Aluminum Stock and Flows in U.S. Passenger Vehicles and Implications for Energy Use

Lynette Cheah, John Heywood, and Randolph Kirchain

Keywords:

aluminum
automobile
dynamic modeling
energy use
industrial ecology
material flow analysis (MFA)

Supplementary material is available on the *JIE* Web site

Summary

In this article, a methodology to model the annual stock and flows of aluminum in a key end-use sector in the United States—passenger vehicles—from 1975–2035 is described. This dynamic material flow model has enabled analysis of the corresponding energy embodied in automotive aluminum as well as the cumulative aluminum production energy demand. The former was found to be significant at 2.6×10^9 gigajoules (GJ) in year 2008 under baseline assumptions. From 2008–2035, the cumulative energy required to produce aluminum to be used in vehicles is estimated at 7.8×10^9 GJ. Although the automotive aluminum stock is expected to increase by 1.8 times by 2035, the corresponding energy embodied is not expected to grow as rapidly due to efficiency improvements in aluminum processing over time. The model's robustness was tested by checking the sensitivity of the results to variations in key input assumptions, including future vehicle sales, lifetimes, and scrap recovery. Sensitivity of energy embodied in automotive aluminum to changes in aluminum production efficiency and aluminum applications within the vehicle were also explored. Using more recycled aluminum or improving the energy efficiency of aluminum production at a faster rate can lower production energy demands. However, aggressive and sustained changes are needed beginning today to achieve meaningful reductions. This may potentially be countered by increased use of stamped aluminum in vehicles.

Address correspondence to:
Lynette Cheah
Massachusetts Institute of Technology
77 Massachusetts Ave., Rm 31-157
Cambridge, MA 02139
lynette@mit.edu
http://msl1.mit.edu/msl

DOI: 10.1111/j.1530-9290.2009.00176.x

Volume 13, Number 5

Introduction

Over the last several decades, global demand for aluminum has been increasing, and it is now the second most widely used metal after steel (IAI 2008). For many applications, aluminum offers an attractive combination of high strength-to-weight ratio, corrosion resistance, and processability—attributes that have promoted its widespread adoption. Today, it is most intensively used in the packaging and transportation sectors (IAI 2008).

Although its use is promoted to achieve energy and environmental benefits, as with the lightweighting of vehicles, its production from primary sources is not without impact. Aluminum may be the third most abundant element in the earth's crust, but deriving the metal from its bauxite ore requires large amounts of energy. Each kilogram of primary aluminum ingot requires 160 megajoules (MJ) of energy to produce, a value that is about seven times that of steel, five times that of cast iron, and 2.5 times that of an average plastic (GREET 2007). The large amount of energy required, primarily electricity used during the aluminum smelting process, has led to aluminum ingots being termed "congealed electricity," or "energy banks" (McCutcheon 1992).

Given the large energy investment required to produce aluminum, the purpose of this article is to (1) carry out dynamic material flow analysis (MFA) to characterize the evolving use of aluminum within an important industrial sector in the United States—transportation; (2) quantify the corresponding implications on energy consumption; and (3) examine the effectiveness of several technological and systemic strategies to minimize those implications.

Passenger vehicles serve as an ideal study because of their significant, growing utilization of aluminum, and the availability of reliable data. Today, a little more than a quarter of aluminum consumed in the United States is used in passenger vehicles, which includes cars, sport-utility vehicles, minivans, and pickups (see the appendix provided as supplementary material on the Journal's Web site). Shipments of aluminum to the automotive industry reached 1.9 million metric tons (MMT) in 2009 compared with 0.9 million metric tons (MMT)[1] in 1990, and growth is expected to continue (Ducker 2002, 2008).

For the analysis described in this article, the key metrics of concern will be energy consumption and percentage improvement over a base case. The focus is on the amount of energy that is invested to process and manufacture the aluminum automotive components. Ultimately, our questions concern the impact of transportation related aluminum production on energy use and the changes that would most effectively reduce that impact. The hope would be that such information will isolate the most important strategies for improvement and underline the importance of timely action for their implementation.

The timeframe of analysis will be from 1975–2035, with a particular interest in exploring ways to reduce energy impact over the next 25 years. A dynamic and forward-looking perspective will allow one to explore the timing and delay in establishing the magnitude of benefit by 2035.

Literature Review

Several previous studies have adopted a dynamic approach to MFA for different materials. (Kleijn et al. 2000; Elshkaki et al. 2005; Daigo et al. 2007) Such an approach, as opposed to a static perspective, is often employed to monitor the accumulation of material stocks over time, assess future material use scenarios, and/or estimate the generation of scrap or waste material from a specific product system.

For aluminum in particular, past dynamic MFA studies have explored the accumulation of this material stock and/or flows from various geographical, sectoral, and temporal perspectives. Analyses that looked at current material flows in the aluminum recycling industry include Boin and Bertram (2005) for Europe and Plunkert (2005) for the United States. Other studies have modeled future aluminum scrap generation in different countries—Melo (1999) reported the scrap potential in Germany up to year 2012, and Hatayama and colleagues (2009) did the same for Japan, the United States, Europe, and China through

2050. Focusing on the automotive industry, future aluminum flow analysis had been carried out by Zapp and colleagues (2002) in Germany up to 2040. Van Schaik and colleagues (2002) created a forward-looking dynamic model to optimize aluminum recycling in vehicles, which was applied to simulated vehicle fleets.

More closely related to the purpose of this article, there are a few known earlier publications that examined the stock and flows of aluminum associated with U.S. vehicles specifically. Gorban and colleagues (1994) carried out a forecast of automotive aluminum recycling in North America and concluded that more than 85% of aluminum scrap reclaimed from automobiles in year 2010 can be used in automotive production. Choate and Green (2004) modeled aluminum scrap availability in the United States from all markets, including transportation, building/construction, and containers/packaging. Included in their model is an estimate of available scrap aluminum from vehicles from 1960–2030. The final is a brief fact sheet issued by the U.S. Geological Survey (2006), which charts the estimated aluminum stock contained in on-road vehicles historically from 1970–2001. In 2001, the embodied aluminum stock was estimated to be 19.1 MMT.

Estimates from these latter three studies are useful in validating our model, although none of them looked beyond aluminum consumption to the implications on production energy requirements. This research will not only account for the accumulation of material stock and quantify flows in the vehicle fleet, but will additionally interpret the dynamic MFA results to assess the evolving energy burden associated with material production. This further analysis on energy use and possible ways to reduce it is currently lacking in the literature and will be a novel contribution of this study. The applicability and value of MFA as a tool to enable exploration of potential energy-saving strategies will hence be demonstrated.

Model and Approach

A spreadsheet-based model has been developed to track the annual aluminum stocks flowing in and through the U.S. passenger vehicle fleet historically, with the capability to assess scenarios to year 2035. These projections are built up from two submodels: (1) the average aluminum content in new vehicles sold in each model year by form (cast or wrought) and type (primary or secondary); and (2) the number of vehicles in the on-road vehicle fleet by age in each year. The latter is modeled by tracking vehicles entering (new sales) and retiring from (scrappage) the fleet. The stock and flows of automotive aluminum are direct derivatives of these inputs.

