Aluminum Industry and Climate Change—Assessment and Responses

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It is now possible to assess the impact of the production processes of aluminum on the environment and to describe some of the ongoing responses and opportunities for improvement. This is compared with the benefits of aluminum in transportation, where the growing usage in various forms of transport due to its low density, high strength, and ability to be recycled enables reduced mass, increased fuel efficiency, reduced emissions and increased safety. It is the purpose of this paper to compare and contrast the emissions generated in the production of aluminum with the benefits accruing from its increased use in transportation.

INTRODUCTION

Aluminum is a latecomer to the suite of industrial metals. It was only relatively recently, in 1886, when commercial application of the metal began following the discovery of the Hall–Héroult reduction process. By contrast, metals like copper, tin, lead, zinc, and iron have been known for centuries. However, by virtue of its light weight and other unique properties, aluminum has now surpassed most metals in terms of global production and is second only to iron (steel). A survey of primary aluminum smelters of the world lists a total global capacity of about 41 million metric tons, although some 7% of this amount has been shut down on a temporary basis.[1] With this large global production, it is logical to ask about the impact of the metal on the global environment.

The industry first began a comprehensive accounting of the energy used, and the emissions generated, during all facets of production in the mid-1990s. This initial effort was undertaken by the Aluminum Association when the industry was challenged by the automotive producers, under the United States Automotive Materials Partnership (USAMP) initiative, to develop a life cycle inventory (LCI) for the metal. The results of the LCI were first published in 1998,[2] and now have been incorporated into an ASM International Sourcebook.[3]

While the domain of this initial study was the North American industry, since it included the chain of plants that supply the big automotive companies, it was in fact global in nature, as it included data from 213 plants located in Australia, Africa, Brazil, and Jamaica as well as from many operations in North America.

The responsibility for continuing this database and extending it globally to Asia and the Far East has now been passed to the International Aluminum Institute (IAI);[3] see Chapter 3 for details of the initial LCI study; see Chapter 4 for more recent IAI surveys and information; see Chapters 5 and 6 for discussions of materials flow modeling of aluminum based on this information; see Chapter 7 for discussion about the beneficial impact of recycling; and lastly see Chapter 10 and related appendices for information about carbon dioxide and other emissions. For current information about industry progress and goals, see the IAI Web site.[4]

With this body of information, it is now possible to assess the impact of the production processes of aluminum on the environment and to describe some of the ongoing responses and opportunities for improvement. This is compared with the benefits of aluminum in transportation, where the growing usage in various forms of transport due to its low density, high strength, and ability to be recycled enables reduced mass, increased fuel efficiency, reduced emissions, and increased safety. It is the purpose of this paper to compare and contrast the emissions generated in the production of aluminum with the benefits accruing from its increased use in transportation.

See the sidebar for background on assessing aluminum production emissions.

How would you…

…describe the overall significance of this paper?

Consistent with earlier predictions, this assessment of the aluminum industry suggests that the reduction of carbon dioxide emissions through the use of aluminum in transportation are growing at a rate greater than the emission generated by increased production. Thus the industry will have a negative carbon footprint likely by 2020.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

This paper describes the actions being taken by the global industry to decrease its environmental footprint such as process efficiency improvements and recycling and contrasts with emission savings through its use in transportation (i.e, automotives). The paper outlines the life cycle flow model being used to assess the situation.

…describe this work to a layperson?

This paper assesses the response of the aluminum industry to environmental challenges and climate changes. Overall, it is suggested that the use of aluminum is beneficial to the environment, especially through its use in the transportation industry, where its light weight makes vehicles more fuel efficient.

FIVE INDUSTRY RESPONSES

Process Efficiency Improvements

The process technology of the industry is continuing to evolve, especially in the regions of low-cost energy. An obvious means to further reduce the CO_2 footprint of the industry is to use energy from the most efficient generating plants and to use a greater proportion of renewable energy. Recently, both Alcoa and Century Aluminum have established smelters in Iceland, where hydro and geothermal power is available. Additional sources of hydro power are being developed in China and Brazil and this trend is expected to continue.

With regard to existing plants in the United States and globally, plants are being upgraded with new technology. For example, in some alumina refineries, the older rotary calcinations technology is being upgraded to the more energy efficient fluid bed technology. In the area of smelter technology, the cell amperage is being increased and, in development activities, cells to operate at 500,000 A are being explored. Higher cell amperages proportionally increase the productivity of the cell. Along with increasing amperage, the use of slotted anodes better enables the escape of the CO_2 gas from the spacing between the electrodes, and improves operation of the cell. Also, better cell controls, the use of magnetic compensation to stabilize cell operation, and the adoption of alumina point feeders all have helped to increase efficiency of cell operations. Using these and other developments over the last 50 years, the average amount of electricity needed to make a pound of aluminum has been reduced from ~12 kWh to ~7 kWh. These significant improvements are expected to continue to gradually improve cell efficiency.

