Roja Modaresi

Dynamics of aluminum use in the global passenger car system

Challenges and solutions of recycling and material substitution

Thesis for the degree of Philosophiae Doctor

Trondheim, May 2015

Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Hydraulic and Environmental Engineering
Industrial Ecology (IndEcol) Programme

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Abstract

This thesis analyzes the relationship between the design of vehicles, end-of-life vehicle (ELV) management, and global material production using aluminum as an example. Vehicle manufacturing, material industries and ELV management face different challenges. An important challenge for vehicle manufacturers is the design of lightweight vehicles to reduce energy use and greenhouse gas (GHG) emissions in the use phase for which an increased use of aluminum of different alloys is an attractive option. The aluminum industry has an interest in reducing energy consumption and GHG emissions, which can be accomplished effectively through recycling. ELV management must be improved to enable the first two systems to use aluminum scrap in a sustainable manner. Today, the sorting of different alloys is limited. As a result of having mixed scrap at the ELV phase and limited opportunities for aluminum refining, there may be a future scrap surplus that cannot be absorbed by the aluminum-recycling sink, which is passenger cars. These three sectors are connected through material flows, and a change in one of the sectors can severely affect the others' options for reaching their goals.

This thesis addresses the following questions: 1) How are the dynamics of the global vehicle stock changing the boundary condition for aluminum recycling? 2) What are the most effective interventions to minimize a future aluminum scrap surplus? 3) What are the options for material substitution in vehicles to reduce direct and indirect GHG emissions over time?

To answer these questions, a system approach is employed to analyze how these three sectors are linked and to explore options for all sectors to reach their objectives in the long term. This thesis employs global bottom-up stock-driven models of the aluminum cycle. A basic model was used to identify the scrap surplus problem. A refined model with segments, components and alloys resolution combined with a source-sink diagram was used to evaluate different solution options. In addition, a global dynamic fleet-recycling MFA model was developed to simulate the future impacts of material substitutions of conventional steel with high-strength steel (HSS) and aluminum on material cycles, energy use and GHG emissions related to the global passenger vehicle fleet.

The main findings in this thesis are: i) a continuation of the current practice of cascadic use would eventually result in a scrap surplus because this practice depends on the continuous and fast growth of the secondary casting stock in the global vehicle fleet, a condition that is unlikely to be met. Model simulation indicated a non-recyclable scrap surplus by approximately 2018±5 if no alloy sorting is introduced. The surplus is potentially substantial and could grow to reach a level of 0.4–2 kg/cap/yr by 2050,

thereby significantly reducing the option of the aluminum industry to reduce its energy consumption through recycling. ii) Drastic changes in ELV management practices are necessary to make use of the growing scrap flow in the future, including further dismantling and efficient component-to-component recycling, alloy sorting of mixed shredded scrap, and designing recycling-friendly alloys that function as alternative sinks for aluminum scrap. iii) Light-weighting has the potential to substantially reduce global emissions of vehicles (9-18 gigatons cumulative CO_2-eq. between 2010 and 2050). In the medium term (5-15 years), global emissions reductions from substituting standard steel with aluminum are similar to those achievable by HSS; however, over a longer term (after 15-20 years), substitution with aluminum can reduce total emissions more effectively, provided that the wrought aluminum will be recycled back into automotive wrought aluminum.

The environmental consequences of products in general and passenger cars in particular have led to an increasing awareness of the dependencies between the shaping of vehicles and the shaping of the environment. Governments and intergovernmental bodies have formulated quality goals for the environment, such as the 2-degree target, and have introduced emissions standards, thereby extending the responsibility of automobile manufacturers to the use phase. On the materials side, legislation has been introduced to extend producer responsibility, mainly with the goal of avoiding toxic substances and reducing the amount of waste, as is noted in different end-of-life vehicle (ELV) legislation and directives. The current ELV directives do not sufficiently address the management of material systems as a whole or quality issues related to material recovery. To harmonize ELV management with goals for the global aluminum cycle and its impacts for the environment, it is essential to understand how the above-mentioned systems interact.

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Asker, February 2015

Roja Modaresi

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List of appended papers and the author’s contributions to them

All papers are published and co-authored. My contribution is indicated for each one.

Paper no. 1: (Published)
The Role of Automobiles for the Future of Aluminum Recycling. Modaresi, R.; Müller, D. B., Environ. Sci. Technol., 2012, 46 (16), pp 8587–8594. DOI: 10.1021/es300648w
Contribution: Part of the research design, data collection, model design and development, analysis, visualization, and writing.

Paper no. 2: (Published)
Aluminium Recycling – Raw Material Supply from a Volume and Quality Constraint System. Rombach, G.; Modaresi, R.; Müller, D. B., World of Metallurgy – ERZMETALL 2012, 65 (3).
Contribution: Data collection and visualization for the section related to automotive casting as a bottleneck for recycling.

Paper no. 3: (Published)
Component- and alloy-specific modeling for evaluating aluminum recycling strategies for vehicles. Modaresi, R.; Løvik, Amund N.; Müller, D. B., The Minerals, Metals & Materials Society (TMS), JOM, 2014, 66 (11) pp 2262-2271. DOI10.1007/s11837-014-0900-8
Contribution: Research design, data collection, model design and development, analysis, visualization (except for Figure 1), and writing.

Paper no. 4: (Published)
Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements. Løvik, Amund N.; Modaresi, R.; Müller, D. B., Environ. Sci. Technol., 2014, 48 (8), pp 4257–4265. DOI: 10.1021/es405604g
Contribution: Part of the research design, part of the data collection and refining.

Paper no. 5: (Published)
Global carbon benefits of material substitution in passenger cars until 2050 and the impact on the steel and aluminum industries. Modaresi, R.; Pauliuk, S; Løvik, Amund N.; Müller, D. B., Environ. Sci. Technol., 2014, 48 (18), pp 10776–10784. DOI: 10.1021/es502930w
Contribution: Research design, parts of the data collection, parts of the model design and writing.

1 Introduction

1.1 Summary of Introduction

Demand for material services has increased sharply over the past decades and is expected to increase further over the next decades as a result of industrial development and population growth (IEA, 2010, Allwood and Cullen, 2012, Krausmann et al., 2009). The consequences are higher materials and energy demand, as well as environmental challenges, such as resource depletion, water stress, land stress, and climate change.

The Intergovernmental Panel on Climate Change (IPCC) found that most of the observed increase in the global average temperature in recent decades is likely a result of anthropogenic GHG concentrations. The 5th Assessment report of the IPCC concludes that to limit the global average temperature increase to 2-2.4°C, a limit to avoid the dangerous effects of climate change, a drastic reduction in GHG emissions is vital: *'Scenarios reaching atmospheric concentration levels of about 450 ppm CO2eq by 2100 (consistent with a likely chance to keep temperature change below 2°C relative to pre-industrial levels) include substantial cuts in anthropogenic GHG emissions by mid-century through large-scale changes in energy systems and potentially land use.'* (IPCC, 2014b).

Figure 1 shows the direct and indirect GHG emissions across sectors in the baseline scenarios. The transport sector produced 6.7 $GtCO_2$ of direct GHG emissions in 2010 (Sims R., 2014, IPCC, 2014b) and was thus responsible for nearly 23% of global energy-related anthropogenic carbon emissions (Allwood and Cullen, 2012, Sims R., 2014). Road vehicles account for more than three-quarters of emissions from the transport sector, and the use of passenger cars accounted for nearly 75% of all road vehicles (OICA, Allwood and Cullen, 2012, Sims R., 2014, IPCC, 2014b). Therefore, direct emissions from passenger cars account for approximately 14% of total energy-related global anthropogenic carbon emissions. Not included in these emissions are the emissions from the production of passenger cars and road infrastructure, including material production, which are allocated to industry emissions.

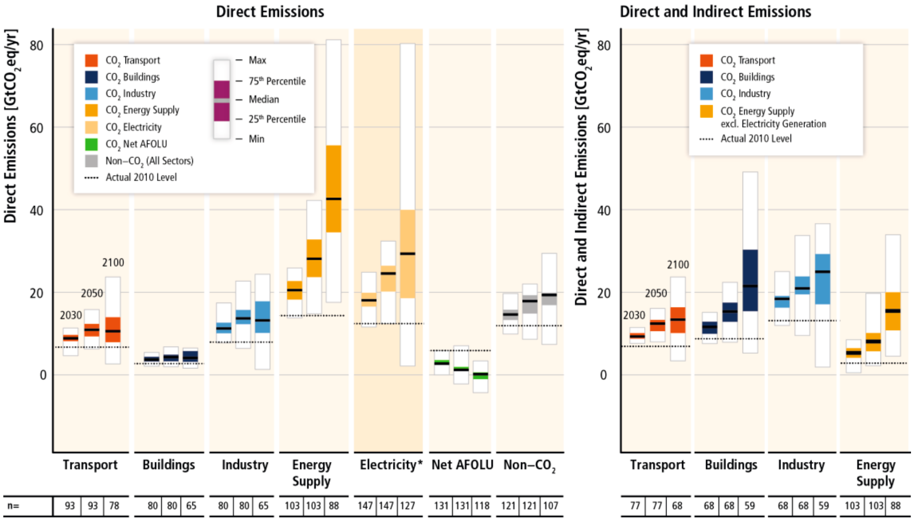


Figure 1 Direct (left panel) and direct and indirect emissions (right panel) of CO_2 and non-CO_2 GHGs across sectors in baseline scenarios. Non-CO_2 GHGs are converted to CO_2-equivalents based on Global Warming Potentials with a 100-year time horizon from the IPCC Second Assessment Report (SAR). In the case of indirect emissions, only electricity generation emissions are allocated from energy supplies to end-use sectors. In the left panel, electricity sector emissions are shown (Electricity*) in addition to energy supply sector emissions, of which they are part, to illustrate their large role on the energy supply side. (IPCC, 2014a)

To quantify the total emissions related to passenger cars and to explore options for their reduction, it is essential to regard passenger cars as a part of a larger system that includes three interlinked sub-systems: 1) vehicle and material production (from an emissions perspective dominated by material production), 2) Use phase or vehicle fleets, and 3) end-of-life vehicle management (see Figure 2).

The aim of this thesis is to analyze the socio-economic metabolism of this system with a focus on aluminum as a case study of a key material in vehicles. Models of the socio-economic metabolism can be defined as the set of processes that are connected by material and energy flows (Ayres and Simonis, 1994, Baccini and Brunner, 1991, Fischer-Kowalski et al., 2011, Fischer-Kowalski, 2011). In-use stocks are important elements of the socio-economic metabolism in material and substance flow analysis (MFA and SFA) (Müller et al., 2006, Müller, 2006, van der Voet et al., 2002, Pauliuk and Müller, 2013). In-use stocks, such as buildings, cars, and infrastructure, provide services to society and fulfill the need for major human activities, such as residing, working, transportation, and communication (Müller et al., 2010, Pauliuk and Müller, 2013, Baccini and Brunner, 1991).