A corresponding embodied energy assessment of automotive aluminum is also computed by combining the above with a third submodel, which tracks (3) the energy use per unit of aluminum produced by year. The embodied energy refers to the energy inputs required to produce the aluminum in the vehicles. It comprehends material extraction and processing steps, but the transportation of materials and assembly of the vehicle have been excluded. The energy required for these latter two steps are a small fraction of the former (GREET 2007).

The fuel-saving benefit of using lighter-weight aluminum over the vehicle's life cycle has been well documented in several previous studies (Stodolsky et al. 1995; Dhingra et al. 2000; EAA 2007). Generally, when aluminum is used to replace iron or steel in a vehicle, the vehicle weighs less and consumes less fuel. Because of the long vehicle lifetime, the fuel-saving benefits realized over the vehicle's use phase will outweigh the additional energy investment associated with processing aluminum. As the focus here is on the embodied energy demands, the lightweighting benefit will *not* be revisited in this analysis.

Given this approach, the mass of aluminum content in all passenger vehicles, $M_{i,t}^{j}$, for each year, t, are separately tracked in terms of raw material source—primary (P) or secondary (S)—indexed on $i \in \{P,S\}$ and for two product types—cast (C) and wrought (W)—indexed on $j \in \{C,W\}$. This aluminum stock is calculated based on the sum product of two variables. The first is the mass of aluminum in the average new vehicle introduced in model year y, $m_{i,y}^{j}$. The second is the number of vehicles introduced in model year y that exist in the fleet in year t, $V_{y,t}$. So for any given year from 1975–2035 (the range

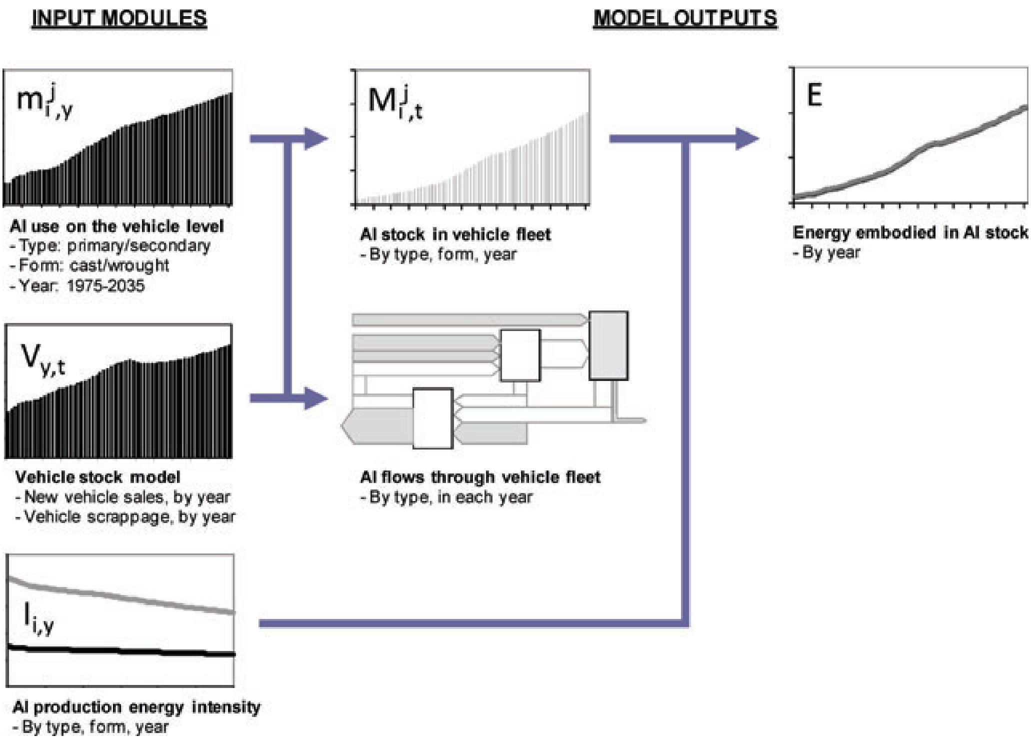

Figure 1 Schematic overview of model.

of t), the model computes the following:

$$\begin{aligned} M(t) &= M_{P,t} + M_{S,t} = M^C_t + M^W_t \\ &= \left(M^C_{P,t} + M^C_{S,t}\right) + \left(M^W_{P,t} + M^W_{S,t}\right) \\ &= \sum_{y=y_0}^{t} \sum_{i\in\{P,S\}} \sum_{j\in\{C,W\}} m^j_{i,y} \cdot V_{y,t} \end{aligned}$$

The energy embodied in the aluminum stock within the passenger vehicle fleet, E, will be a function of the energy intensity of aluminum production in year y, $I_{i,y}$ (in megajoules per kilogram [MJ/kg][2] of aluminum) and the total mass of aluminum in vehicles introduced in that year, $M_{i,y}$. It is assumed that aluminum in vehicles is produced in the same year that the vehicle is sold. The impact allocation procedure adopted is the cutoff method, which will be described later. Using this approach, the energy embodied in the aluminum stock is computed as:

$$E(t) = \sum_{y=y_0}^{t} \sum_{i\in\{P,S\}} I_{i,y} \cdot M_{i,y}$$

A schematic overview of the model is depicted in figure 1. More details and assumptions made in building these three sub-models will now be described in the following sections.

Aluminum Use on the Vehicle Level

Aluminum use in passenger vehicles has been steadily increasing. The average aluminum content per new vehicle has grown at a compounded annual rate of 4.4% since 1975, and is 148 kg per vehicle today (Ducker 2008). This trend has been spurred by efforts to replace heavier iron and steel with aluminum to reduce vehicle weight and enable better performance and/or lower fuel consumption, for better styling, and in some instances to reduce cost.

Most of the aluminum embodied in the vehicle—81% by mass—exists as cast parts, usually in the engine block, cylinder head, and wheels. Other common aluminum applications include heat exchangers, encasings in the transmission, and control arms in the chassis (see

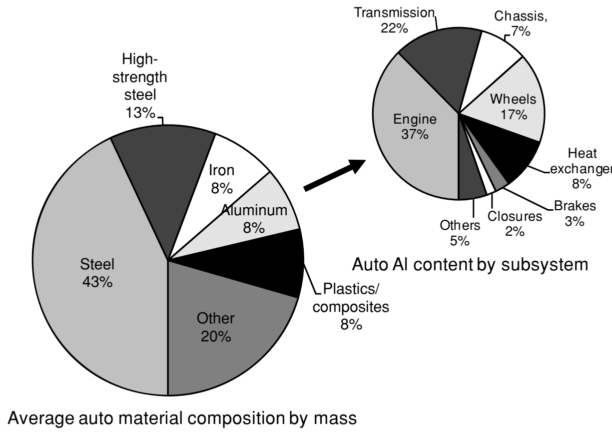

Figure 2 Average material composition of a U.S. automobile by mass in 2007 (*Source:* Davis et al. 2009), and aluminum content by vehicle subsystem (*Source:* Ducker 2008).

figure 2). In today's vehicles, 43% of the aluminum content in the vehicle is made from primary, or virgin, aluminum, while the rest is made from secondary, or recycled, aluminum (Ducker 2005, 2008).