More radical energy efficiency improvements have been limited by the extremely corrosive and aggressive cell environment and by the lack of materials to withstand exposure to the cryolite electrolyte at the operating temperature of ~950°C. Two significant cell design improvements have been pursued intermittently with limited success by various companies over the past three decades, but the costs and operating lifetime of available materials has limited their economic effectiveness. These technologies are the use of wettable / drained cathodes and the use of inert anodes. Both of these technologies promise to improve efficiency by reducing the ohmic resistance within the anode cathode distance (ACD) in the cell. The ACD is typically 4–5 cm and constitutes about 40% of the overall cell resistance. For a more complete discussion of these electrode systems and the complex issues involved see Reference 5.

ASSESSMENTS OF ALUMINUM PRODUCTION EMISSIONS

The energy to produce aluminum in the United States has been reduced by 64% over the past 45 years. This reduction has come about by technical progress (22%) and by the growth of recycling (42%). Globally, these energy saving trends are similar, and in some countries the energy savings may be accentuated because newer technology smelters with better energy efficiency are being built overseas.

Despite this significant progress, aluminum remains one of the energy-intensive materials to produce. The U.S. aluminum industry directly consumes 42.3×10^9 kWh of electricity annually, or 1.1% of all the electricity consumed by the residential, commercial, and industrial sectors of the U.S. economy.[5]

The energy values discussed in this paper are tacit energy values; in other words they include the value for the fuel to create the energy in the first place as well as the value for the actual energy used in the process itself. Many different fuels are used in the overall production process throughout the world depending on the region—for an extensive discussion on fuel usage, see Reference 6. In all cases, the industry has sought to use hydro power where available and the carbon footprint of hydro power is generally considered to be zero. Currently, the industry use of hydro power in the United States is ~40% and globally is ~50%. Nuclear power also has a low carbon footprint, but its use by the industry in the United States is less than 2%.

Specifically, the most energy intensive phases of aluminum production are the electrolysis or reduction step, followed by the anode preparation for the reduction process, and then the alumina production process. In total, it requires 60.5 kWh/kg to produce primary metal ingot whereas it only requires 2.8 kWh/kg to produce secondary, or recycled metal. Thus, ~95% of the energy embedded in the metal during the reduction process is saved when the metal is recycled. Also, virtually the same proportion of process emissions is eliminated by recycling.

There are two significant emissions from the fuel used in the process. In alumina calcination, the fuel used is combusted to carbon dioxide. In anode preparation, the fuel and the excess carbonaceous material within the coke and pitch likewise is eventually converted to CO_2. In fact, in most anode baking furnaces, the fuel residual in the pitch is fully utilized in the process to assist with heating the baking furnace and minimize the need for additional fuel. Again, the process offgas is eventually lost as CO_2.

In the smelter cell itself, the cell reaction produces oxygen which reacts with the carbon anode and generates a mixture of mostly CO_2 with a small amount of carbon monoxide. There is also some additional burning of the anode materials, independent of the electrochemical reaction, which also yields CO_2. All cell gases are captured and treated in a gas handling system but CO_2 is eventually released to the atmosphere.

Other gases, called perfluorocarbons (PFC), are released from the cell during upset conditions when the supply of alumina is depleted in the cell and an alternative anode reaction becomes dominant. These gases are tetrafluoromethane (CF_4) and to a much less extent hexafluoroethane (C_2F_6). These gases are significant since they have considerable global-warming potential and are equivalent to 6,500 and 9,200 times that of CO_2, respectively. In other words, 1 kg of CF_4 released to the atmosphere is equivalent in its warming capacity to 6,500 kg of CO_2. On average, in a modern cell the PFC emissions account for 2.2 kg CO_2 / kg Al (see Table D4 in Reference 3).

The industry has been proactive in seeking a reduction of the PFC emissions. In fact, while worldwide production of aluminum has increased ~24% since 1990, the emissions of PFCs have declined ~39% from the 1990 baseline. This is due to better cell control and the introduction of point feeder systems that enable a more precise addition of the amount of alumina that is added to the cell. This beneficial trend is expected to continue.