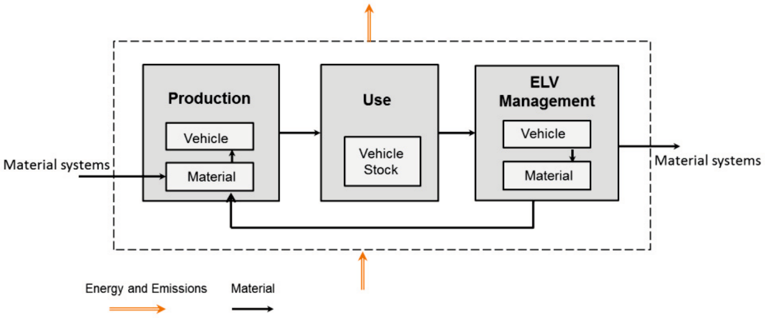


Figure 2 Generic material flow model from production to end-of-life

Following is a summary of key points for the global vehicles system, the global material system and the end-of-life management system and the main interlinks with the two other systems:

- The global vehicle stock has been growing remarkably as a result of population growth and lifestyle changes (IEA, 2012, Joyce Dargay, 2007, Bandivadekar et al., 2008). This has resulted in increasing material demand, scrap availability, and direct (use phase) and indirect emissions (production phases). The definitions for direct and indirect emissions are used differently in this study from the IPCC definition. We include material production emissions in addition to fuel production emissions for the indirect emissions.
- There is a strong correlation between car weight and fuel consumption. Car weight has risen in recent decades mainly as a result of the increased use of safety and comfort features. Finding a balance between weight reduction, safety and comfort is a challenge that can be resolved with light-weighting strategies, including material substitution, vehicle redesign, or a shift to smaller cars (Cheah, 2010, Kim et al., 2010a, Bandivadekar et al., 2008). All light-weighting strategies have an impact on material use and thus on end-of-life management.
- One of the largest and fastest growing reservoirs of aluminum in use resides in automobiles (EAA 2008). Aluminum use in new passenger cars has grown fivefold in the last three decades (Ducker 2009). The main penetration occurred with castings (used in engines, among other parts), whereas the major future growth potential is expected in wrought aluminum, used mainly in components for the body-in-white (BIW). This has significant implications for the recovery of aluminums in end-of-life vehicle management (and the recycling of aluminum in the automotive industry) because automobile cast aluminum is currently the only relevant sink for aluminum scrap from the automotive sector or other sectors.
- Steel is currently the most widely used material within the automotive industry. Due to the need for light-weighting strategies, high-strength steel (HSS) and

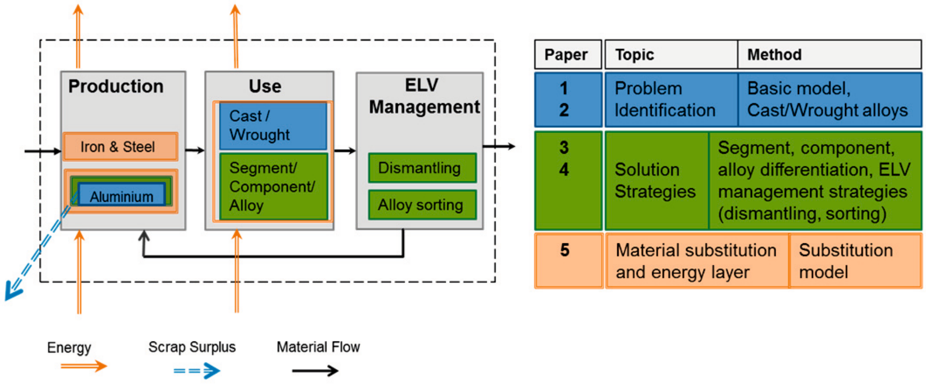
other light-materials, such as aluminum, started to be substituted for conventional steel in the last few decades.

- Efficient ELV management is becoming essential due to the increasing number of ELVs and the high market value for scrap from the vehicles. Although most national and regional legislation set specific goals to reach a certain overall recycling rate, goals for the quality of the recovered materials, for example, the purity of different alloys and the recovery of critical metals, which are used in small amounts, are largely ignored. In the case of aluminum, different alloy types are often recovered as one mixed aluminum scrap fraction. Due to refining difficulties, the aluminum scrap is blended and recycled to alloys that can accept a higher amount of alloying elements. This alloy cascade can potentially limit the use of this mixed scrap in the future.

This thesis tests the following hypothesis: a continuation of the current aluminum recycling practice will eventually lead to the formation of large amounts of highly alloyed material, which may no longer find an application in the automotive market. Such a resource loss would have implications for energy use because the surplus scrap could not be used to replace aluminum from primary production, resulting in an unusable energy savings potential. Suitable policy options must be identified to avoid or delay the scrap surplus problem.

In this thesis, the following questions are addressed: 1) How are the dynamics of the global vehicle stock changing the boundary conditions for aluminum recycling? 2) What are the most effective interventions to minimize a future aluminum scrap surplus? 3) What material substitution options for vehicles exist to reduce direct and indirect GHG emissions over time?

Five papers have been developed to answer the proposed research questions. These papers constitute the core of this thesis which is shown in Figure 3.



Paper	Topic	Method
1 2	Problem Identification	Basic model, Cast/Wrought alloys
3 4	Solution Strategies	Segment, component, alloy differentiation, ELV management strategies (dismantling, sorting)
5	Material substitution and energy layer	Substitution model

Figure 3 Structure of the thesis and organization of the appended papers

In the introduction section, trends in private transportation, material use, and ELV management are described in chapters *1.2* to *1.4*. These trends provide a basis for an elaboration of potential challenges and solutions for aluminum recycling (chapter *1.5*), as well as the motivation and research questions (chapter *1.6*).

1.2 Trends in private transportation

1.2.1 Global vehicle stock growth due to population and car ownership growth

Worldwide transportation studies confirm that the vehicle stock has been increasing over time due to population growth and lifestyle changes (IEA, 2010, Bandivadekar et al., 2008, Joyce Dargay, 2007, IEA, 2012). According to the IPCC fourth assessment report (IPCC, 2007), the world auto fleet has grown with remarkable speed – between 1950 and 2000, the number of vehicles increased from approximately 50 million vehicles to 600 million vehicles, an increase that is five times higher than the growth in population over the same period. This fact can also be observed in Figures 4-6.

It is expected that the global vehicle fleet will surpass 2 billion units by 2030 (Joyce Dargay, 2007, IEA, 2012). Dargay (2007) projected the global vehicle fleet based on pooled time-series data from 1960-2002 and cross section data for 45 of the most populated countries, assuming different saturation levels for the studied countries by accounting for the proportion of the urban population and population density, economic development and per capita income. The result of the study shows that the percentage of the world's vehicles owned in non-OECD countries was 24% in 2002 and is expected to increase to 56% by 2030. In particular, China's vehicle stock is expected to increase by a factor of 20 in the period from 2002 to 2030 (Joyce Dargay, 2007).

This remarkable growth in vehicle stock has significant implications for material demand, scrap availability, and direct and indirect emissions, as well as scrap to be handled by the ELV management system.

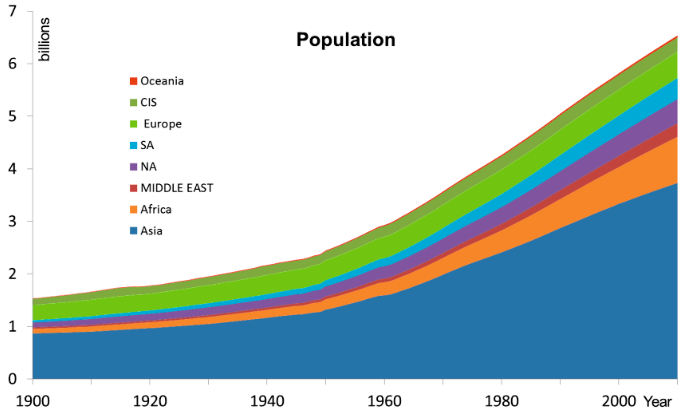


Figure 4 Population in different world regions. (UN, 2003, UN, 2010).

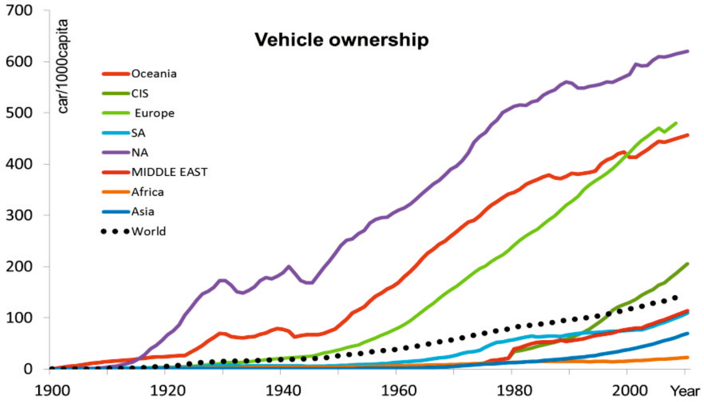


Figure 5 Passenger car ownership in different world regions (TheWorldBank, 2013, Joyce Dargay, 2007, Mitchell, 2007b, Mitchell, 2007c, Mitchell, 2007d, Mitchell, 2007a).

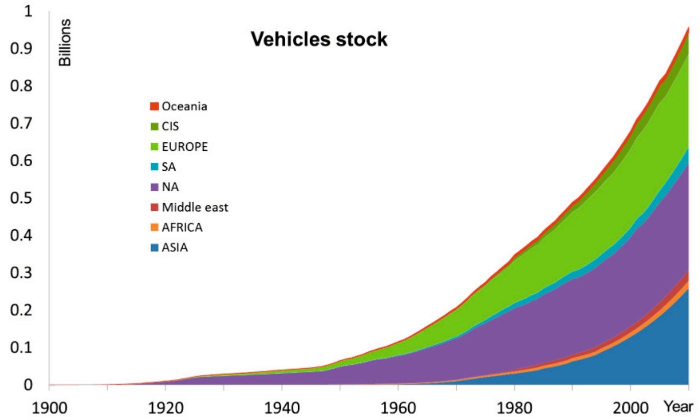


Figure 6 Passenger car stock in different world regions (calculated from data shown in Figures 4 and 5).

1.2.2 Segments

Although trends in some developed countries, such as those in North America, exhibit a tendency toward larger cars (Cheah, 2010), global vehicle production has a tendency toward smaller car segments in recent years (see Figure 7). This may be explained by the use of smaller cars in developing countries and emerging economies, such as India and China.

There are several different methods of car classification around the world. Generally, the boundaries between car segments are defined by factors, such as size and weight. The most common classification, according to European Commission regulation (EEC) No 4064/89, is: A-segment (mini cars, such as Ford Ka, Smart), B-segment (small cars, such as Ford Fiesta), C-segment (medium cars, such as Ford Focus, Honda Civic), D-segment (large cars, such as Audi A4, BMW 3 series), E-segment (executive cars, such as Ford Taurus) and F-segment (full-frame and luxury cars, such as Audi A8, BMW 7 series). Sport coupes, multi-purpose, and sport utility (including off-roads), which are categorized as S, M, and J-segments, respectively, do not have a significant global market share and are thus not considered in Figure 7.

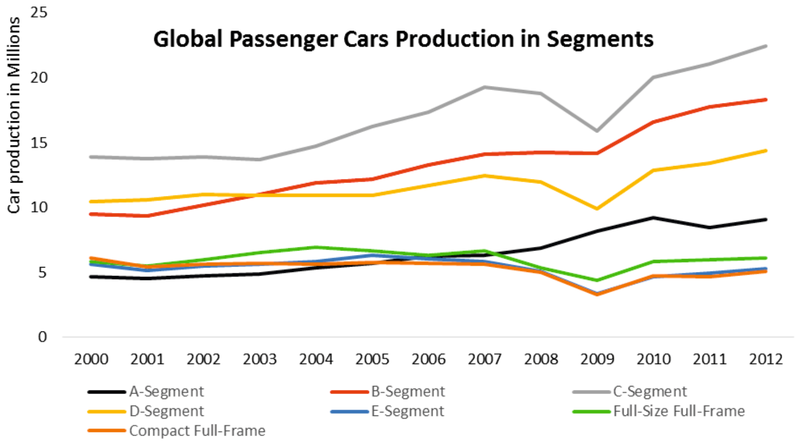


Figure 7 Global passenger car production with segments details (IHS, 2010).

1.2.3 GHG emissions

Human activities are tightly linked to material production and consumption. The transport sector contributes significantly to global energy-related anthropogenic carbon emissions, and passenger cars account for approximately 14% of total energy-related global anthropogenic carbon emissions (OICA, Allwood and Cullen, 2012, Sims R., 2014, IPCC, 2014b).

Figure 8 shows the key contributors to global anthropogenic CO_2 emissions arising from energy production and industrial processes. In addition to direct emissions from the use phase, passenger cars also contribute to initial emissions from the upstream production of materials. The pie chart shown on the right in Figure 8 shows the contribution of the industrial carbon emissions, which include 36% of total global human-made carbon emissions. This pie chart shows the contributions from the production of different materials in global industrial activities. Steel and aluminum contribute 25% and 3%, respectively, to industrial carbon emissions, representing 9% and 1% of global anthropogenic carbon emissions.

Various materials are used in car production; inter alia, steel and aluminum play a significant role in car production and global material GHG emissions. Material selection and specifications for vehicles are complex processes governed by a broad set of requirements, including functional performance and physical/chemical properties, structural integrity, safety, durability, aesthetics, material and fabrication costs, and recyclability (Keoleian and Sullivan, 2012).