In the future, aluminum faces competition from magnesium alloys, compacted graphite iron (especially for cast parts), high strength steel, and plastics/polymer composites. Despite this, growth in aluminum content per vehicle is expected to continue. By 2011, PricewaterhouseCoopers (2007) predicts that 82% of engine block and cylinder head units sold in North America and the European Union will be made of aluminum alloys, up from 72% today. Ducker Worldwide (2008) also foresees growth in aluminum use in this and other parts, including vehicle hoods (see figure 3). Based on expert interviews and studying the trends of aluminum use in automotive components, Ducker estimates that the aluminum content per vehicle will increase to 171 kg by 2020.

Given these historical trends and forecasts, this analysis assumes that the average aluminum content per new vehicle will continue to grow at a compounded rate of 1.3% per annum from today to 2035. As shown in figure 4, average aluminum content would reach 171 kg per vehicle in 2020, which corresponds to Ducker Worldwide's estimate, and continue increasing to 207 kg by 2035. (Herein, average aluminum content is defined following Ducker (2008) as the expected [mean] mass [kg] of aluminum in a vehicle sold in the United States in a given year.)

From 2009 onwards, it is assumed that the split between cast versus wrought aluminum parts in new vehicles will remain at today's level of 81:19. As such, 19% of the aluminum content in future new vehicles would be in wrought parts, which include aluminum stampings, forgings, and

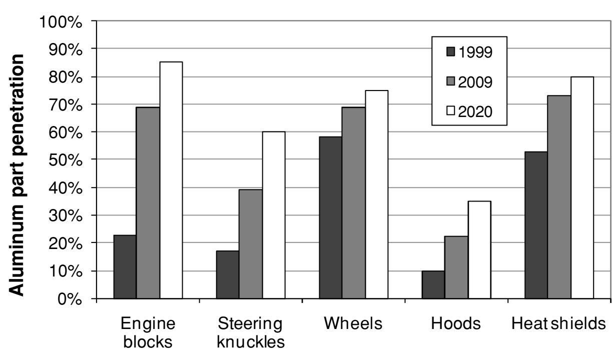

Figure 3 Historical and forecasted aluminum auto part penetration in North America. *Source:* Ducker 2008.

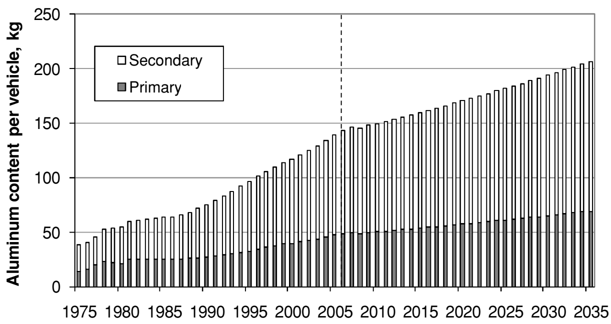

Figure 4 Historical and forecasted primary and secondary aluminum content per vehicle in the United States.

extrusions. This ratio is held constant because forecasts project growth in both castings, such as engine blocks, knuckles, and wheels, as well as wrought components, such as hoods and heat shields.

It is also assumed that up to 80% of the raw materials used to produce cast components can come from secondary resources. For wrought parts that tend to require alloys that are more compositionally restrictive, we assume that only 10% can be composed of secondary aluminum. These assumptions are similar to that adopted in the ecoinvent Centre's ecoinvent database (2004). A breakdown of the average aluminum composition by type (primary versus secondary) and form (cast versus wrought) in each year is provided in the appendix on the Journal's Web site.

Details on the types of aluminum alloys and grades used within the vehicle have not been included in this analysis. Other studies (Ng et al. 1999; Gesing and Wolanski 2001; Gaustad et al. 2007) have explored the impact of changing alloy specifications on vehicle recyclability, but this aspect is decidedly excluded from the scope of this article. A particular concern regarding this simplification is whether the compositional and other quality specifications of automotive products and automotive-derived scrap will considerably diverge over time. For most metals, in a growing market, such mismatch is unimportant as some sink for scrap material is generally available. However, given the significance of the automotive market in terms of supply and consumption of scrap, this may not always hold. Future work should explore the implications of this simplification. In addition, this work assumes that the dynamics of interest regarding mass flows and energy consumption can effectively be captured by treating the vehicles sold in a given year as homogeneous and characterized by mean fleet behavior. Although the authors are unaware of specific issues for the questions at hand, as more data becomes available, future work should explore the implications of this simplification as well.

To model the flows of aluminum to and through the vehicle fleet, some additional assumptions need to be made. First, regarding aluminum inflows, a fifth of new vehicles sold from today are assumed to be imported while the rest are domestically manufactured. This is the current characteristic of the new vehicle fleet. Aluminum content within domestically manufactured vehicles is either imported or produced in the United States. This split in the automotive aluminum supply will again be based on the current proportion that characterizes the entire U.S. aluminum supply. So, imports of aluminum metal are assumed to form about 45% of the automotive aluminum supply.

Second, the amount of new or prompt scrap generated during automotive part fabrication/manufacturing (as opposed to old scrap generated from retired vehicles) has been previously estimated at 15% to 27% (Gorban et al. 1994; Ginley 1994). In this study, we assume that this "offal rate" will be 22% of aluminum inflows in all years.

Third, the recovery rate of old aluminum scrap from retired vehicles is assumed to be 85%. This is the amount of old scrap that is currently captured for recycling, taking into account losses over all metal recycling processes. Published estimates of this number range from 80% to 93% (Gorban et al. 1994; Stodolsky et al. 1995; AA 2003).

Finally, it is assumed that that there are no time lags in the system other than those associated with the lifetime of vehicles in the fleet. This means that automotive aluminum parts are processed and fabricated in the same year they are introduced into the vehicles, so there is no time lag between part fabrication and utilization. Also, no time lag exists in the availability of scrap aluminum recovered from retired vehicles. The sensitivities of some of these assumptions are explored in the appendix on the Journal's Web site.

Energy Intensity of Aluminum Production

This study is interested in the energy requirements during the processing and manufacturing of automotive aluminum components, without detailing the sources of this energy. For primary aluminum, this includes the energy used to mine bauxite ore, refine the bauxite to alumina using the Bayer process, reduce the alumina using the Hall-Héroult process, produce the necessary carbon anodes used in this smelting process, and cast ingots for further forming as well as to form parts—stamped or cast. For secondary aluminum, this includes the recovery of scrap and scrap preparation (that is the activities involved in the consolidation and segmentation of aluminum scrap from other forms of waste), remelting, and part manufacturing. Energy use for transport of the minerals and materials has been excluded.

The energy intensity data for each of these stages is obtained from Argonne National Laboratory's energy use in transportation (GREET) dataset. The GREET dataset was developed to compare vehicles used in the United States and is used because it is freely and publicly available and because the results of this study are not significantly affected by the selection of the data source across well-known life cycle inventory (LCI) databases. A comparison of the GREET data with two other aluminum LCI data sources is included in the appendix provided as supplementary material on the Journal's Web site. Using the GREET data for year 2000 and applying our earlier stated assumptions of the amount of primary and secondary aluminum that is embodied in average stamped and cast aluminum parts, a breakdown of the production energy requirements by processing/manufacturing stage is shown in figure 5.

It is acknowledged that there is geographical variation in the energy intensity of aluminum production (McMillan and Keoleian 2009), which, depending on the source of the metal utilized in U.S. vehicles, will affect the analysis. This detail, however, has been excluded from the scope of this study and suggested for future work.