The carbon cathode is made "wettable" by the addition of small quantities of titanium diboride which is baked into the cathode. TiB_2 is expensive and is slowly consumed during the process which is a further drawback. However, it is estimated that a wettable cathode can improve the cell performance by ~15% and it is thought that several companies are currently testing this technology. The combination of a wettable cathode, together with an inert anode, which would enable a decrease, and more precise control of the ACD, is estimated to improve cell performance by ~20%. Alcoa, Hydro, and Moltech are companies known to be exploring inert anode technology.[7]

From the environmental viewpoint, the inert anode is the Holy Grail of the industry at present since its use would eliminate the need for carbon anodes and the related anode baking completely, and would generate oxygen, instead of CO_2, as the cell off gas. This would have a huge impact on the industry, eliminating more than 60% of its CO_2 footprint. Of course, it would cost some energy to make the inert anodes but this is difficult to estimate since it is not known whether the best electrode material will be ceramic, metallic or cermet. Regardless, the beneficial impact would be huge.

Finally, if these electrode materials can be proven on an industrial scale, it is a relatively easy step to visualize additional improvements in cell design from the exclusively horizontal electrode assembly used in industry today to a more compact, energy-dense, vertical electrode assembly. However, this is probably some two or three decades in the future. Thus, there are many options for future improvements, though the best options still require extensive research and development.

Recycling

As stated previously, recycling of aluminum saves ~95% of the energy and emissions as compared to primary production. While the industry always has been proactive in emphasizing the need for recycling (i.e., in the case of used beverage cans (UBC), the need now is to reemphasize recycling of UBC but in addition to push for all other types of recycling, especially of automotive aluminum).

With regard to UBC material, the rate of recycling in the United States is a lackluster 52% as compared to rates of ~95% for Brazil and Norway. This means that the balance is being lost in landfills around the country. It has been estimated that there is an accumulated total of 20 million tons of UBC material in the United States. This equals the annual production of three new aluminum smelters! This has led to the suggestion to mine the landfills to recover the buried cans.[8] An attractive alternative is not to bury the material in the first place—possibly through the sorting of municipal waste prior to land filling. In this regard, it is noteworthy that Alcoa has now set a goal and called upon the industry to raise the UBC recycling rate to 75% by the year 2015.[9]

For the future, the more important area for recycling will be automotive aluminum, as the volume of recycled aluminum from automotive components exceeded the metal coming from UBC for the first time in 2005.[10] With the growth of automotive aluminum for light weighting, fuel efficiency and safety considerations, this area is anticipated to become even more dominant, especially with the recent increases in fuel prices (see the next section).

With regard to processing of automotive wastes, the important recent development is the introduction of the industrial shredder. This has automated the process of vehicle recycling and, unlike the case of an individual beer or beverage can, it has taken the decision away from the hands of individual consumers. Virtually all used vehicles are shredded, and the U.S. Environmental Protection Agency (EPA) estimates that ~90% of all automotive aluminum is now recovered and recycled.

To capitalize on the benefits of the shredder, there is now a need to improve and extend the dismantling and presorting of vehicle components. A key issue in recycling is the control of the alloying additions and impurities to retain the value of the secondary metal. Some alloys can be recycled better than others. For example, the 3xxx, 5xxx, and 6xxx alloys generally used in automotive applications have similar alloying additions of magnesium and silicon and can be readily commingled for melting. However, if a 7xxx alloy containing zinc and copper additions and normally used for high-strength aerospace applications is used as a bumper in a vehicle application, the zinc and copper alloy additions enormously complicate the recycling procedures and reduce the value of the metal. Different streams of recycled metal will be needed to fully benefit from the metal that is recovered.

There is a need to make automotive designers aware of the complexities of recycling and the impact that certain designs may have on the quality and economics of recycled metal. Also, there is a need to refine dismantling and presorting procedures prior to shredding and to refine separation and sorting of the non-magnetic metallic concentrate after shredding. The recent demonstration of laser based post-shredder sorting technology (e.g., LIBS) by the Huron Valley Steel Corporation[11] has been a great tool to sort material, but as yet it is just being used to beneficiate 3xxx alloy feedstock even though in concept it could enable individual alloy separation. Equipment cost and process time limit the application.

Further, there is a need to explore the development of recycle-friendly aluminum alloys for certain market segments of the industry. Conceptually, these alloys would have alloy additions and impurity contents that likely would fit recycle metal streams and would not require any, or at least a minimum, of post processing for reuse. These issues are discussed at length in Reference 10. Another way to improve the quality of recycled metal is to employ a rudimentary alloy separation during recycling. For example, most aluminum used in the building and construction market is either the 5xxx alloy, mostly in sheet form, or the 6xxx alloy, generally used as an extrusion. Accordingly, if the dismantlers segregate the different shapes at the job site an effective alloy separation can be achieved and the resultant secondary melt quality will be improved. These and other issues are detailed in Reference 12. Lastly, for the most efficient recycle process, it is important to adopt the best melting practice which limits the exposure of the molten metal to oxygen and reduces metal loss through dross formation.