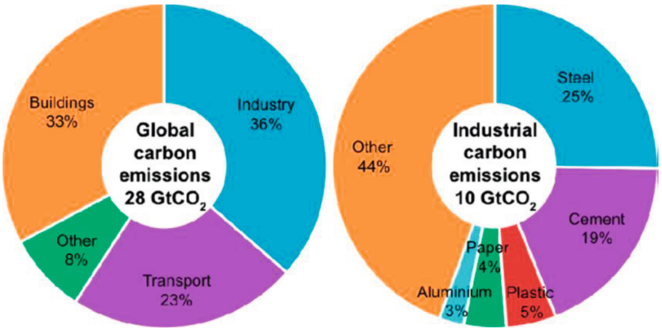


Figure 8 Global anthropogenic CO_2 emissions related to energy and industrial processes for the year 2006 (Allwood and Cullen, 2012).

1.2.4 Correlation between vehicle weight and fuel consumption

There is a strong correlation between car weight and fuel consumption. A 10% reduction in car weight typically reduces the fuel consumption by approximately 3-7% (Allwood and Cullen, 2012, Cheah, 2010, Bandivadekar et al., 2008, Martin Johannaber, 2007, Kim and Wallington, 2013). The first oil crisis in the early 1970s and the adaptation of fuel economy standards in North America made the automotive industry adopt light weighting measures to improve fuel economy (Horvath, 2010). The average weight of North American vehicles declined by approximately 20% in the period from 1976 to 1986 (Ducker, 2011b). However, vehicles have become heavier since then (Figure 9), largely due to added safety and comfort equipment as well as customer demand for larger cars (EAA, 2006, EAA, 2012, Pinto, 2009). To reach the desired performance level, the weight of components, such as the engine, transmission, and brakes, had to be increased accordingly (EAA, 2012). This phenomenon is known as the 'weight spiral.' Today, one of the most demanding dilemmas for the automotive industry is to reduce overall vehicle weight while providing high levels of safety and comfort (EAA, 2012).

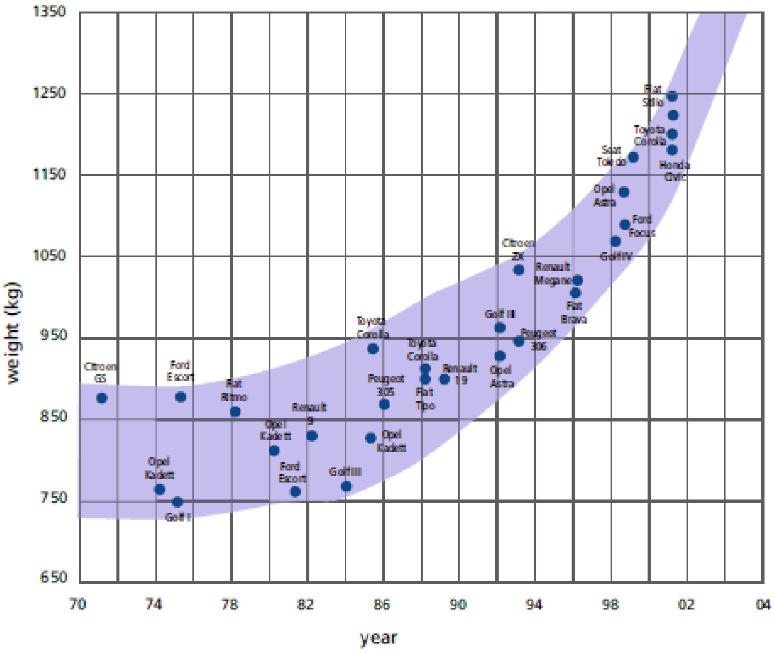


Figure 9 Evolution of weight in the compact class during the period 1970-2004 (EAA, 2006).

New regulations for direct emission reductions appear to be a strong incentive for extra light-weighting efforts among car manufacturers. EU regulations, for example, set emission targets for the average fleet of new cars entering the market to 130 grams of CO_2-eq. per kilometer beginning in 2015 (ICCT, 2014), and the US Corporate Average Fuel Economy (CAFÉ) regulation set a target of 102-133 grams of CO2-eq. per kilometer for the average fleet from 2025 (An et al., 2011).

To invert the weight spiral, a reduction in vehicle mass is essential, in addition to other technological developments for fuel efficiency. A reduction in vehicle weight can be achieved by different strategies that may be combined, including (1) material substitution, (2) vehicle redesign, and (3) vehicle downsizing (Cheah, 2010). Material substitution strategies involve the use of light-weight materials that can fulfill several criteria, such as economic viability, weight saving potential, and environmental and safety factors (Ghassemieh, 2011, Allen et al., 2007), in addition to physical properties, such as strength, stiffness and formability (Cheah, 2010, Kim and Wallington, 2013).

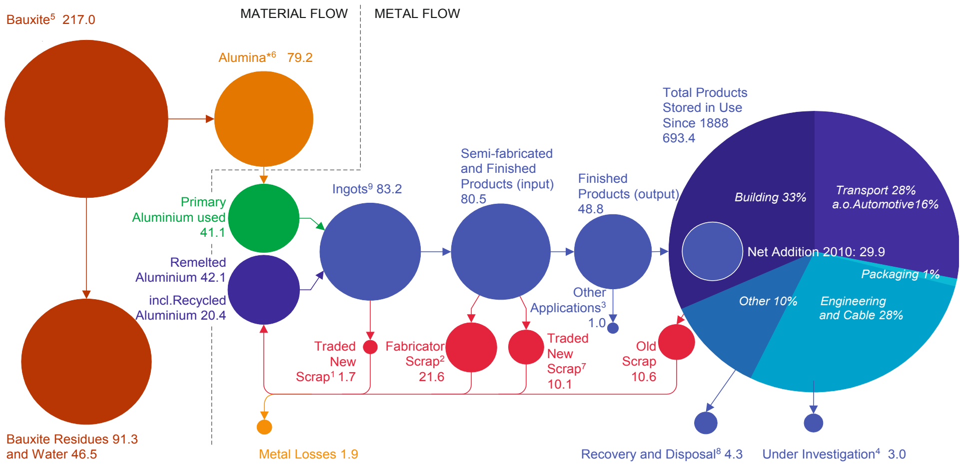
Because aluminum and high-strength steel (HSS) are the most cost-effective candidates for light-weighting in large-scale production, their use in car manufacturing is expected to increase in the future (Kim et al., 2010a, Ghassemieh, 2011, Cheah, 2010, Bandivadekar et al., 2008, Allwood and Cullen, 2012).

1.3 Trends in material use

1.3.1 Aluminum

Although it is the most abundant metal in the earth's crust (approximately 8% by weight), aluminum was identified as a metal only in 1808, and the first commercial aluminum production process, developed by Henri Sainte-Claire Deville, started in 1855 (Totten and MacKenzie, 2003). Today, aluminum is the second most used metal after iron and steel, and similar to steel, aluminum is often used in alloyed form to augment performance. Global aluminum primary production increased from 5 to 35 million tons per year between 1960 and 2005 (IAI, 2009). Figure 10 shows the global aluminum mass flow model (GARC, 2011) from bauxite extraction to the end-of-life for the year 2010.

The main raw material for aluminum production is bauxite, which is extracted from bauxite mines, then processed to alumina, which is used for aluminum production in an electrolytic process. The abundance of bauxite is relatively limited. Aluminum production results in large amounts of red mud, which needs special handling due to residual alkaline content. Currently, red mud is typically deposited near mining sites in sealed ponds from which excess water is returned to the bauxite mining process (EAA, 2008).



Values in millions of metric tonnes. Values might not add up due to rounding. *Change in stocks not shown
1 Aluminium in skimmings; 2 Scrap generated by foundries, rolling mills and extruders. Most is internal scrap and not taken into account in statistics; 3 Such as deoxidation aluminium (metal property is lost) 4 Area of current research to identify final aluminium destination (reuse, recycling, recovery or disposal); 5 Calculated based on IAI LCI report - update 2005. Includes, depending on the ore, between 30% and 50% alumina; 6 Calculated. Includes on a global average 52% aluminium; 7 Scrap generated during the production of finished products from semis; 8 Either incinerated with/without energy recovery, material recovery or disposal; 9 Estimated stock increase 980,000 tonnes.

Figure 10 Global aluminum mass flow model. The model was developed by IAI's Global Aluminium Recycling Committee (GARC) (GARC, 2011)**.**

Another concern regarding the primary production of aluminum is greenhouse gas (GHG) emissions and energy use. Overall, the production of primary aluminum accounts for 1% of world GHG emissions (Allwood and Cullen, 2012, McMillan et al., 2012). GHG emissions occur in all production stages, from bauxite mining to aluminum production, as shown in Figure 11 (Liu et al., 2013a). The figure shows that smelting and other primary-production-related processes (mining, refining and producing anodes for smelting) together are responsible for over 90% of total aluminum production emissions.

Between 1990 and 2005, the global average intensity of electricity consumed by primary aluminum smelters decreased from 16.5 to 15.6 kWh/kg (McMillan and Keoleian, 2009). Modern primary aluminum production facilities consume 13-14.1 kWh/kg of aluminum, which is approximately double the thermodynamic limit of 6.3 kWh/kg (IAI, 2009). Therefore, further improvements will become increasingly difficult to achieve.

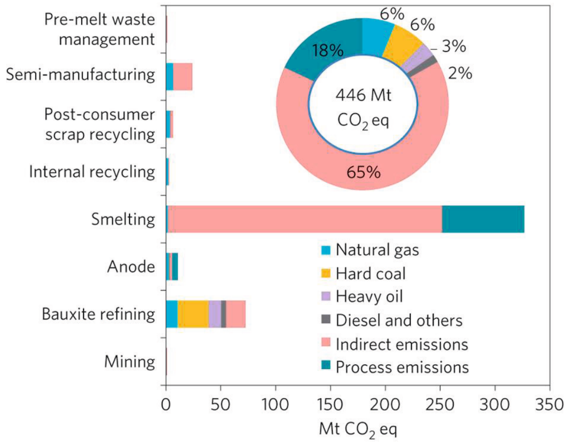


Figure 11 GHG emissions in all production stages of the global aluminum cycle in 2009 (Liu et al., 2013a).

In contrast, aluminum production from scrap requires approximately 20 times less energy (IAI, 2009). Aluminum, once produced, embodies large amounts of energy that can be saved if the end-of-life scrap is recovered for recycling. For this reason, aluminum in use can be regarded as an energy bank. Figure 12 shows that the ratio of secondary aluminum production from all types of scrap, including manufacturing and post-consumer scrap, grew from 17% in 1960 to 33% in 2006, and is expected to reach 40% by 2040 (IAI, 2009).

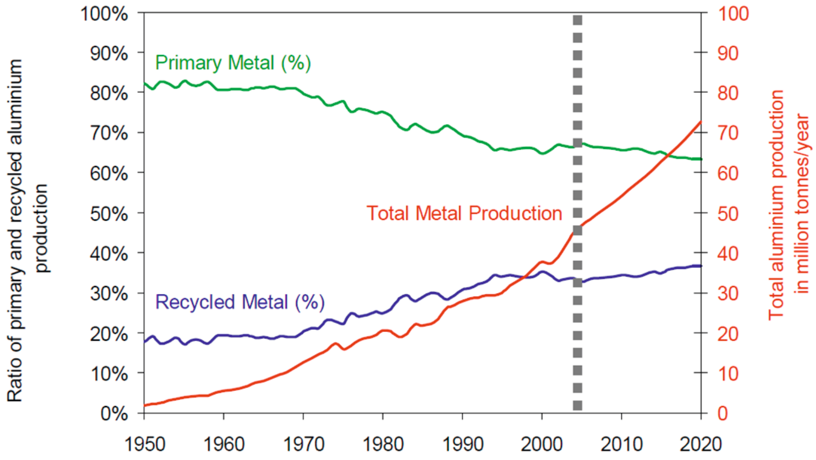


Figure 12 Share of recycled and primary aluminum (IAI, 2009).

The anthropogenic aluminum cycle has been quantified and analyzed using mass balances or quasi-stationary and dynamic MFA models. Chen and Graedel (2012) provide a review of anthropogenic element cycles with 26 different MFA studies of aluminum across a range of geographical scales and lifecycle stages (Chen and Graedel, 2012).