Regarding the inventory allocation scheme, the cutoff method has been used to characterize the open-loop recycling of aluminum. In the cutoff criterion, only the energy intensity of producing the materials actually used in the product

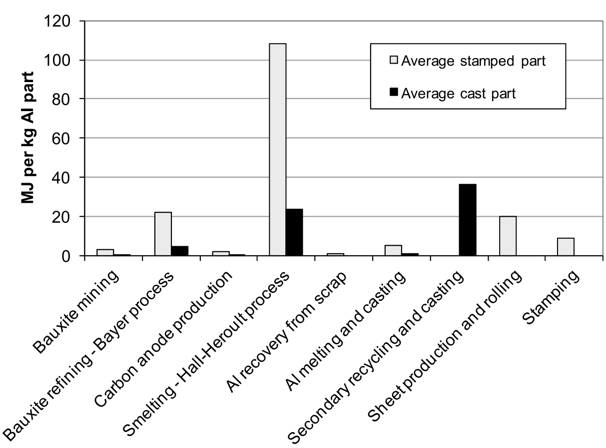

Figure 5 Production energy requirements for automotive aluminum parts in 2000, by processing stage.

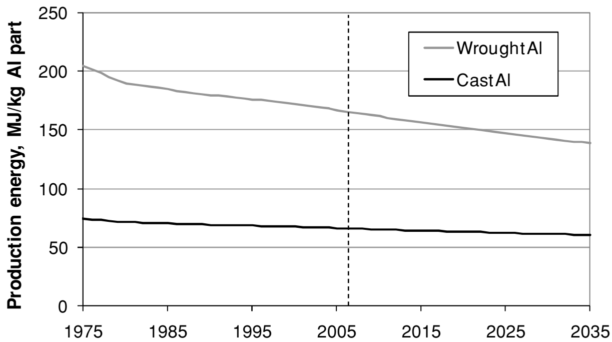

Figure 6 Production energy requirements for automotive aluminum parts over time.

of interest, here the vehicles, is considered. The energy burden associated with the prior origins of the secondary aluminum is not included, nor is any consideration given to avoided impacts associated with material made available at end of life (Huppes 1994). This assumption seems particularly appropriate for this analysis, which comprehends 60 years of production. In addition, because the recycled content for vehicles is limited to material made available from previous vehicles and because this leads to a near net scrap balance (as will be discussed later), initial and terminal materials represent only a small fraction (less than 5%) of the total amount of material accounted.

Notably, the energy required to process aluminum has not been a constant over time. With continuous efficiency improvements over the years, especially in the smelting process, the energy requirement has been declining and would be expected to continue. From 1960 to 2000, the electricity requirement for smelting was successfully reduced by 35% (Choate and Green 2003), and the North American aluminum industry is targeting a further 27% reduction by 2020 (AA 2003). It is expected that technical efficiency improvements in primary aluminum processing will take place, focusing on developing more advanced Hall-Héroult cells. In this study, it is assumed that the aluminum smelting energy requirements will decline into the future at a compounded rate of −1.06% per annum, which is the historical rate of decline from 1960–2000, and is slightly less optimistic than the published industry target. The sensitivity of this assumption shall also be explored later.

The resultant future variation of automotive aluminum production energy over time is depicted in figure 6. We have assumed that the energy demanded by all other aluminum processing steps other than smelting remains constant. The energy requirement is also based on the earlier-mentioned assumption that 80% of cast, and 10% of wrought components are made from secondary aluminum.

U.S. Passenger Vehicle Stock Model

About 250 million passenger vehicles are driven on U.S. roads today. In 2006, 17 million new vehicles entered the fleet while 13 million older vehicles were retired. A spreadsheet-based fleet model developed at MIT by Bandivadekar and colleagues (2008) is used to model the annual stock of both cars and light trucks[3] being driven on the roads, or the "vehicle parc," based on assumed vehicle sales and scrappage rates.

In this model, historical sales data were obtained from the Transportation Energy Data Book published by Oak Ridge National Laboratory (Davis et al. 2008). Projecting ahead, new vehicle sales are assumed to decline to 10 million in 2009 and return to 16 million by 2014. This is the short-term forecast of the U.S. market by R. L. Polk & Co. (2009) given the current economic conditions. Subsequently, we assume that new vehicle sales will grow at a rate of 0.8% per year until 2035, in tandem with the expected U.S. population growth.

A logistic function is used to estimate the survival rate of vehicles:

$$\text{Survival rate} = 1 - \frac{1}{\alpha + e^{-\beta(t-t_0)}}$$

Where,

α = Model parameter, set to 1;
β = Model parameter that determines how quickly vehicles are retired. A fitted value of 0.28 is used for cars, and 0.22 for light trucks;
t = The age of the vehicle in a given year; and
t_0 = Median lifetime of the vehicle. From 1990, the model assumes a median vehicle lifetime of 16.9 years for cars, and 15.5 years for light trucks, which are estimates from the U.S. Department of Energy (Davis et al. 2008).

With this model, one is able to project the age of vehicles within the fleet as well as estimate the number of vehicles, by year of production, that are leaving the fleet from 1975–2035. Figures of the estimated vehicle survival rate and the modeled size of the vehicle parc over time are available in the appendix on the Journal's Web site.

Results

By combining the submodel of average aluminum content per vehicle and the submodel of the vehicle parc, it is possible to project the expected annual aluminum stock and flows in the U.S. passenger vehicle fleet. Figure 7 shows the historical and projected aluminum stock from 1975–2035. The aluminum contained in all vehicles in use today (2008) is about 30 MMT. In the future, as the aluminum content per vehicle is expected to rise along with the size of the vehicle fleet, the aluminum stock in vehicles is projected to reach 54 MMT by 2035.

Together with the stock of aluminum in the U.S. vehicle fleet, the submodel on aluminum production energy intensity can be used to project the corresponding embodied energy consumption. Taking into account the variation of automotive aluminum production energy over time, the energy embodied in automotive aluminum is shown as a line in the same figure 7. In 2008, this is estimated to have been 2.6×10^9 gigajoules (GJ) and is expected to increase to 4.2×10^9 GJ by 2035. These figures represent the energy input that went into producing both primary and secondary aluminum that is within vehicles on the road in that year. The rate of increase is slightly less than the growth in aluminum stock because the energy requirement for primary aluminum production is expected to decline gradually over time.

Figure 8 shows the annual aluminum production intended for new U.S. passenger vehicles and the corresponding energy demand over the same time period. Again, energy demand grows less quickly than aluminum production due to efficiency improvements. From today, the cumulative amount of energy required to produce aluminum used in vehicles is projected to reach 7.8×10^9 GJ by 2035.

The stock of aluminum contained in U.S. vehicles is a major potential source of secondary aluminum. However, given the around 16-year lifetime of vehicles, it takes time for the aluminum scrap from automobiles to enter the supply market. Figure 9 shows Sankey diagrams in 2008 and 2035, which represent snapshots of the annual flow of aluminum entering and leaving the vehicle fleet. Additions to stocks and external flows are indicated in shaded boxes or arrows.

