,453	34,587	28.70	41,703
2	**India**	1,294	5,350	1.82	2,358	1,367	7,103	2.60	3,560	1,431	9,517	4.17	5,967
3	**USA**	332	49,254	29.37	9,751	346	54,789	29.39	10,169	359	61,215	29.40	10,554
4	**Indonesia**	244	5,003	1.70	414	254	5,847	2.02	513	263	6,871	2.48	654
5	**Brazil**	203	10,339	4.86	986	209	11,642	6.14	1,282	214	13,181	7.94	1,699
6	**Pakistan**	206	3,004	1.12	230	226	3,494	1.24	280	246	4,097	1.40	345
7	**Bangladesh**	175	2,792	1.07	187	186	3,353	1.20	223	195	4,082	1.40	273
8	**Russia**	138	18,615	16.17	2,232	135	25,464	24.89	3,360	132	34,851	28.74	3,794
9	**Nigeria**	176	1,467	0.80	142	193	1,876	0.88	169	210	2,418	0.98	207
10	**Japan**	126	37,126	29.00	3,654	124	41,651	29.25	3,627	121	47,127	29.35	3,552
11	**Mexico**	116	12,201	6.75	784	120	13,673	8.58	1,030	123	15,464	11.16	1,372
12	**Philippines**	102	6,569	2.34	238	110	7,410	2.77	305	117	8,477	3.42	400
13	**Vietnam**	94	5,032	1.71	160	98	6,741	2.42	237	102	9,084	3.84	392
14	**Germany**	81	36,096	28.90	2,349	80	40,299	29.20	2,347	79	45,110	29.33	2,326
15	**Ethiopia**	96	1,087	0.74	71	108	1,296	0.78	84	120	1,561	0.82	98
16	**Egypt**	92	5,510	1.88	173	99	6,547	2.33	230	105	7,847	3.02	317
17	**Turkey**	80	12,296	6.86	549	84	15,690	11.50	965	87	20,156	18.58	1,624
18	**Iran**	80	10,274	4.80	382	84	12,454	7.05	590	87	15,275	10.87	947
19	**Thailand**	70	11,918	6.44	450	71	14,891	10.30	735	73	18,691	16.30	1,183
20	**France**	64	35,516	28.83	1,842	65	38,608	29.11	1,889	66	42,044	29.26	1,925
			Total		**39,300**		**Total**		**61,500**		**Total**		**79,300**
			World Total		**58,700**		**World Total**		**91,900**		**World Total**		**119,000**

92. World aluminum consumption, which was 45.3 Mt in 2006, is estimated to be 59 Mt in 2015, 92 Mt in 2020, and 120 Mt in 2025. Most of the increases are estimated to occur in low- and middle-income countries. Notably, the BRIC countries (Brazil, Russia, India, and China), which accounted for 26% of world consumption in 2006, are expected to account for 31% of world consumption in 2015, 42% of world consumption in 2020, and 45% of world consumption in 2025. Consumption by the United States, Japan, Germany and France, which was 16.1 Mt in 2006 (36% of world consumption), is estimated to be 18 Mt in 2025 (15% of world consumption).

4. CONCLUSIONS

93. A number of important conclusions can be reached based upon this study. The conclusions are organized by the section of the report on which they are based to allow easy access to information related to the formation of the conclusions.

Methodology of Present Study (2.3)

94. A focus on changes in mineral consumption as countries experience economic growth and a rise in income (GDP per-capita) can yield important insights into dynamic material flows.

Macro-Level Flows (3.1.1)

95. Macro-level flows estimated by this study for bauxite production, alumina production, and primary aluminum production are similar to those calculated by IAI for 2006.

96. Secondary aluminum production estimated by this study was significantly lower than that estimated by IAI for 2006. In addition, the ratio of post-consumer to total scrap estimated by USGS (Papp, 2009) for the United States differs significantly from the IAI estimate of that ratio for the world.

Micro-Level Flows (3.1.2)

97. The "European" model of alumina refineries and aluminum smelters presented in this section of the report demonstrates that the application of existing technologies could reduce byproduct wastes produced as a result of aluminum production.

98. Ongoing research is identifying uses for some wastes such as "red mud." These uses could significantly reduce some wastes from aluminum production.

99. Reduction of GHGs from aluminum production is under the control of two groups. PFCs and CO_2 generated from fuel use and reduction processes are under the control of the producer of the aluminum. GHGs generated to produce the electricity used by aluminum producers are under the control of the owners of the electrical grid.

Consumption (3.1.3)

100. In high-income countries, such as Germany, Japan, and the United States, aluminum consumption per-capita is either growing very slowly or is not growing. In a few countries in the European Union, such as France and the United Kingdom, economic integration and relocation of industries have led to a decrease in aluminum consumption.