Mass balances and quasi-stationary MFA models were used to characterize the aluminum cycle for a single year or selected years on a country level, inter alia, Italy (Amicarelli et al., 2004), the US (Plunkert, 2006), and China (Chen et al., 2010). Dynamic MFA models of the aluminum cycle in individual countries were introduced for Germany by Bever (1976) and later refined by Melo (1999), and for the US by Hatayama et al. (2009), Chen and Graedel (2012), Liu et al. (2011), and McMillan et al.(2010). The aforementioned studies considered historical consumption data and product lifetimes to calculate scrap generation. A study by Boin and Bertram (2005), conducted at the EU level, traced aluminum scrap flows coming from six sectors of building, transportation, beverage, foil, engineering and consumer durables.

The study of aluminum through MFA was further expanded to the global scale by the Global Aluminium Recycling Committee (GARC) (Bertram et al., 2009b, Martchek, 2006). Figure 10 shows the global aluminum mass flow model – GARC for the year 2010 (GARC, 2011).

Cullen and Allwood (2013) mapped the global flow of aluminum from liquid aluminum to end-use goods and illustrated the results in a Sankey diagram for the year 2007. The main focus of the study was to understand the material efficiency of the industry and recycling of post-consumer scrap by providing a detailed analysis of aluminum scrap flows and considering dilution with primary materials to reach the required quality. Predictions of global aluminum demand are typically calculated based on extrapolations of market growth assumptions (Rombach, 2002, Schwarz et al., 2001) or economic indicators, such as price or per-capita GDP (Luo and Soria, 2008, Menzie et al., 2010).

Liu et al. developed a dynamic material flow analysis model to simulate the future global aluminum cycle and emissions pathways and mitigation potentials (Figure 13). The model enables an integrated analysis of the material, energy and emissions nexus. It considers i) system feedbacks, which mean the scrap availability influences primary production, and ii) time lags, which mean the accumulation and replacement of in-use stocks is calculated based on the mass balance principle. Liu et al. calculated historic aluminum in-use stocks based on production, trade data, and product lifetime assumptions, and future aluminum based on the scenarios measured by the stock-driven model (Liu et al., 2013a). According to the study, the global aluminum in-use stock has reached approximately 90 kg per capita in 2009, with a range of 10-60 kg per capita for developing countries and 200-600 kg per capita for developed countries.

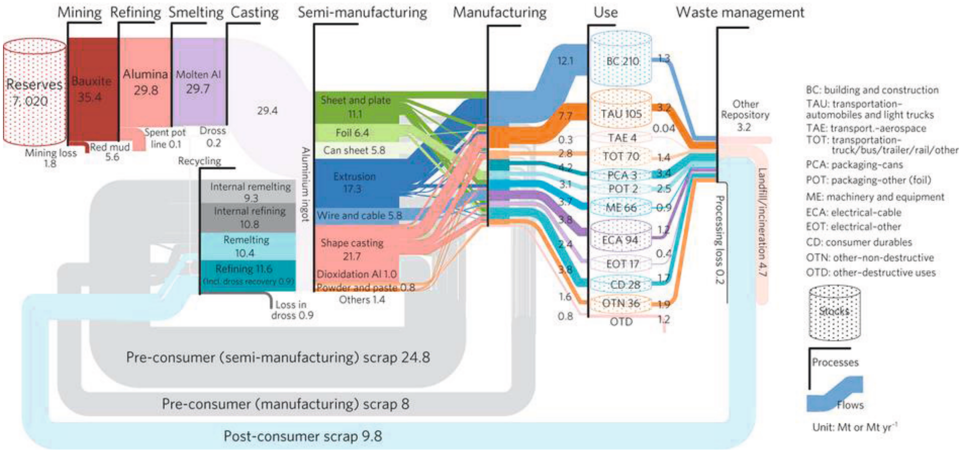


Figure 13 Global anthropogenic metallurgical aluminum cycle in 2009 (Liu et al., 2013a). The flows' widths are proportional to their magnitude. Building and construction (210 Mt), transportation (180 Mt, TAU, TAE, and TOT together) and electrical engineering (110 Mt, sum of ECA and EOT) constitute the largest components of the global aluminum in-use stock (636 Mt).

1.3.2 Steel

The global annual demand for steel is ca.1.4 billion tons (Gt) per year (Menzie et al., 2013). This high material demand is driven by the need to create and maintain the stock of steel products mainly used in construction, vehicles, industrial equipment, and metal products, such as packaging and appliances (Cullen et al., 2012). Steel production accounts for 25% of industrial carbon emissions and 9% of global anthropogenic energy- and process-related greenhouse gas emissions; therefore, climate change mitigation may represent a major constraint to future production growth (Allwood and Cullen, 2012). To develop roadmaps for emission reductions, information on trends in steel use, steel demand, and scrap availability is required. Figure 13 (Cullen et al., 2012) shows the global steel flow in 2008 from steelmaking, from intermediate products to end-use goods, and the complex interactions of the steel supply chain.

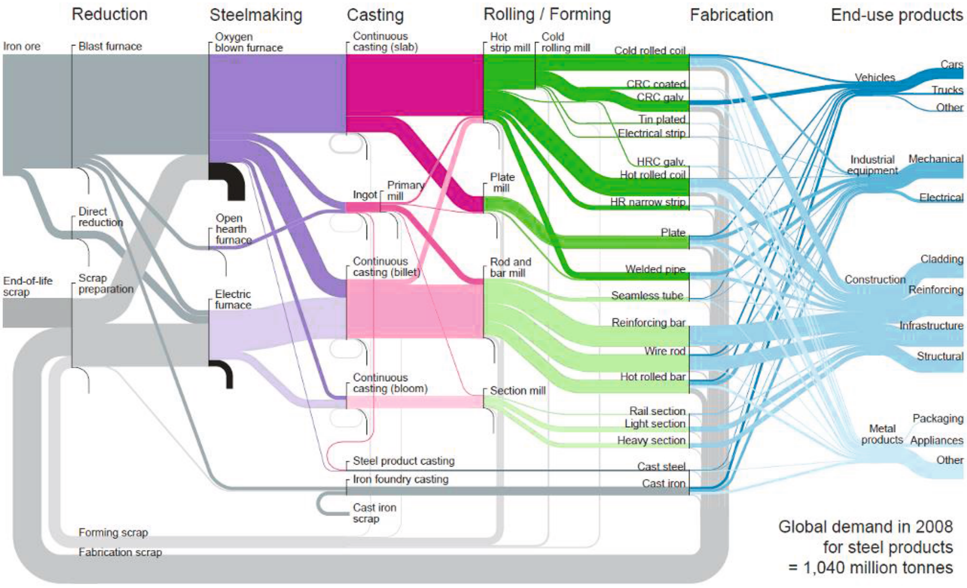


Figure 14 Global flow of steel from liquid metal to end-use good (Cullen et al., 2012).

Quality concerns for secondary production are mainly relevant for sectors that depend on high-quality steel, such as vehicles (Pauliuk et al., 2013a, Nakamura et al., 2012). The mentioned quality challenge is mainly due to tramp elements, such as copper and tin, which accumulate in the recycled material (Pauliuk et al., 2013a, Ohno et al., 2014). Figure 14 shows that most of the steel scrap ends in the construction sector, whereas vehicles are mainly recipients of primary steel due to the low tolerance of tramp elements for steel components. In addition, end-of-life vehicles are one of the major sources of copper contamination for iron and steel scrap (Nakamura et al., 2012, Igarashi et al., 2007, Ohno et al., 2014).

Primary steel is one of the most widely used materials within the automotive industry (Ducker, 2011b). Since the first car generations, mild steels, or as they are more accurately referred to, low-carbon steels, were dominantly used due to favorable properties, such as strength, formability, cost and design flexibility. However, the first oil crisis in the early 1970s and the adaptation of fuel economy standards in North America made the industry begin to seriously look toward light-weighting options and the substitution of higher-strength steels to improve fuel economy (Horvath, 2010). Car models in 1975 contained 56% (mild) steel, 4% medium- and high-strength steels (HSLA), 2% other steels and 15% cast iron. In 2007, mild steel contributed 43%, medium- and high-strength steel together with advanced high-strength steel (AHSS) 12%, other steel 2% and cast iron 7% (Ducker, 2011b). The same study predicts that North American light vehicles in 2015 will contain 34% mild steel, 10% AHSS and 8% HSLA, 2% other steel and 6% cast iron (Schultz, 2009, Ducker, 2011b). Figure 15 shows North American light vehicle iron and steel content in kg per vehicle for snapshots of 1975, 2007, and 2015.

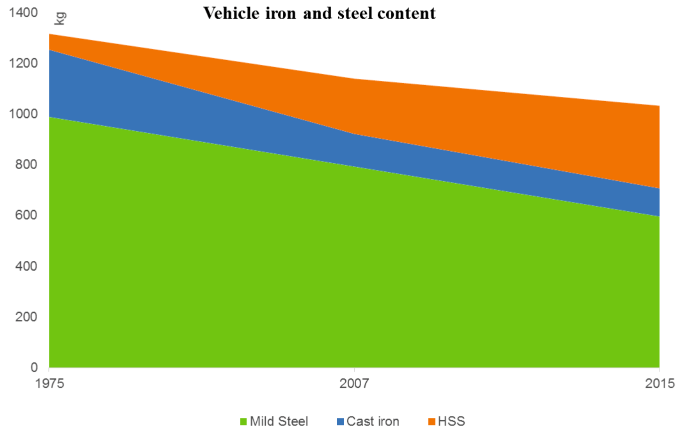


Figure 15 North American trends of light vehicle iron and steel content from 1975 to 2015 according to (Schultz, 2009).

1.4 Trends in ELV management

1.4.1 Current practices

Waste management is an important topic in environmental issues and, among all, the vehicle sector generates approximately 5% of the world's industrial waste (Simic, 2013). The recent decade's substantial growth in car ownership globally will lead to significant growth in the number of deregistered cars and ELV flows. Although the management of ELVs is required in every country, it is notably important that large countries and regions with high growth rates in their markets, such as China and India, are able to address future ELV challenges and complexities (Sakai et al., 2014).

The handling of ELVs is similar in most countries regardless of the legislative management system (Sakai et al., 2014). The process of ELV recycling generally starts with i) depollution, where hazardous substances, such as lead batteries, mechanical oils and refrigerant gases, are collected; ii) recovery of recyclables and materials suitable for secondary use, including dismantling of engines, tires, and bumpers; iii) remaining car hulks are shredded; iv) the shredded materials are sent to an air classifier, where the light automotive shredding residue (ASR), or so-called fluff, is removed from the remaining fraction; v) ferrous material, mainly metals, are removed by magnetic and eddy current separation (Sakai et al., 2014, Zorpas and Inglezakis, 2012, Gaustad et al., 2012); and vi) sink float or heavy media separation is used to separate non-ferrous materials with different densities; typically Mg, Cu, Zn, and Pb, can be sorted out from aluminum in this step (Gaustad et al., 2012). Color sorting appears to be an effective way to sort shredded ELVs (Gaustad et al., 2012). Zinc, copper, brass, and stainless steel can be separated from aluminum in a non-ferrous scrap stream. Hand sorting is a prevalent practice in countries with low labor costs, such as India and China. It is estimated that hand sorting of aluminum automotive shred can achieve 99% accuracy (Gaustad et al., 2012). In addition, wrought and cast aluminum fractions can be sorted by hand due to distinctive surface characteristics (Gaustad et al., 2012, Rao, 2006). Color sorting can also be achieved by automated processes by analyzing images of each scrap piece and directing the pieces to different feeds. To further separate non-ferrous metallic fractions, chemical etching is used in combination with color sorting. However, this method requires using chemicals that may have additional environmental impacts; furthermore, the automated process is not yet cost efficient (Gaustad et al., 2012). There are other spectroscopy techniques that are used for the identification and sorting of shredded scrap; in particular, laser induced breakdown spectroscopy (LIBS) has shown great promise for sorting wrought and cast aluminum (Gesing, 2004, Cui and Roven, 2010, Gesing, 2006). However, this technology is still too expensive to compete in the market and also requires that the scrap be free of lubricant, paint, other coatings, and oxide formation.