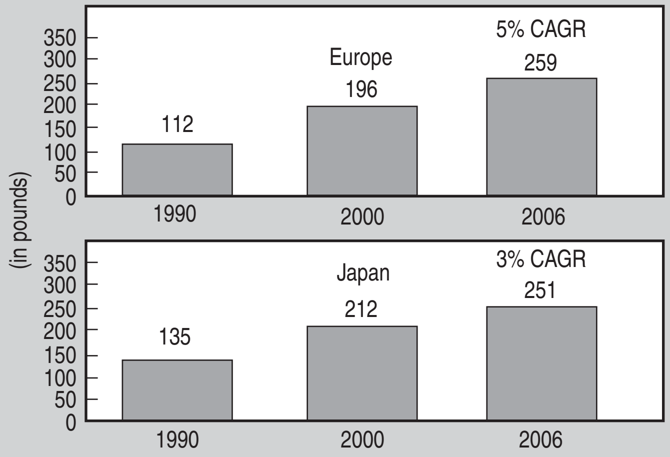

Figure 1. Growth in aluminum content in Japanese and European light vehicles. (Charts: Ducker Worldwide.)

Promote Aluminum Use in Transportation to Reduce Emissions

The unique properties of aluminum make it an ideal material to reduce the mass of transportation vehicles. Reduction of mass directly converts to a saving of fuel. This applies to all forms of transport such as aircraft, railcars, ships, and especially cars and trucks and buses. Less fuel usage in turn reduces CO_2 emissions.

Properties that are key are its light weight (roughly a third of the density of steel), high strength, and corrosion resistance. Light weighting of the vehicle structure reduces fuel requirements, and enables bigger, lighter structures with "crumple" zones and other features to improve passenger safety.

The growth of aluminum usage has been ongoing for more than 30 years and is a global trend (see Figure 1). Recent increases in the price of oil and gas and concerns for the carbon footprint of vehicles will almost certainly enhance this trend. In North America in 2007, the average light vehicle contained 327 lb. of aluminum and there are no obvious factors, other than the metal's price, to constrain this trend (see Figure 2).

Earlier problems with the metal's formability have been reduced as designers have become familiar with aluminum alloys and fabricators gain more experience with forming it. Future high-mileage vehicles will need to contain large quantities of light metals such as aluminum, magnesium, and titanium to attain their high-performance goals.

Two additional factors are important with regard to aluminum use in vehicles and directly follow from the extensive life cycle inventory and materials flow modeling of the industry. First, each pound of aluminum replacing two pounds of traditional materials (iron or steel) in a vehicle can save a net 20 pounds of CO_2 emissions over the lifetime of the typical vehicle. Second, a fuel savings of 6–8% can be gained for every 10% weight reduction resulting in fewer greenhouse gas (GHG) emissions.

Further, according to the EPA, nearly 90% of automotive aluminum is recovered and recycled. It is estimated that about 57% of the aluminum content in North American vehicles was sourced from recycled material. The alloy specifications for cast aluminum alloys, used for items like engine blocks and motor housings, are quite tolerant of recycled material. For additional discussion, see Reference 13.

Carbon Trading

Although the outlines of a carbon trading scheme are not yet developed and far from clear, such a system probably would have a significant impact on the aluminum industry. For example, a little more than 0.4 kg of carbon anode is consumed to make 1 kg of aluminum. Accordingly, a carbon trading scheme would strongly encourage development to make the technical breakthrough to achieve a viable inert anode material. Success here would eliminate the need for carbon anodes completely and have a huge impact on the greenhouse gas footprint of the industry for the reasons cited above.

Another result expected from a carbon trading scheme is that the recycling of aluminum (secondary production) would be favored over primary production. This follows from the fact that only 5% of the energy is required for recycling as compared to primary production and no carbon anodes are involved in the recycling process. An additional benefit is that recycling facilities (remelters) are smaller facilities and only require about 10% of the capital costs of a new smelter installation. Thus, carbon trading might favor more remelters construction in consumption-rich countries like China and India where the supply of scrap is more likely to be available. It is unlikely to modify production technology in the energy-rich areas of Iceland and the Middle East where scrap availability is limited.

ADDING IT ALL UP

Figure 3 illustrates a material flow model for the global aluminum industry throughout its life cycle that has been developed by IAI for the year 2004—for additional details, see Reference 3, p. 95. The values cited are in millions of metric tons.