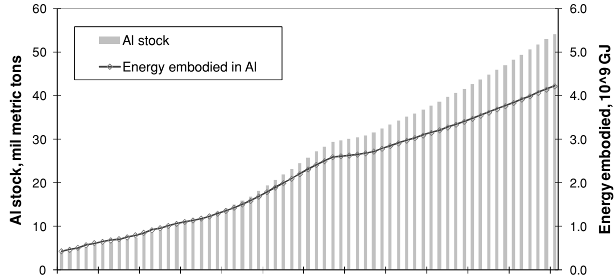

Figure 7 U.S. automotive aluminum stock and energy embodied within the aluminum.

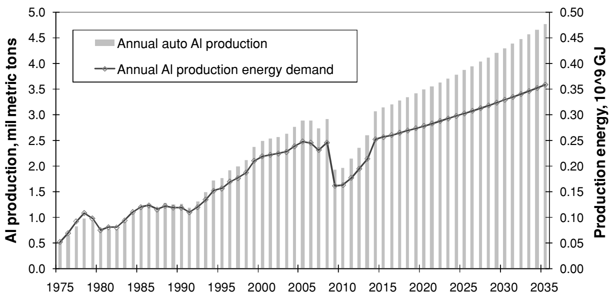

Figure 8 Annual U.S. automotive aluminum production and energy demand.

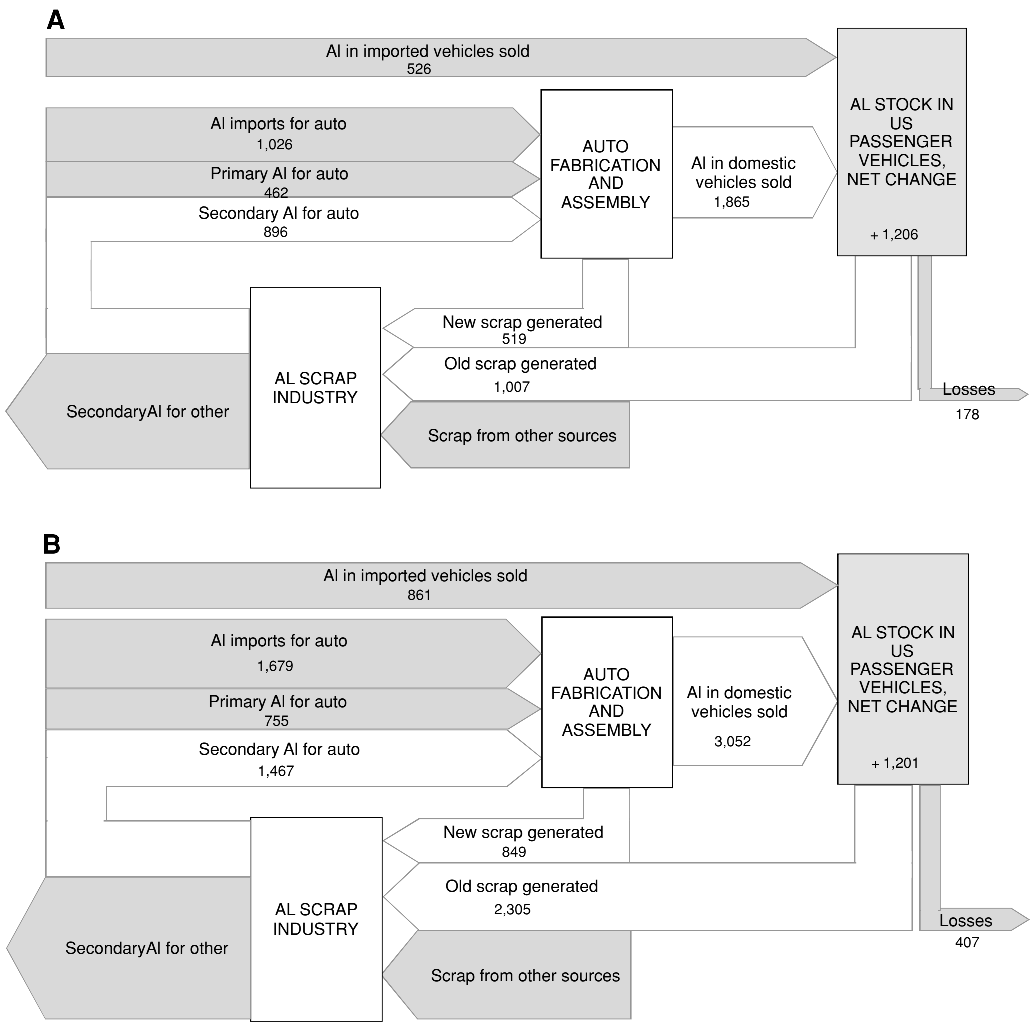

Figure 9 Sankey diagrams of aluminum stocks and flows in the U.S. passenger vehicle fleet (figures in thousand metric tons). (A) In 2008. (B) In 2035.

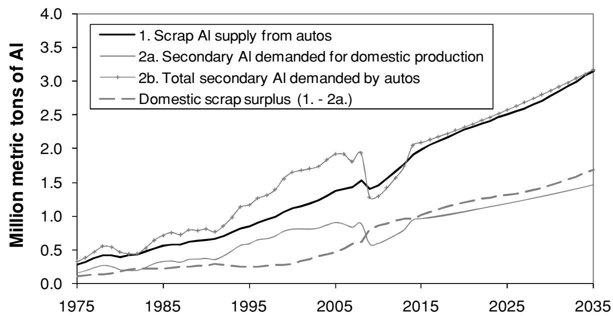

Figure 10 Evolution of automotive aluminum demand and scrap supply from U.S. vehicles.

In 2008, 2.4 MMT of aluminum was supplied to the automotive sector for part fabrication and automobile manufacturing in the United States. Of this, 1.0 MMT of the metal was imported while the rest was domestically produced. About a third of the domestically produced aluminum was primary metal, and the rest is secondary. Taking into account the outflow of aluminum in retired vehicles, the net addition to the aluminum stock in vehicles was 1.2 MMT. In 2035, the model projects that these figures grow, but the relative proportions of the flows remain similar to that in 2008.

Of the aluminum scrap generated in both years, about one third was new or prompt manufacturing scrap. It is unclear how much of this new scrap is internally cycled back directly within the auto fabrication plants (termed home scrap), as opposed to being sent to an external aluminum scrap processing facility. For simplification, all new scrap is depicted in this diagram as being directed to the secondary market, even though it is noted that an unknown fraction could be internally recycled.

Figure 10 shows how the scrap supply from and secondary aluminum demanded by the vehicle fleet evolves over time. Line 1 indicates the scrap supply, which includes both new and old scrap, with recovery losses accounted for. Line 2a is secondary aluminum demanded for domestic auto fabrication and assembly. 2b reflects secondary aluminum demanded by all vehicles, including that already in imported metal and imported vehicles. The supply curve is dissimilar from the demand curves because it is smoothened by the assumed vehicle scrappage rate.

The model results suggest that aluminum demanded by automobiles will always need to be supplemented by domestic primary aluminum production and imports. Nevertheless, the supply of scrap aluminum from vehicle manufacturing and retired vehicles is projected to be sufficient to meet the domestic demand for secondary aluminum for automotive parts, and it is expected that there would always be a positive contribution to the national scrap aluminum supply. This contribution or domestic scrap surplus is indicated as a dashed line in the same figure. From 2008–2035, the fraction of secondary aluminum demand over scrap supply (line 2a divided by line 1) averaged 0.47. So the total amount of scrap aluminum coming from the automotive industry is around twice that of secondary aluminum required for domestic production. If using the broader definition of scrap demand (including scrap content demand for domestic production and that embedded within imported aluminum, or line 2b), the model suggests that demand does not or will only marginally exceed U.S.-derived automotive scrap supply over the modeled period from 2008–2035. Over that period, the model suggests that the scrap deficit never exceeds 7% of the scrap supply.