1.4.2 Legislation

ELV management is becoming more important due to the increasing number of vehicles reaching the end-of-life and the increasing complexity of materials. A recent comparative study of end-of-life vehicle recycling system declared that legislative ELV recycling systems are established in the EU, Japan, Korea, and China, whereas in the US, ELV recycling is managed under existing laws on environmental protection (Sakai et al., 2014).

In the EU, the EU-directive 2000/53/EC on ELVs was enacted in 2000. The initiative for the EU-directive started in 1989, the year in which the European Commission set up a program of actions on ‘priority waste streams,’ including ELVs (Smink, 2007). In 1991, a European ELV-project group was established with representatives from different stakeholders that were identified in the process. The effort resulted in a set of key documents, such as a legislative proposal that focused on the synchronization of ELV legislation, among different national schemes for addressing ELVs. Later, the European Parliament called on the European Commission to legislate on waste streams, in particular ELVs, based on producer responsibility. These efforts lead to a proposal for a Directive on ELVs (COM (97) 358), which later resulted in the EU-Directive 2000/53/EC (Smink, 2007, European-Commission, 2000). The directive will ensure that all Member States have uniform legislation on the re-use and recycling of cars at the end of their useful life. The EU-Directive 2000/53/EC (European-Commission, 2000) set a target for the reuse and recycling rate of ELVs in the Member States, and states: i) by 01/01/2006, the reuse and recovery rate should reach 85% on a mass basis (recycling 80%) for vehicles produced after 1980 and ii) by 01/01/2015, the reuse and recovery rate should reach 95% on a mass basis (recycling 85%). According to Zorpas and Inglezakis (2012), currently approximately 75% of ELV total weight is recycled, whereas the remaining 25% is ASRs. Therefore, the automotive industry may face a challenge in meeting EU 2015 environmental standards.

In Japan, the law for the recycling of ELVs was enforced in 2005. The act emphasized the specific components to be recycled, and the target is to recycle 80% of airbags and 85% of ASRs by 2015. Recycling fees are paid by buyers at the time of purchase, and these fees are deposited into the deposit management system (Sakai et al., 2014).

In Korea, the act for ‘Resource Recycling of Electrical and Electronic Equipment and Vehicles’ was enforced in 2008. Under the current act, the responsibility for ELV recycling is placed on all stakeholders, including manufacturers, importers, dismantlers, shredders, ASR recyclers, and refrigerant gas processors. The material recycling and energy recovery target is set at a minimum of 85% by 2014, including energy recovery of less than 5%, and at least 95% after 2015, including energy recovery of less than 10% (Sakai et al., 2014).

In China, recycling rates are to reach approximately 85% (or at least 80%) material recycling by 2010, approximately 90% (or at least 80%) by 2012 and approximately 95% (or at least 85%) by 2017 (Sakai et al., 2014).

In the US, ELV recycling has been promoted by the Automotive Recyclers Association. The rate of material recycling was reported to reach 80% (Kumar and Sutherland, 2009, Sakai et al., 2014).

In most European countries, 80% of the ELV total weight is recycled, and the remaining 20%, which is automotive shredder residue (ASR), is currently disposed in landfills. Therefore, reaching the required target of the EU directive requires a considerable increase in ASR recycling, which can be challenging using current practices (Zorpas and Inglezakis, 2012). Reuter et al. stated that by minimum dismantling, and advanced post-shredding technologies, recycling quotas of approximately 85% are difficult to achieve (Reuter et al., 2006).

All of the reviewed ELV management legislation around the world failed to consider quality aspects. They only set targets for recycling quotas but, for instance, alloy separation is not considered, which can have negative effects on the recycling of those metals with limited refining options, such as aluminum (see chapter *1.5.2*). Even a small amount of unrecyclable ELV scrap could pose a challenge to the fulfillment of the EU-wide ELV Directive.

It is likely that the degree of scrap contamination will increase in the future due to the increased use of more complex appliances for safety and comfort purposes (Igarashi et al., 2007) or due to the fate of material quality over time and across products in open-loop recycling systems (Nakamura et al., 2014, Nakamura et al., 2012).

1.5 Challenges for aluminum recycling

1.5.1 Current challenges: insufficient scrap

Models of the global aluminum cycle show that aluminum recycling is still highly constrained by the amount of post-consumer scrap (GARC, 2011, Rombach et al., 2012, Liu et al., 2013a). In 2010, approximately 48 MMt of aluminum entered the use phase while 11 MMt of post-consumer scrap was collected for recycling, whereas approximately 30 MMt of aluminum products were added to the global aluminum stock in 2010 (GARC, 2011, Liu et al., 2013b). Excluding packaging applications, aluminum is used mainly in sectors with long lifetimes, such as buildings, transportation and engineering. Accumulated primary aluminum production in the period from 1950-2010 was approximately 900 MMt, of which 700 MMt is still in the use phase (Rombach et al., 2012, Liu et al., 2013b).

Today, the utility of aluminum is maintained through blending of mixed scrap with other types of scrap and primary metal. As noted above, there are no signs of a flattening of aluminum stocks; however, once the fast stock growth declines and more of the already produced aluminum reaches the end-of-life, there will be a large potential for recycling and reducing raw material use. Nevertheless, as the share of post-consumer scrap rises, aluminum recycling is likely to face new challenges related to alloying elements and impurities in the scrap.

1.5.2 Future challenge: use all scrap and maintain quality

The second challenge aside from the increasing number of ELVs and consequent complexities in end-of-life management is contamination by alloying elements and refining difficulties in aluminum recycling (Nakajima et al., 2010, Van Schaik et al., 2004). Figure 16 is borrowed from a study of thermodynamic analysis of contamination by alloying elements in some base metals, such as Fe, Cu, Zn & Pb, Pb, and Al, recycling (Nakajima et al., 2010). This radar chart is an extended work on the concept of 'metal wheel,' which was introduced by Verhoef et al. (2004) and demonstrates the importance of understanding metal linkages in natural resource processing. It is specifically relevant for recycling possibilities of metals based on the thermodynamic behavior of alloying elements in the metal, slag, and gas phases of the base metals. The smaller grey circles denote typical additive elements. In the case of aluminum, the figure indicates that Mg, Ca, and Ba can be removed by oxidization (transferred to slag) and that Zn, Cd, and Hg can be removed by evaporation. The removal of the other 39 elements is extremely difficult, as they tend to remain in the metal phase. In comparison with other metals, the removal of alloying elements is far more difficult for aluminum than for iron, copper, zinc, and lead (Nakajima et al., 2009). The difficulty of designing material specifications in the refining and recycling process narrows possibilities to use aluminum in recycling.

Cu, Fe, Mn, Si, and Zn are the most common alloying elements of aluminum (Nakajima et al., 2010). Casting alloys generally contain more alloying elements than wrought alloys and can therefore be produced from mixed scrap (McMillan et al., 2012), although they may require blending with other types of scrap or primary aluminum to reach the required concentration of alloying elements. Conversely, most wrought alloys contain fewer alloying elements in lower concentrations and therefore have a low tolerance for accepting alloying elements and impurities from mixed scrap (McMillan et al., 2012).

Consequently, if the scrap mixture is not sorted before melting, recycling depends on growing casting stock to absorb scrap.

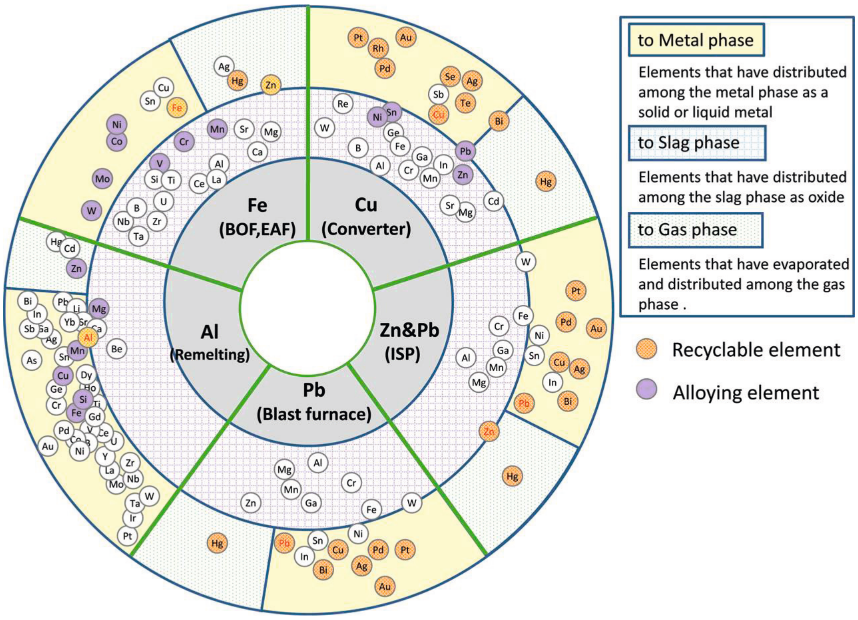


Figure 16 Element radar chart for the metallurgical process of base metals (Nakajima et al., 2010).

1.5.3 *Role of vehicles in the global aluminum cycle*

The study of aluminum recycling in the automobile industry has gained attention because passenger cars form a quality bottleneck in aluminum recycling. Passenger cars embody most of the secondary castings, which are in turn the major recipients of recycled aluminum from all other sectors (Gesing, 2004, Furrer, 2010, Hatayama et al., 2007, Modaresi and Müller, 2012, Hatayama et al., 2012).

Aluminum use in passenger cars has been growing from 32 kg in 1978 to 149 kg in 2009 and approximately 156 kg in 2012 for average passenger cars (Ducker, 2009). Recent studies showed that one of the largest and fastest growing reservoirs of aluminum in-use resides in automobiles (IAI, 2006, EAA, 2008, Liu et al., 2013a). Today, the transportation market accounts for nearly 43% of the metal used in Japan and 35% of North American and West European aluminum shipments, whereas 40 years ago, transportation was responsible for only approximately 20% of the total consumption in the major car manufacturing countries of United States, Japan and Germany (Nappi, 2013).

Today, most of the aluminum is used in the powertrain, with 80-85% of cast parts that typically contain high alloying contents that can be produced from post-consumer or new scrap (European Aluminium Association, 2011, Furrer, 2010, Gesing, 2004).

It is generally expected that the largest growth potential for aluminum use in passenger cars is in wrought aluminum alloys and in components such as BIW, closures, bumpers and crash boxes, and suspension frames (Ducker, 2009, Ducker, 2011a, Ducker, 2012a, Hirsch, 2004, Gesing, 2004, Ducker, 2012b).

Figure 17 shows the common recycling paths (due to quantity and quality reasons) of aluminum scrap from different end-use sectors in a simplified manner. This current practice of cascadic use depends on the continuous and fast growth of the passenger car stock; otherwise, there will be a scrap surplus that cannot be absorbed by the automotive industry, if closed loop recycling into new vehicles is assumed. Consequently, the development of the global vehicle stock – in terms of size and composition – is crucial to the future demand of primary and secondary aluminum as well as the future supply of scrap from retiring vehicles. It is crucial to know the timing and amount of the future scrap surplus.

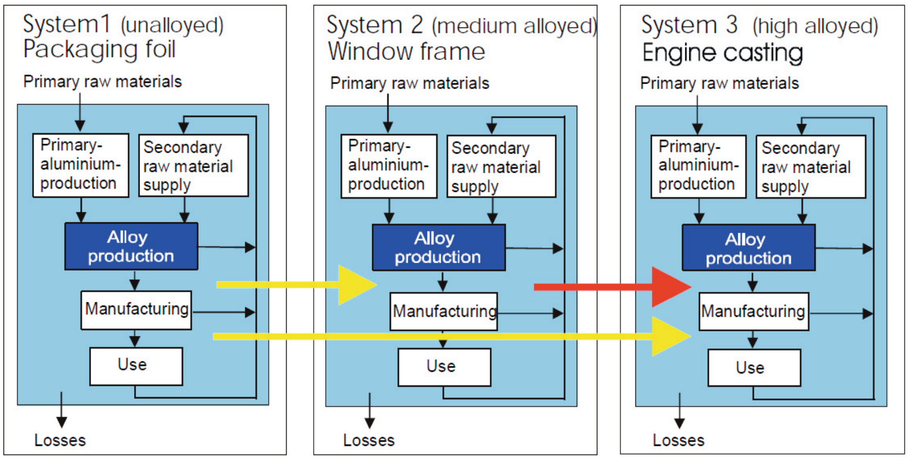


Figure 17 Interaction in open-loop aluminum recycling systems (Rombach, 2001).