101. Aluminum consumption per-capita increases rapidly to about 20 kg/person from 2 kg/person as per-capita income increases to $20,000 from $5,000.

102. The end-uses to which aluminum is put appear to differ significantly between high-income countries and low- to middle-income countries. In low- and middle-income countries, the main uses of

aluminum are in electrical systems and construction. In high-income countries, the largest use of aluminum is in transportation. Inconsistent end-use classifications, however, limit the quantification of these differences.

103. Because of the long in-service times of electrical systems and buildings and other construction, recycling of significant amounts of post-consumer scrap is unlikely to begin in the countries that are currently experiencing rapid economic growth until 2020 to 2025.

104. Recycling rates of used beverage cans (UBCs) can be high in low- and middle-income countries owing to the availability of low wages for labor; however, the amount of material going into packaging is relatively small in these countries.

105. As shown for light vehicles, production data for goods can be combined with intensity of use data to estimate material in use. When these data are combined with estimates of aluminum shipments and the in-service life of the good, it is possible to estimate the contribution of that type of good to new and post-consumer scrap. For example, the manufacture of light vehicles generates relatively small volumes of new aluminum scrap from fabricators and manufacturers. In contrast, commercial aircraft manufacturing generates almost 1 t of new scrap for each ton of material in an aircraft.

Future Global Mass Flows of Aluminum (3.2)

Short- to Medium-Term Forecasts (3.2.1)

106. Based upon announced production plans, the capacity of bauxite mines is expected to increase to 270 Mt by 2015 from 183 Mt in 2006. This represents an almost 48% increase over 2006. Major increases in mine capacity are expected in Australia, China, Brazil, India, Saudi Arabia, Russia, and Guinea in order of size of the capacity increase.

107. Future aluminum production capacity based upon announced production plans is expected to reach 61 Mt in 2015 from 45.3 Mt in 2006. This represents an increase of almost 3.4% per year. The largest increases are expected to occur in China, Brazil, the UAE, Canada, India, South Africa, Saudi Arabia, and Qatar in order of size of the capacity increase.

Long-Term Forecasts (3.2.2)

108. Based on a model relating consumption to income, by 2025 aluminum consumption is likely to be 120 Mt compared with 45.3 Mt in 2006. This represents a growth rate of 4.1% per year. Most of the increased consumption will take place in countries that consumed only modest amounts of aluminum in 2006. China, which consumed about 6.6 kg per-capita in 2006, is expected to consume 28.7 kg per-capita in 2025. Russia, which consumed 7.4 kg per-capita in 2006, is expected to consume 28.7 kg per-capita in 2025, and Brazil, which consumed 5.5 kg per-capita in 2006, is expected to consume 7.9 kg per-capita in 2025. Brazil’s consumption is based on a relatively modest projection that its rate of economic growth will only be 3% per year; recent data could indicate that Brazil’s future rate of growth may be greater than 3%. India, which consumed 1.8 kg per-capita in 2006, is expected to consume 4.2 kg per-capita in 2025. Consumption in high-income countries is not expected to rise significantly on a per-capita basis, but total consumption may increase modestly owing to population increases.

Implications of the Forecasts (3.3.3)

109. To meet a consumption of 120 Mt of aluminum, the world will need to produce about 570 Mt of bauxite and about 230 Mt of alumina. This production will generate significant levels of wastes even if technological improvements are made to current production processes.

110. A key question related to this increased consumption will be what portion of the consumption is satisfied by primary aluminum and what portion is from secondary aluminum as this will have a considerable influence on the amount of GHGs generated by aluminum production. That portion of secondary aluminum that comes from new scrap is likely to increase proportionately with overall consumption. However, the data on changing patterns of end-use with increased income suggest that, at least initially, the proportion of aluminum that is generated from old scrap may fall as countries undergoing economic growth initially use aluminum to mainly add to infrastructure that has long terms of in-service use. Later, as these countries continue to experience economic growth, they are likely to increase the amount of aluminum they consume in transportation end-uses. As this takes place, recycling of post-consumer scrap will rise but the timing of the increase will be governed by the mix of transportation and the in-service terms of individual modes of transportation. China and India are increasing their use of vehicles at a very rapid rate; if the in-service terms of the vehicles are 10 to 12 years, then post-consumer scrap from this increase is not likely to appear until sometime between 2020 and 2025. Rates of recycling of used beverage cans are typically high in low- to middle-income countries; however, the amount of material recovered is likely to remain modest as the volume of such material will remain at low levels for most of the period of the forecast.

111. If the proportion of aluminum production that comes from primary smelters increases, at least until 2025, a reduction in GHGs must come from increases in the efficiency of aluminum smelters or in reduced use of fossil fuels for generation of the electricity used in aluminum production. The magnitude of the increases in aluminum consumption suggests that both gains in efficiency and switching of fuel sources will need to be substantial just to maintain emissions at current level.

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