Sensitivity Analysis

We are interested in characterizing the effectiveness of various changes to the way aluminum is produced and used in vehicles towards reducing projected energy demand. To this end, sensitivity analysis is used to explore the impact of varying the following on embodied energy:

- efficiency improvements in primary aluminum processing;

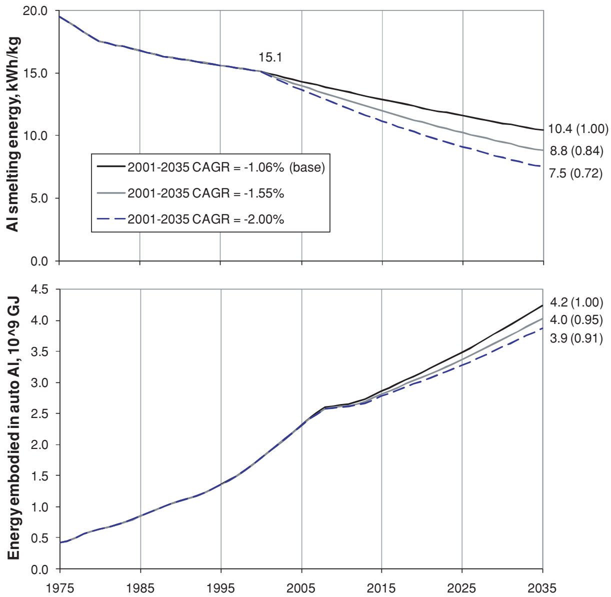

Figure 11 Scenarios of future aluminum smelting energy requirements (top) and the corresponding energy embodied in aluminum contained in vehicles (bottom) (relative fraction of 2035 projection compared to base scenario in parentheses).

- the extent of secondary/recycled aluminum use in vehicles; and
- the extent of sheet aluminum parts use in vehicles.

Greater Efficiency Improvements in Primary Aluminum Processing

The results obtained on embodied energy are based on a baseline assumption that aluminum smelting energy requirements will decrease at a compounded rate of −1.06% per annum, which is the historical rate of decline. At this rate of improvement, the smelting energy requirement would be expected to decrease from 15.1 kWh/kg aluminum in 2000 to 12.2 kWh/kg by 2020 and eventually reach 10.4 kWh/kg by 2035 (see figure 11). As points of comparison, the aluminum industry had defined a target to reduce smelting energy use to 11.0 kWh/kg by year 2020 (AA 2003), with the theoretical minimum estimated at 6.0 kWh/kg (Choate and Green 2003).

Clearly, more optimistic rates of efficiency improvements could reduce the projected energy embodied in passenger vehicle aluminum. As shown in the same figure 11, if the compounded annual rate of decline in aluminum smelting energy from 2001–2035 is −1.55% instead of −1.06% (the base case), the total energy embodied in year 2035 will be 4.0×10^9 GJ. This is the rate of decline that will meet the 2020 target stipulated by the Aluminum Association. If the future aluminum smelting energy declines more dramatically at −2.00% per annum, the total energy embodied will be a lower 3.9×10^9 GJ. So doubling the rate of efficiency improvements in primary aluminum processing can reduce the total energy embodied in all automotive aluminum in 2035 by 9% over this timeframe.

Increased Use of Secondary/Recycled Aluminum in Vehicles

Moving from aluminum processing and manufacturing, we now examine the sensitivity of the model results to potential changes in future automotive aluminum use and part design.

The first change to explore is the increased use of secondary or recycled aluminum to replace primary aluminum used in vehicles. The current assumption in the model corresponds to typical current practice, where around 80% of the metal used in cast aluminum parts, but only 10% of metal for wrought parts derives from secondary aluminum. These figures translate to 67% of all aluminum contained in a vehicle being metal that has been recovered from scrap. Because the energy required to produce parts from secondary aluminum is significantly less than that required using primary aluminum, increasing these

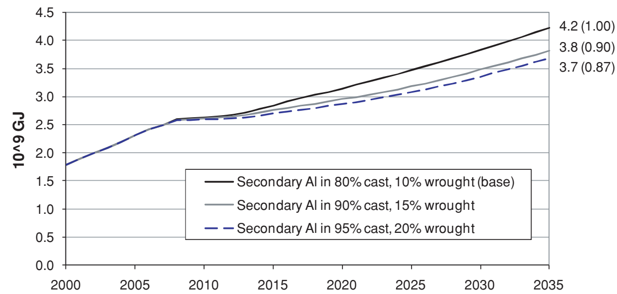

Figure 12 Energy embodied in aluminum contained in vehicles—sensitivity to use of secondary aluminum (relative fraction of 2035 projection compared to base scenario in parentheses).

percentages into the future will lower the energy embodied in automotive aluminum.

Two alternative scenarios of secondary aluminum use are depicted in figure 12. In one scenario, the use of recycled metal increases to 90% of cast parts and 15% of wrought parts, or 76% of all aluminum parts. In this scenario, the corresponding energy embodied in aluminum contained in passenger vehicles in 2035 is projected to decline by 10% from 4.2×10^9 GJ to 3.8×10^9 GJ. If use of secondary aluminum is raised slightly more, the energy embodied in 2035 lowers further to 3.7×10^9 GJ.

In general, for every 5% increase in secondary aluminum use in cast automotive parts by 2035 (while keeping the percentage of secondary aluminum use in wrought parts constant at 10%), the total energy embodied in that year will decline by 4%. For every 5% increase in secondary aluminum use in wrought parts (while keeping that in cast parts constant at 80%), the energy embodied will decrease by a mere 1%.

Increased Use of Sheet Aluminum in Vehicles

Use of aluminum in sheet applications, such as closures and body panels, has been making inroads in vehicles. Today, vehicle models that extensively use sheet aluminum stamped to shape in the body structure include the Jaguar XJ, Audi A8, and Acura NSX. Although aluminum sheet applications have been only been used in select, high-end vehicle models to date, primarily to achieve vehicle weight savings, their use could potentially spread to higher volume production vehicles as well.

The current assumption in the model is that wrought applications, including aluminum stampings, account for 19% of the aluminum content per vehicle by mass while the remaining exist as cast parts. If this fraction of wrought aluminum in the average new vehicle is increased, the embodied energy will increase as well because these parts require use of more energy-intensive primary aluminum. When this fraction is increased to 30%, and then to 40%, the energy embodied in automotive aluminum in use in 2035 then increases from 4.2 to 4.7 and 5.0×10^9 GJ, respectively (see figure 13). Although 40% of wrought aluminum content per vehicle is a rather extreme scenario, such changes in the way aluminum is utilized in vehicles appears to have a moderate impact on the aluminum production energy required.