1.6 Motivation for the development of global stock dynamics models

The future scrap surplus problem was already discussed over a decade ago. Zapp et al., (2002) analyzed the long-term supply of aluminum to the European automotive industry and compared future casting demand with scrap amounts from different sources, using historic production data and assumptions of future car market developments and use of aluminum in cars. This study estimated casting demand and scrap supply independently using trend analysis, thereby ignoring their connection through the dynamics of the vehicle stock. They found that old scrap availability would eventually exceed casting demand in 2040. Gesing (2004) conducted a study at the global scale that simulated the mass balance in the vehicle system based on historic data on global aluminum consumption in vehicles and global aluminum recycling from vehicles and other sectors. The study, which was only based on historic trends without any scenario development, concluded that there would be a scrap surplus that could not be absorbed by cast alloys production, which would be unsuitable for wrought alloys due to the high alloying elements concentration. However, the study was not able to predict the timing and extent of the future scrap surplus. These two studies were only based on studies of flows and therefore are unable to study the stock development and to analyze vehicle and aluminum stock dynamics. Therefore, such models are unable to calculate the expected scrap from end-of-life.

In-use stocks provide services to society. For instance, vehicle stocks provide mobility. Consequently, material stocks in vehicles provide services to society throughout the vehicle lifetime. A traditional view on materials is based on a production-driven approach (van der Voet et al., 2002, Brattebø et al., 2009, Baccini and Brunner, 1991, Krausmann et al., 2009), in which a stock is calculated as a function of production and lifetime, but this method is insufficient to predict the future stock. In contrast, the stock-driven approach includes parameters (population, service per capita, and lifetime) that determine the stocks, whereas the flows are derived from the stock development (Müller, 2006, Bergsdal et al., 2007, Pauliuk et al., 2013b). A stock-driven approach is proven to be more robust compared to the flow-based intensity of use models because stocks reflect the ultimate demand for services in the built environment (Müller, 2006, Gordon et al., 2006, Müller et al., 2010, Pauliuk et al., 2011, Hatayama et al., 2009).

A dynamic MFA approach to model vehicle in-use stock and related aluminum recycling system has been used in some previous studies (van Schaik et al., 2002, Cheah et al., 2009, Hatayama et al., 2009, Hatayama et al., 2012).

Van Schaik et al., 2002 developed a dynamic model for passenger cars that defined the link between end-of-life vehicles and the recovery of various metals, including aluminum. They predict the number of ELVs in the Netherlands using different distribution functions for lifetime assumptions based on passenger car production data and combined the model with an optimization model for recycling, which calculates the recovery rate of aluminum as a function of variables with regard to different material streams, such as aluminum alloys found in scrap fractions. Cheah et al. (2009) employed a dynamic MFA model to calculate the annual stock and flows of aluminum in the US passenger cars from 1975 to 2035. The US vehicle stock is calculated based on historic vehicle sales and scrappage rates and future forecasts of the US market. The main intention was to analyze the corresponding energy embodied in automotive aluminum and cumulative aluminum production energy demand. These two studies calculate vehicle stock and were thus able to follow stock development and connect supply and demand. However, the main driver for the vehicle stock was production data; therefore, they were unable to predict the future based on demand from society.

Hatayama et al. (2009) estimated the amount and quality of aluminum in-use stock and scrap generation in different sectors, such as automotive, construction, beverage cans, and machinery, in Japan, China, the US, and Europe using a dynamic MFA. The concentration of alloying elements in stocks and flows were calculated by counting the consumption in each end use by alloy type. Then, from the relation between the amount of in-use stock and per capita GDP in the past, future in-use stock change was predicted using GDP and population forecasts. Later, in another study, Hatayama et al. 2012 employed a stock-driven dynamic MFA approach to the automotive sector for the same selected regions. The model was used to analyze how the recycling of aluminum will change by 2050 by introducing next-generation vehicles and scrap sorting. The model distinguished between wrought and casting aluminum. A comparison of demand with discard was used to evaluate the amounts of primary aluminum required and scrap that cannot be recycled because of a high concentration of alloying elements. The result of their study showed that there would be 6.1 Mt of unrecyclable scrap in 2030 in the selected regions. This study still lacks a global scale, which is necessary to anticipate the timing of scrap surplus.

The reviewed previous studies demonstrate that there have not been any global stock-driven approaches that analyze global aluminum recycling challenges. Previous studies were either only trend analyses based on historic data that was extrapolated or only regional studies. Trend analysis is not sufficient to predict future material cycles because it is only based on historical production data. On the other hand, future stock changes are based on societal demands, which can only be captured by stock-driven models and by including demand parameters.

It is important to study the scrap surplus using a global scope because countries are open systems with trading of all relevant aluminum products along the cycle. If one region or country faces a surplus of scrap, it may export scrap to other regions with a scrap deficit; as a consequence, the problem will manifest on a global scale, provided that transport costs do not inhibit trade. If transport costs limit trade, scrap shortages would occur at different times in different regions; however, prices for sorted aluminum scrap have historically been close to primary aluminum prices, and transport costs have not been an important trade barrier.

In this thesis, a stock-driven approach is used to study the selected material cycle of the global passenger car fleet. Employing a stock dynamics approach for scrap surplus calculations allows for mass balance consistent estimations of aluminum demand, scrap availability, and stock in service.

In addition to the lack of information about the timing and amount of the future scrap surplus on a global scale, there was a lack of understanding regarding the most effective combinations of interventions to avoid a future scrap surplus. Some previous studies, such as Gaustad (2011), employed optimization or allocation models in addition to a dynamic MFA model to analyze options to mitigate the negative impacts of accumulation on scrap utilization. This study was able to allocate scrap and primary material to individual products. However, it is only possible to capture all of the required information by considering component and alloys levels within a product category. Therefore, there is a need for a detailed study that uses optimization models based on refined models.

To evaluate different solution strategies, it is necessary to simultaneously forecast scrap supply and aluminum demand on a component and alloy basis. An understanding of component levels and the alloying element resolution is necessary to quantify the capacity for scrap use. This information allows us to test whether the separated scrap fractions could be used in components that contain alloys other than secondary castings aluminum.

The global emission reduction potential of light-weighting passenger cars depends on fleet development. Whereas light-weighting cars reduce emissions in the use phase, upfront emissions in the production phase may be intensified depending on the materials used and the share of secondary production (recycling), which may in turn depend on scrap from retiring vehicles.

Traditionally, LCA has been used to address questions related to emissions, material use and end-of-life management in vehicle systems (Kim et al., 2010b, Keoleian and Sullivan, 2012, Geyer, 2008, Mayyas et al., 2012, Das, 2005, Das, 2014, Stodolsky et al., 1995, Bertram et al., 2009a). A review of 43 LCA studies on the emissions benefits of light-weighting in automobiles were compiled in a publication from Kim and Wallington (2013). Typical LCAs consider functional units or single vehicles only, and practitioners must make assumptions on how the background economy evolves over the product's life cycle. This includes assumptions about material recycling within and outside the vehicle system, which in many cases is the single most important measure to reduce emissions from material production systems. To assess the possible overall emissions reduction, material challenges and potentials related to passenger car systems over the next decades, it is not sufficient to simply scale up the LCAs of single vehicles for the following reasons: (i) the vehicle stock is composed of different cohorts, which limits the rate at which new cars can penetrate the fleet; (ii) technological changes in vehicles and the material and fuel supplying industries must be considered; and (iii) changing material composition will change the scrap flows from end-of-life vehicles, which can impact the recycled content of new cars in the future and hence reduce embodied emissions. Furthermore, the dynamics of the system dictate the availability of scrap, and hence the possibilities for recycling, through the extended lifetime of vehicles. On a global scale, the level of recycling and the resulting emission savings are limited by the total scrap availability, which changes substantially over time. Some of these limitations are related to scale, and some are related to dynamics that can be overcome by modeling the entire vehicle fleet at a global scale with a dynamic MFA approach, including demand drivers (population and vehicles per capita), technological change, and material recycling. These aggregate dynamic effects have not been studied before. Therefore, there is a need for dynamic fleet-recycling models that allow us to assess specific technologies in a global setting. Such a model connects population estimates, lifestyle choices, and utilization parameters to inventories of specific drive technologies and material production processes. The scrap availability and sales potential for end-of-life vehicle scrap are taken for granted in LCA, whereas the dynamic fleet-recycling model showed that scrap availability changes over time, depending on several factors that can be made explicit.

There is a need for a model that is able to capture different cohorts in vehicle stocks while considering technological and material composition changes over time. Therefore, we developed a dynamic stock model of the global car fleet and combined it with a dynamic MFA of the associated steel, aluminum, and energy supply industries. This dynamic fleet-recycling model provides estimates of the emission saving potentials under different scenarios for the substitution of conventional steel with high-strength steel (HSS) and aluminum at different rates combined with recycling scenarios over the 2010-2050 period.

1.7 Goals and research questions

This thesis aims to fill the mentioned gaps of understanding the linkage between the global vehicle system and material cycles, such as the aluminum cycle, on a global scale over time. The main questions to be addressed in this PhD project are:

1. How are the dynamics of the global vehicle stock changing the boundary conditions for aluminum recycling?
2. What are the most effective interventions to minimize a future aluminum scrap surplus?
3. What material substitution options for vehicles exist to reduce direct and indirect GHG emissions over time?

2 Discussion and outlook

This section aims to answer the three research questions, and it discusses the strengths and weakness of the approaches and the implications of this thesis for policy and research.

2.1 Main findings and reflections on the research questions

2.1.1 Aluminum recycling and the dynamic of the global vehicle stock

The first proposed research question was:

- How are the dynamics of the global vehicle stock changing the boundary conditions for aluminum recycling?

The vehicle fleet is an important driver of aluminum demand and scrap generation. More importantly, the vehicle fleet is the key carrier for casting, accounting for more than 70% of the total casting demand. Therefore, it currently creates the main sink for aluminum scrap from all sectors. The global vehicle stock is growing substantially and this fast growth in vehicle fleets allows secondary casting in vehicles to absorb scrap. However, the study result shows that the scrap absorption capacity of secondary cast in the vehicle fleet may not grow sufficiently fast in the long term. This can be explained by 1) a decline in the growth rate of the vehicle fleet and 2) a tendency toward smaller amounts of secondary castings per vehicle due to changes in new powertrain technologies. Diesel and electric vehicles use approximately 20% and 50% less cast aluminum, respectively, compared to gasoline vehicles. Castings have a smaller potential for growth because their application in engine components has already penetrated the market to a high extent, and there is a trend to replace gasoline engines with new technologies, such as diesel, hybrid, and electric, which use less or no secondary casting. Starting from the current level of 100 kg, saturation levels of 80-130 kg are expected. 3) The growth potential for wrought aluminum in passenger cars is considerably higher than for castings, mainly due to promising new applications in body-in-white (BIW). Wrought aluminum growth is assumed to increase substantially from the current level of approximately 50 kg to 100-300 kg by the end of 2100.

Due to the different penetration rates of wrought and casting aluminum in vehicles, the rate of scrap generation is growing faster than the demand for secondary castings. The results confirm that the automotive aluminum sector may go from being a net scrap consumer to a net scrap producer in the coming decade.

Referring to the results of papers I and II, all scenarios reach a point at which the sum of the scrap supply from passenger cars and additional minimum aluminum resources for dilution exceed the secondary castings demand. The timing of the surplus occurs in

2018 for the base scenario and is relatively robust, from between 2012 and 2028, depending on different parameter variations. With the highest dilution rate assumption, the model shows the most extreme result, in which the surplus would occur in 2012. However, wrought separation in ELV management is the most effective parameter to delay the future scrap surplus until 2028.

The gap between demand and supply varies considerably under different parameter assumptions. The scrap surplus reaches a level of 3.3-18.3 million metric tons per year in 2050.

Higher population and car ownership can delay the time of the scrap surplus by one or two years; however, higher population and car ownership will create a significantly larger scrap surplus in the long term. An extension of vehicle lifetimes delays the scrap surplus by two years and keeps the scrap surplus at a slightly lower level.