The area of the circles illustrates the relative volume of the flows. The total products in use, an estimated 538 million metric tons, represent more than 70% of all of the aluminum that has ever

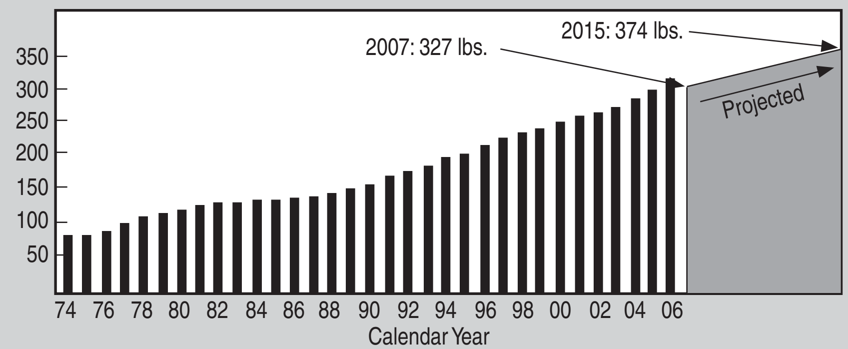

Figure 2. North American light vehicle content (in lbs.) : trends and projection. (Ducker Worldwide)

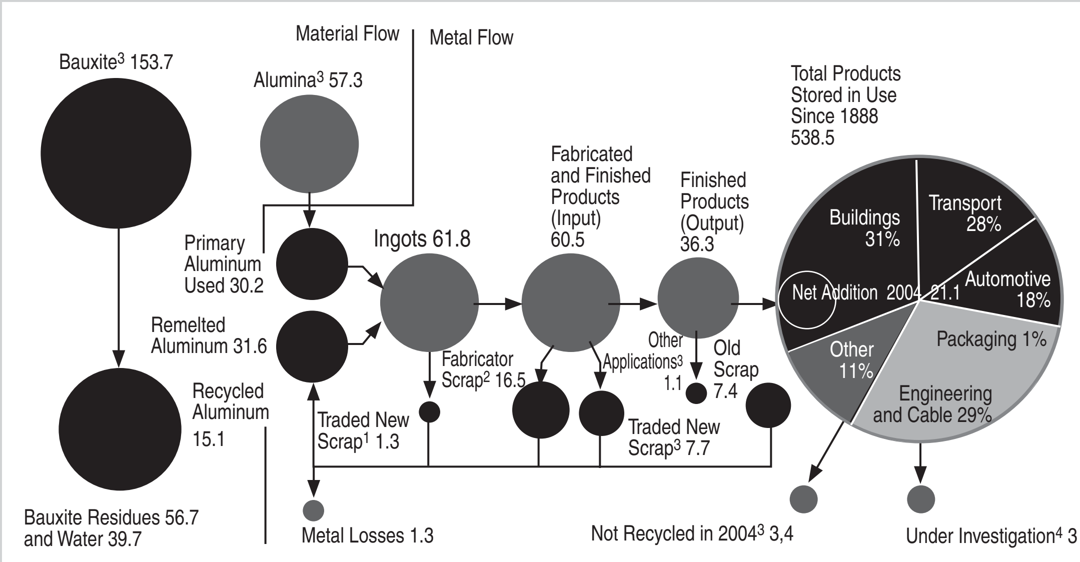

Figure 3. A material flow model for the global aluminum industry throughout its life cycle, developed by IAI for the year 2004. For additional details, see Reference 3, p. 95. Values cited are in millions of metric tons.

been produced. With this database it is possible to assess current energy and emissions intensity and project ahead for future years the energy use and GHG footprint of the industry.

Based on the growth of recycling and the reducing energy intensity of the primary production and the significantly lower PFC emissions, the CO_2 emissions footprint of the industry is decreasing on a per ton basis, although the industry continues to expand production. On the other hand, the savings of CO_2 emissions from the transportation use of aluminum are continuing to grow as more and more metal is used and the resultant fuel savings accumulate and the amount of recycled material is increased. Assuming the global industry can be updated to the best available technology as of 2003, the model indicates that the fuel efficiency and emissions savings due to aluminum use in transportation will surpass the global industry's production emissions by 2020 (Reference 3, see Chapters 5&6). The 2007 Alcoa Annual Report contains the statement "the use of aluminum in planes, trains, and automobiles is projected to make the entire aluminum industry greenhouse gas neutral by the year 2025." Whatever the precise date, this is indeed an encouraging sign!

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