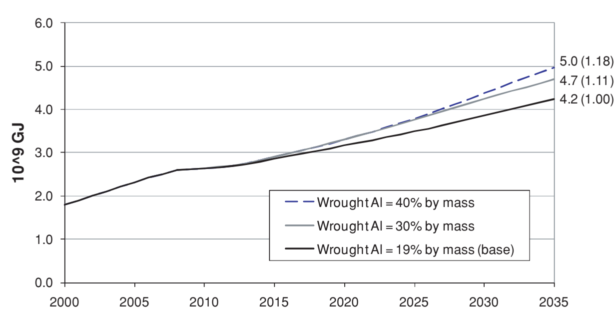

Figure 13 Energy embodied in aluminum contained in vehicles—sensitivity to use of wrought aluminum (relative fraction of 2035 projection compared to base scenario in parentheses).

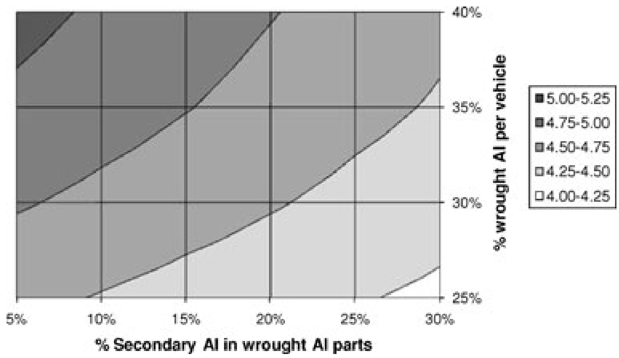

Figure 14 Energy embodied in aluminum contained in vehicles in 2035 (in 10^9 GJ)—two-way sensitivity analysis of the use of wrought aluminum and its secondary aluminum content.

A two-way sensitivity analysis is also carried out to examine the effect of varying both the fraction of wrought aluminum content and the proportion of recycled metal within it simultaneously. The effects of these two variables are depicted in the contour plot in figure 14, which shows the energy embodied in all automotive aluminum in year 2035 (in 10^9 GJ). As expected, a higher fraction of wrought and a lower fraction of secondary aluminum content in the future will lead to greater energy demands.

With more wrought aluminum content per vehicle, it is found that greater use of secondary aluminum leads to slightly more marked percentage decreases in embodied energy. For example, when the amount of recycled aluminum in wrought parts is increased from 10% to 15%, the 2035 embodied energy decreases by 2.0% if wrought aluminum makes up 40% of the average vehicle's total aluminum content in that year. The embodied energy reduction is only 1.6% when wrought aluminum content is 25%.

Reducing Aluminum Production Energy Demand

The model can also be used to explore ways to curb projected future aluminum production energy demand. The approach taken here is to assess the degree of change necessary to reduce future cumulative energy demand from 2008–2035 by a targeted 10% from the base case. Two possible means of achieving this would be the same factors introduced earlier—making efficiency gains in aluminum processing and using more secondary aluminum.

As reported, the cumulative amount of energy required to produce aluminum to be used in future vehicles is projected to reach 7.8×10^9 GJ by 2035. To reduce this figure by 10%, it is found that the rate of efficiency improvement in aluminum smelting must more than double. The energy intensity of smelting must decline at an aggressive −2.34% per annum from today to reach 6.7 kWh/kg by 2035 as compared with −1.06% assumed in the baseline scenario. Alternatively, a 10% reduction in cumulative energy demand may also be achieved by increasing the secondary or recycled aluminum content per vehicle to 80% instead of remaining at 67% as assumed in the baseline. These effects are shown in figure 15.

So to curb energy consumption for automotive aluminum production, the model reveals that significant and sustained changes will need to be made. Most likely this will involve a portfolio of changes, including both improvements in efficiency and shifts to secondary material. Whatever the solution, realizing significant improvement even by 2035 will require action, starting from today.

Summary and Conclusion

In this article, a dynamic material flow model has been described that tracks the annual stock and flows of aluminum in a key end-use sector in the United States—passenger vehicles—from 1975–2035. The material stock in this sector is expected to accumulate at a compounded rate of 2.3% per year, growing from 30 MMT today to reach 54 MMT by 2035.

This stock represents a growing potential source of scrap aluminum, although it takes time for the material to enter the scrap market due to long vehicle lifetimes. The effect of this delay

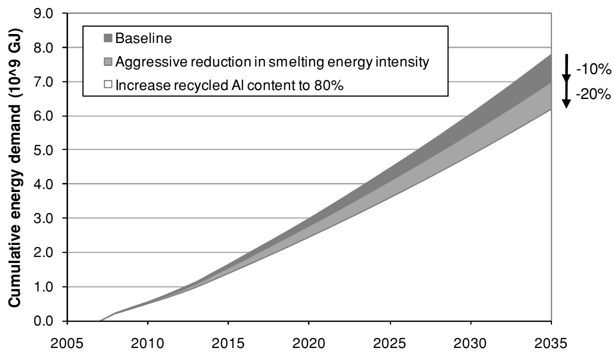

Figure 15 Changes necessary to reduce cumulative energy demand for aluminum production.

due to the evolution of the vehicle fleet has been captured in the model. The outflow of scrap from passenger vehicles is projected to increase in tandem with the aluminum stock, and the analysis finds that the scrap supplied will always exceed the secondary aluminum demanded by the domestic automotive industry. So the automotive aluminum scrap system will remain in balance.

The material flow model has enabled analysis of the corresponding energy consumption. Energy embodied in automotive aluminum was found to be significant at 2.6×10^9 GJ in year 2008. Looking ahead, the production energy demand associated with the aluminum contained in vehicles is not expected to grow as rapidly as the material stock due to efficiency improvements in primary aluminum processing.

Sensitivity of the amount of energy embodied in automotive aluminum to future changes in aluminum production efficiency and aluminum applications within the vehicle were also explored. Using more recycled aluminum and/or improving the energy efficiency of aluminum production at a faster rate can lower the production energy demands. For every 5% increase in secondary aluminum use in automotive parts, the total energy embodied in aluminum contained in vehicles in 2035 can decline by up to 4%. Doubling the rate of primary aluminum processing energy efficiency improvement between now and 2035 can also reduce the same metric by 9%.

As seen using the model, however, using these means to reduce aluminum production energy use may potentially be countered by efforts to use more lightweight sheet or stamped aluminum in vehicles. Wrought aluminum currently makes up 19% of the total aluminum content in vehicles. For every 5% increment by 2035, the total energy embodied in automotive aluminum increases by 2% to 4%.

In sum, by detailing and carrying out a dynamic material flow and energy analysis, the implications of delays in the passenger vehicle fleet system on aluminum recycling; and vehicle design choices on overall energy use are better characterized and understood. The dynamics of time-varying aluminum use in vehicles has been captured to quantify these effects in this important and growing product system. Such a model makes it clear that the energy use associated with aluminum in vehicles is substantial. To reduce this impact over the next 25 years, sustained and significant changes will have to be made at a rather aggressive pace.

Notes

1. One million metric tons = 1 teragram (Tg) = 10^9 kilograms (kg, SI) = 10^6 tonnes (t) $\approx 1.102 \times 10^6$ short tons. Unless otherwise noted, all tons in this article are metric.
2. One megajoule (MJ) = 10^6 joules (J, SI) $\approx$ 239 kilocalories (kcal) $\approx$ 948 British thermal units (BTU). One kilogram (kg, SI) $\approx$ 2.204 pounds (lb).
3. Light trucks are sport utility vehicles (SUVs), minivans, and pickup trucks with a gross vehicle weight of less than 10,000 pounds or 4,540 kilograms.