According to paper IV's simulation, scrap surplus occurred from 2025, which is 7 years later than in the base scenario of our previous model. The main reasons for this variation are: 1) magnesium removal is considered for the base scenario in paper IV, whereas no refining option is considered in the model for papers I and II and 2) recycled content assumptions were fixed for papers I and II (56% for cast alloys and 0% for wrought alloys). However, in paper IV, the recycling content was changing and was determined by the chemical composition of scrap and alloys.

Regardless of this variation in the results of these simulations, the expected surplus is less than one vehicle generation in the future. Thus, the problem is largely determined by the vehicles stock currently in use and the consequent scrap generation rate, which reduce the uncertainty of the results. The new powertrain technologies affect scrap generation only in the longer term and thus have a minor impact on surplus timing; however, they may play a significant role in the magnitude of the surplus problem in the longer term.

2.1.2 Effective interventions and factors to overcome the scrap surplus

The second proposed research question was:

- What are the most effective interventions to minimize a future aluminum scrap surplus?

The model simulation showed that all sectors involved in the vehicle-related aluminum cycle could make contributions to solve the scrap surplus challenge. Figure 18 shows the most relevant interventions along the cycle. Aluminum recycling is becoming increasingly complex and requires multi-stakeholder governance. Although the motivation for such interventions comes mainly from the aluminum industry, their realization depends mainly on stakeholders in other parts of the system.

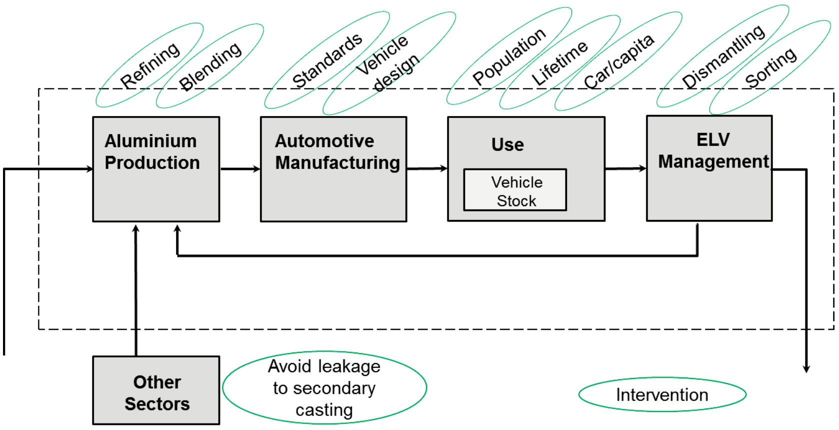


Figure 18 Relevant interventions to minimize a future aluminum scrap surplus.

The aluminum industry has two options to mitigate the scrap surplus problem directly; all other interventions require cooperation with other sectors. **Refining technologies** can be used for separating alloying elements and impurities from the aluminum melt (such as chlorination, electrolysis, fractional crystallization, hot crush, filtration, or floatation). They are currently expensive and have significant environmental drawbacks, including a high energy demand. For example, magnesium could be removed from molten aluminum scrap to achieve the low levels required in the most common secondary cast alloys. Due to the high value of magnesium, refining costs, and chlorine emissions, it is not the most desirable option. Reducing the dilution rate through the intelligent **blending** of different scrap alloys, is a cost-effective option to delay the scrap surplus. The effectiveness of the two latter interventions is limited, and as mentioned above. **Avoiding leakages to secondary casting** can be achieved by scrap recovery and sorting in nonautomotive sectors**,** such as packaging and building. This could reduce the amount of cascaded scrap currently being absorbed by automotive secondary castings.

In addition to the above options related to aluminum production, the two most effective interventions are related to the ELV management (increased dismantling and sorting), which can improve the quality of treated scrap and consequently widen the possibilities to recycle the scrap.

Increased sorting (automatic or manual) of mixed aluminum scrap into casting, wrought aluminum, and different alloy families has a high potential for avoiding excess scrap in the medium and long term. Additional alloy sorting of mixed shredded scrap requires further advanced technology development, such as laser-induced breakdown spectroscopy (LIBS), with relatively fast and high market penetration. According to the model simulations, an excess of scrap can be avoided if the enhanced sorting technologies are deployed rapidly on a global scale. Our calculations show that rapid market penetration of these technologies is even more important than the starting time of their deployment. If the technology is introduced in 2012, but over a 20-year time horizon, the surplus time is not delayed significantly. On the other hand, if the technology starts to penetrate the market in 2017, but with a shorter technology uptake period of 10 years, the surplus can be delayed until 2028.

Increased dismantling of components could reduce the mixed scrap by approximately one third. Potentially attractive candidates for cost-effective dismantling include wheels, closures, suspension frames, heat exchangers, bumpers, and crash boxes. A strategy of increased dismantling is best confined with a strategy of component-to-component recycling, which also requires interventions in automotive manufacturing and aluminum production. Increased dismantling does not require new technologies and could be implemented rapidly, provided that dismantlers have appropriate incentives to do so. However, the use of these components for alloy-specific recycling is currently limited by the complex composition of components (mixed material design and applied joining techniques, i.e., steel bolts or rivets, different welding wire composition) and strict safety requirements from the automotive industry that practically prevent producing safety-relevant parts from recycled material. In some cases, such as wheels, component-to-component recycling may require new standards to enable their production from scrap. Currently, automotive manufacturers mandate strict recipes for the composition of aluminum alloys for safety components, which require the use of only primary sources. Instead, mandating properties would provide aluminum producers more flexibility in developing new alloy types that meet the required qualities with the use of obsolete scrap. This requires changing the **standards** in automotive manufacturing, and may therefore delay the implementation of a component-to-component recycling strategy.

In addition to cast alloys, there are few other alloys that can potentially absorb mixed scrap, such as alloy 6082, which can be a sink for a mixture of wrought alloys. Developing alternative sink alloys or recycling-friendly alloys in **vehicle designs**, which function as ‘intermediate reservoirs,’ can be an effective intervention for the future scrap surplus. Although intermediate reservoirs may not be the final solution to the alloy problem, they could be important in a transition phase by delaying the problem, because they can absorb some of the scrap and create a larger bottom reservoir for aluminum recycling while more advanced separation techniques are developed. Components can be designed to be more suitable for disassembly and recycling. This can be achieved, for example, by reducing the number of alloys employed in car components and reducing the material complexity in connections and joints. However, the desired effect would be delayed by approximately a vehicle lifetime, which is insufficient to address the scrap surplus problem without additional measures in ELV management.

Changes in the use phase parameters also affect the timing of the scrap surplus. Higher **population** and **cars per capita** and longer vehicle **lifetimes** result in a several year delay of the scrap surplus. Interventions related to the use phase, population and cars per capita are not considered useful for relevant policy suggestions in this context because they may contradict several other environmentally friendly policies. However, extending the lifetime of a vehicle may be a relevant intervention that can be suggested to users.

2.1.3 Material selection in vehicles and consequences for global material cycles and energy use

The third proposed research question was:

- What material substitution options for vehicles exist to reduce direct and indirect GHG emissions over time?

This study showed that light weighting of passenger cars by material substitution could save between 9 to 18 gigatons of $CO_{2\text{-eq}}$ between 2010 and 2050. However, this range is considered an upper limit and its realization requires: (1) a rapid penetration of light-weight materials to their technically feasible potential by 2030 and (2) the utilization of the secondary mass saving potential in which lighter and smaller powertrains and other components can be produced as a result of primary mass saving while still keeping the same functionality. In addition, a potential increase in the mass of other vehicle components due to higher safety standards or more luxurious features (counter-effects), is considered.

Approximately 85-90% of GHG emissions occur during the use phase of vehicles (direct and indirect emissions) and 10% comes from the material production phase. Despite the lower emissions from material production compared to the use phase, the study of material substitution in global vehicle fleets is of high importance due to the light weighting benefits they provide and consequently the reductions in the use phase emissions. In addition, the relation between material supply, material efficiency, and recycling has long-term effects on GHG emissions.

The full benefits of currently available light-weighting options can be realized only in a few decades, when the global vehicle fleet is replaced by lightweight vehicles. In addition, the full benefits of recycling will become apparent only once the currently rapidly growing in-use stock of aluminum flattens and the scrap from ELVs becomes available for recycling. The effect of recycling on emissions is more important for aluminum than for steel because the relative savings are higher for aluminum and because the aluminum stock in vehicles is growing faster than that of steel. Looking at the near future, up until 2025, the material choice for light-weighting is less important because savings in the use phase are higher than the material production emissions, but in the long term, aluminum has a higher potential to reduce emissions than HSS, providing that there will be significant improvements in the aluminum recycling system.

For the allocation of emissions to different metals, it is important to consider the exchange of scrap between the sectors. In the case of aluminum, the vehicle stock is a net sink of scrap from other sectors (mainly construction). In contrast, vehicles are a net source of steel scrap, which is used mainly to produce steel for the construction sector, which has lower quality requirements. Primary metal production and internal recycling can be expected to dominate the supply of automotive steel due to high quality standards.

In our model, which is limited to the automotive sector and related material sectors, we solved this allocation problem by assuming that emission benefits are only allocated inside the system boundary, and as long as the scrap is used for vehicle production, emissions benefits are assigned to the vehicle system regardless of which sector was the source of this scrap. In the same manner, where steel scrap left the system boundary for the construction sector, the vehicle system would need primary materials instead and therefore lost the benefits of recycling. Allocating emissions benefits of using secondary material is only possible with multi-sectorial analysis by considering all of the material transitions between sectors.

2.2 Methodology discussion

The results of papers I and II indicated that new recycling strategies would be needed to avoid a future scrap surplus. The study was the first scrap excess estimation that was an explicit system definition with transparent model assumptions. The dynamic MFA model used in papers I and II allowed for a robust identification of the scrap surplus problem. However, the crude resolution of alloys (casting versus wrought) and the lack of a component resolution result in high uncertainties and do not allow for a practical evaluation of interventions, such as the dismantling of components. The model cannot simultaneously forecast scrap supply and aluminum demand both on a component and alloy basis, which is necessary to test whether the separated scrap fractions could be used in components that contain alloys other than secondary castings aluminum.

Therefore, in papers III and IV, the previous dynamic MFA model used detailed additional data distinguishing 5 car segments, 14 car components, and 7 alloy groups to track aluminum alloys in component groups. In addition to the development of a detailed model, a source-sink diagram was developed to identify potential alloys that could serve as alternative sinks for the growing scrap supply. The source-sink diagram and model were used in combination with expert consultation to discuss alternative ELV management strategies on a component-by-component level from a chemical, quantitative, and practical perspective. The solution strategies are evaluated in papers III and IV.

Paper IV employs a model with alloy chemical element resolution, combined with an optimization procedure to quantify the scrap surplus and recycling paths under maximum scrap utilization. This paper focused mainly on intervention options in industries (ELV management, secondary aluminum industry, and component manufacturing).

In paper V, the model for aluminum in vehicles was extended to include steel as a second material, as well as energy use for material production and vehicle operation. The vehicle fleet was divided into ten drive technologies (conventional gasoline, gasoline hybrid, conventional diesel, diesel hybrid, plug-in hybrid gasoline, plug-in hybrid diesel, electric, natural gas, H_2 combustion, and H_2 fuel cells) and five different fuel types were considered (gasoline, diesel, electricity, natural gas, and hydrogen). Annual kilometrage and age-cohort-technology-specific fuel efficiency were used to determine the total fuel demand. The material layer includes a dynamic MFA of the key automotive elements: steel (divided into cast iron, standard steel, and high strength steel) and aluminum (cast and wrought aluminum). The following processes for secondary material production were considered: (1) recycling (cascading) scrap from other sectors for use in automobiles, which can typically only be used to produce aluminum castings; (2) scrap use within the automotive sector; and (3) automotive scrap that is exported to other sectors due to quality constraints, such as construction.

The dynamic fleet-recycling model that was developed in paper V allows us to assess specific technologies in a global setting. The model connects population estimates, lifestyle choices, and utilization parameters to inventories of specific drive technologies and material production processes. It can help to design portfolios of emission mitigation strategies that bridge the gap between product-specific strategies and global emission reduction targets or benchmarks. Energy and material supply, energy and material efficiency, and lifestyle changes can be included. The model includes material production (primary and secondary), car manufacturing, use (vehicle fleet), and end-of-life vehicle management. Material recycling can only be understood properly from a fleet perspective. The comparative success of a certain emissions mitigation strategy was determined by system-wide emergent effects, such as the potential for material recycling, and not by individual material choices or product designs.