References

Aluminum Association, Inc. (AA). 2003. *Aluminum industry technology roadmap*. Washington, DC: The Aluminum Association, Inc.

Bandivadekar, A., K. Bodek, L. Cheah, C. Evans, T. Groode, J. Heywood, E. Kasseris, M. Kromer, and M. Weiss. 2008. *On the road in 2035: Reducing transportation's petroleum consumption and GHG emissions*. Cambridge, MA: MIT Laboratory for Energy and the Environment.

Boin, U. and M. Bertram. 2005. Melting standardized aluminium scrap: A mass balance model for Europe. *JOM* 57(8): 26–33.

Choate, W. and J. Green. 2003. *U.S. energy requirements for aluminum production: Historical perspective, theoretical limits and new opportunities*. v 1.1. Columbia, MD: BCS, Incorporated.

Choate, W. and J. Green. 2004. Modeling the impact of secondary recovery (recycling) on U.S. sluminum supply and nominal energy requirements. In *Light metals 2004*, edited by A. T. Tabereaux. Warrendale, PA: TMS.

Daigo, I., Y. Igarashi, Y. Matsuno, and Y. Adachi. 2007. Accounting for steel stock in Japan. *ISIJ International* 47(7): 1065–1069.

Davis, S., S. Diegel, and R. Boundy. 2008. *Transportation energy data book*. Edition 27, ORNL-6981. Oak Ridge, TN: Oak Ridge National Laboratory.

Davis, S., S. Diegel, R. Boundy. 2009. *Transportation energy data book*. Edition 28, ORNL-6984. Oak Ridge, TN: Oak Ridge National Laboratory.

Dhingra, R., J. Overly, G. Davis, S. Das, S. Hadley, and B. Tonn. 2000. A life-cycle-based environmental evaluation: Materials in new generation vehicles. SAE 2000-01-0595. SAE World Congress, March 6–9, Detroit.

Ducker Research Company, Inc. 2002. *Global Automotive Aluminum Content Forecast through 2010 with emphasis on North America and Comparisons to Europe and Japan*. Troy, MI: Ducker Research Company, Inc.

Ducker Worldwide. 2005. *Aluminum Content for Light Non-Commercial Vehicles Assembled in North America, Japan and the European Union in 2006*. Presentation slides. Troy, MI: Ducker Worldwide.

Ducker Worldwide. 2008. *Aluminum Association Auto and Light Truck Group, 2009 Update on Aluminum Content in North American Light Vehicles, Phase I, October 31, 2008*. Troy, MI: Ducker Worldwide.

ecoinvent Centre. 2004. ecoinvent v1.3 database, accessed using SimaPro 7.1 software.

Elshkaki, A., E. van der Voet, V. Timmermans, and M. van Holderbekeb. 2005. Dynamic stock modelling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics. *Energy* 30(8): 1353–1363.

European Aluminium Association. 2007. Study proves increasing use in aluminium in new European cars, saving weight, reducing fuel consumption and cutting CO_2 emissions. Alu*Drive* Newsletter, Spring 2007.

Gaustad, G., S. Das, and R. Kirchain. 2007. Identifying scrap friendly alloys using chance constrained modeling. In *Proceedings of the Annual Meeting of TMS: Light Metals Division*. Orlando, FL, February 25–March 1, 2007, pp. 1153–1160.

Gesing, A. and R. Wolanski. 2001. Recycling light metals from end-of-life vehicles. *JOM* 53(11): 21–24.

Ginley, D. 1994. Material flows in the transport industry – An example of industrial metabolism. *Resources Policy* 20(3): 169–181.

Gorban, L., G. Ng, and M. Tessieri. 1994. An in-depth analysis of automotive aluminum recycling in the year 2010. SAE 940156. SAE International Congress, Detroit.

GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation). 2007. Version 2.8a, UChicago Argonne, LLC.

Hatayama, H., I. Daigo, Y. Matsuno, and Y. Adachi. 2009. Assessment of the recycling potential of aluminum in Japan, the United States, Europe and China. *Materials Transactions* 50(3): 650–656.

Huppes, G. 1994. A general method for allocation in LCA. In *Proceedings of the European Workshop on Allocation in LCA*. Leiden, The Netherlands, February 1994. pp. 74–90.

International Aluminium Association. 2008. www.world-aluminium.org. Accessed 1 August 2008.

Kleijn, R., R. Huele, and E. van der Voet. 2000. Dynamic substance flow analysis: The delaying mechanism of stocks, with the case of PVC in Sweden. *Ecological Economics* 32(2): 241–254.

McCutcheon, S. 1992. *Electric rivers: The story of the James Bay Project*. Montreal: Black Rose Books.

McMillan, C. and G. Keoleian. 2009. Not all primary aluminum is created equal: Life cycle greenhouse gas emissions from 1990 to 2005. *Environmental Science and Technology* 43(5): 1571–1577.

Melo, M. T. 1999. Statistical analysis of metal scrap generation: The case of aluminium in Germany. *Resources, Conservation and Recycling* 26(2): 91–113.

Ng, G., J. Miller, and M. Tessieri. 1999. Aluminum usage in the PNGV and its impact on the recycling infrastructure. SAE 1999-01-0674. SAE International Congress and Exposition, Detroit.

R. L. Polk & Co. 2009. Polk Predicts Global Light Vehicle Sales Will Drop 13 Percent in 2009. News release, February 10, 2009.

Plunkert, P. 2005. *Aluminum Recycling in the United States in 2000*. Report 2005-1051. Reston, Virginia, USA: U.S. Geological Survey.

PricewaterhouseCoopers. 2007. *Aluminum Foils the Competition*. PwC Automotive Institute Analyst Note, Global Powertrain Update.

Stodolsky, F., A. Vyas, R. Cuenca, and L. Gaines. 1995. Life-cycle energy savings potential from aluminum-intensive vehicles. SAE 951837. In *Proceedings of the 1995 Total Life Cycle Conference, P-293*.

U.S. Geological Survey. 2009. *2007 Minerals Yearbook – Aluminum* (Advance release).

van Schaik, A., M. Reuter, U. Boin, and W. Dalmijn. 2002. Dynamic modelling and optimisation of the resource cycle of passenger vehicles. *Minerals Engineering* 15(11/S1): 1001–1016.

Zapp, P., G. Rombach, and W. Kuckshinrichs. 2002. The future of automotive aluminum. In *Light Metals 2002*, edited by W. Schneider. Warrendale, PA: TMS-AIME.

About the Authors

Lynette Cheah is a doctoral candidate in engineering systems at Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, USA. **John Heywood** is Sun Jae Professor of Mechanical Engineering and Director of the Sloan Automotive Laboratory at MIT. **Randolph Kirchain** is an Associate Professor of Materials Science and Engineering Systems, also at MIT.

Supplementary Material

Additional Supplementary Material Information may be found in the online version of this article:

Supplement S1. This supplement contains eight appendices: A chart of U.S. aluminum demand by sector; a table on the historical and assumed future aluminum content in new U.S vehicles; charts of aluminum stock in in-use U.S. passenger vehicles, the estimated survival rate of vehicles, and the modeled annual stock of vehicles; sensitivity analysis on the modeled aluminum stock and flows; a comparison of aluminum life cycle inventory databases; and a table of aluminum production energy requirements based on the U.S. Argonne National Laboratory's GREET model.

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supplementary materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.