The main limitation in paper V relates to the focus of the study, which was the vehicle sector, and the model only able to show how increased recycling from introducing different recycling scenarios could reduce emissions inside the system boundary. From a direct emissions perspective, the automotive aluminum industry benefits from scrap generated by other sectors, whereas the automotive steel industry cannot even benefit from recycling its own scrap. In addition, the aluminum scrap surplus and consequently the limited recycling capacity were not considered in this paper because the effect was related to outside of the defined system boundary. The model was able to calculate this effect; however, assumptions were simplified. If it was considered in the model calculation, the impact would be a reduction in overall emissions benefits in cases in which scrap surplus would occur because the scrap would not be used in any other applications. The main concern in such studies is how the system boundary should be defined and the emission benefits should be allocated.

In general, the models' limitations for other papers are also related to the resolution of the system definition and data availability. The main limiting factor in this study is the focus on only one sector (vehicles) and the definition of the system boundary only for the vehicle system. Therefore, the model is unable to capture the exchange of material and study the effects of interactions between sectors in relation to material cycles and emissions allocations. To understand the full consequences of the border shift between sections, a model including all of the relevant sectors' interactions inside the system boundary with economic considerations would be required. However, extending the system boundary would require enormous amounts of bottom-up data that are extremely difficult to extract, especially in sectors that have large regional differences and practices. Gathering bottom-up data from vehicle systems as the most harmonized sector at a global scale was still a significant challenge. In some cases, data were gathered from meetings with several experts in the aluminum, steel and automotive industries. As such, data gathering for relevant aluminum components in passenger cars and the composition of different alloys in each component can be mentioned.

Although it was essential to study the aluminum recycling issue at the global scale to capture the overall picture and avoid trade complications, if the markets for aluminum-containing products (including scrap) do not function perfectly, we might expect that a scrap surplus could occur in some areas earlier than in others. Furthermore, the parameters used in the model have strongly differing uncertainties. Nevertheless, the parameter variation showed that the result regarding the timing of the scrap surplus is relatively robust and the robustness of the model results partly from the fact that the expected surplus is less than one vehicle generation in the future. Thus, the problem is largely determined by the vehicle stock currently in use, not by hypothetical future vehicle stocks, for which uncertainties are considerably larger.

2.3 Implications of the work for research and policy making

Legislation for ELV management around the world focuses on the total amount of scrap to be recovered from ELVs for specified target years. The legislation is limited because it is exclusively focused on the total quantity of materials to be recovered. It is important to measure the success of recycling strategies according to existing regulations and to make improvements in the policies. Vehicle-fleet recycling models allow for an increased focus on quality aspects to ensure that the recovered scrap can be used. Through studies of the dynamics and patterns of stocks in use, the timing and extension of the probable oversupply of post-consumer scrap can be captured. In addition, the most effective interventions could be found. Furthermore, policymakers to set realistic targets given the linkage between ELV management and the coordination of interventions between the sectors needed to solve recycling challenges. The results in the global context provide guidance for the aluminum industry and decision makers on when and how new ELV management strategies would need to be adopted to make use of increasing amounts of post-consumer scrap.

Papers I-II showed that there will be challenges in meeting the recycling targets in ELV management in the future. Papers III and IV provided strategies for ELV management that can avoid or delay the scrap surplus of aluminum.

The effectiveness of emissions mitigation strategies, including material substitution, depends on the evolution of the recycling system. Current policies, such as the US and European regulations, focus on reducing the tailpipe emissions of new vehicles. Current LCA research suggests that emissions reduction policies should not focus on tailpipe but on lifecycle emissions (Kim and Wallington, 2013). These studies have highlighted the importance of using a lifecycle approach to avoid merely shifting the problem from direct emissions in the use phase to emissions in the production phase. Although this is an important aspect that is neglected in current policies, LCAs with a single car perspective have severe shortcomings; they cannot capture changes in the recycling system, which have substantial impacts on industrial emissions. Dynamic effects of the different material cycles, especially the recycling potential, must be anticipated and included in emissions reduction policies. Therefore, beyond the common LCA, an alternative approach that considers vehicle fleet development over time and the implications for material cycles is suggested. The dynamic fleet-recycling approach models the impact of current consumption on the future recycling potential and analyses the relative effect of different interventions along the entire system over time. This study can be informative for policy makers to anticipate future challenges in the end-of-life vehicle management.

Models, such as the one applied here, can help to design emissions mitigation strategies that connect product-specific strategies to sector- and economy-wide emissions targets. Focusing on one sector represents a significant limitation in emission allocations. Therefore, expanding this type of study to other relevant sectors and increasing the system boundary to include linkages between sectors are suggested.

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Paper I

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The Role of Automobiles for the Future of Aluminum Recycling

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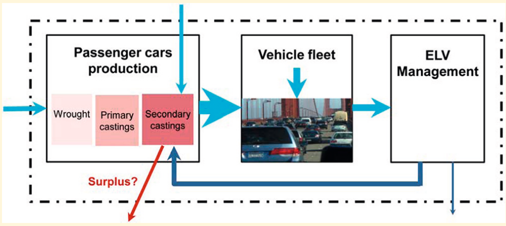
Ⓢ *Supporting Information*



ABSTRACT: To reach required product qualities with lowest costs, aluminum postconsumer scrap is currently recycled using strategies of downgrading and dilution, due to difficulties in refining. These strategies depend on a continuous and fast growth of the bottom reservoir of the aluminum downgrading cascade, which is formed by secondary castings, mainly used in automotive applications. A dynamic material flow model for the global vehicle system was developed to assess the likelihood, timing, and extent of a potential scrap surplus. The results demonstrate that a continuation of the above-mentioned strategies will lead to a nonrecyclable scrap surplus by around 2018 ± 5 if no additional measures are taken. The surplus could grow to reach a level of 0.4–2 kg/cap/yr in 2050, corresponding to a loss of energy saving potential of 43–240 TWh/yr electricity. Various intervention options for avoiding scrap surplus are discussed. Effective strategies need to include an immediate and rapid penetration of dramatically improved scrap sorting technologies for end-of-life vehicles and other aluminum applications.

1. INTRODUCTION

Although the environmental profile of aluminum is strongly related to the large use of electrical energy in its primary production, recycling can reduce energy demand by up to a factor of 20.[1,2] In addition, postconsumer scrap recycling also reduces greenhouse gas emissions, demand for bauxite ore, waste, and costs. Today, aluminum recycling is mainly constrained by insufficient scrap availability for an adequate price. However, the amount of postconsumer scrap is expected to grow in the future due to the large increase in aluminum use in recent decades. Growth in the use of postconsumer scrap in recycling may lead to increasing quality challenges,[3] because postconsumer aluminum scrap is often contaminated with other metals and consists of many different alloys that are collected in a single mixed aluminum fraction. In contrast to most other nonferrous metals, recycling of postconsumer scrap aluminum is subject to particular thermochemical constraints that limit the options for removing alloying elements and impurities in refining.[4−6] For aluminum refining, there are chemical options such as chlorination, and pyro metallurgical options such as filtration and electrolytic, but currently they are costly, involve use of hazardous chemicals, and can lead to metal loss.[7,8]

Given this limitation of refining, the current practice for recycling of castings and mixed contaminated scrap deals with quality challenges by deploying two strategies that are often used in combination: (1) scrap is diluted with primary aluminum or low-alloyed scrap to reduce the alloy concentration below critical levels; and (2) recycled scrap is used in products with a higher alloy content, typically secondary castings, which are employed mainly in automotive applications. Here, we discuss whether these two strategies will be sufficient to ensure that the increasing amounts of postconsumer scrap will find useful applications, and, if not, what alternative measures could be taken to make use of the increasing postconsumer scrap.

Passenger cars form a quality bottleneck in aluminum recycling because they embody most of the secondary castings, which are in turn the major recipients of recycled aluminum from all sectors.[7,9] Furthermore, aluminum scrap from car shredders, which includes a mix of aluminum alloys with low and high alloy content (e.g., castings), can only be used to produce secondary castings in vehicles if no alloy sorting is applied.[10] In this article, the term "secondary castings" refers to castings mainly produced from a mixture of different types of aluminum scrap, in contrast to primary castings, which are made exclusively from primary aluminum.

But, is downgrading a problem? In the current situation, downgrading is economically attractive because no costly separation is needed, and it is ecologically meaningful because it reduces the need for primary resources in the form of alloying elements. However, such a recycling system relies on a continuously and rapidly growing demand for secondary castings, a situation that may not be sustained over a long period of time. Therefore, a system that works perfectly today may not be sustainable in the future.

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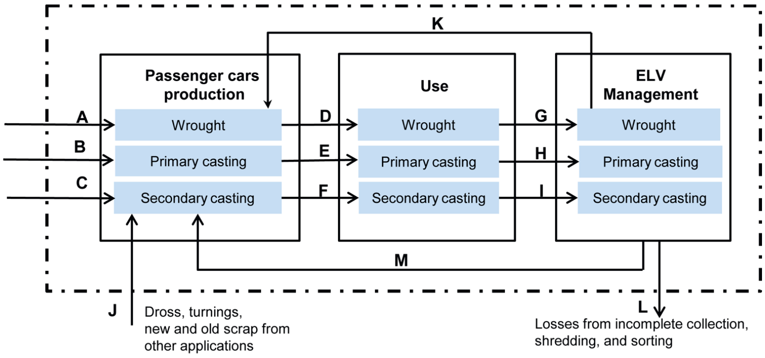

Figure 1. Simplification of aluminum system in passenger cars.

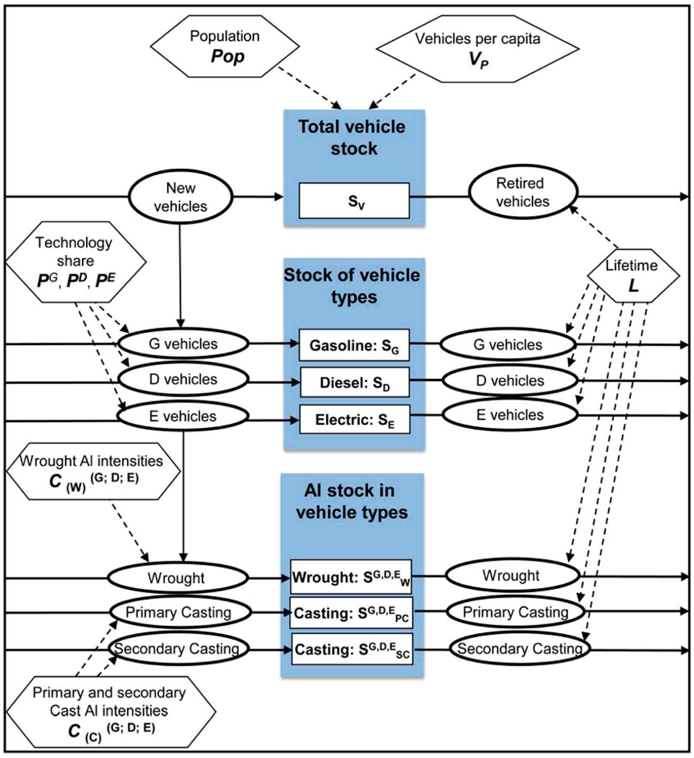

Figure 2. Extended dynamic model for aluminum in passenger car stock.

The possibility of oversupply of aluminum scrap from end-of-life vehicles (ELVs) was first mentioned several decades ago.[11,12] The first quantitative study on this topic was conducted by the European Aluminum Association which quantified European casting demand and scrap from ELVs for 1997.[13] By extrapolating data, it was found that a scrap surplus for cast alloys production would occur by 2015 if Europe was an isolated system. Zapp et al.[14] analyzed the long-term supply of aluminum to the European automotive industry and compared future casting demand with scrap amounts from different sources. They found that old scrap availability will eventually exceed casting demand by 5−25% in 2040. Both studies estimated casting demand and scrap supply independently using trend analysis, thereby ignoring their connection through the dynamics of the vehicle stock. Scacchetti[15] used a dynamic MFA model to estimate cast aluminum inflow to and outflow from the Norwegian passenger car stock, and found that a scrap surplus would occur around between 2030 and 2040, if Norway was an isolated system.

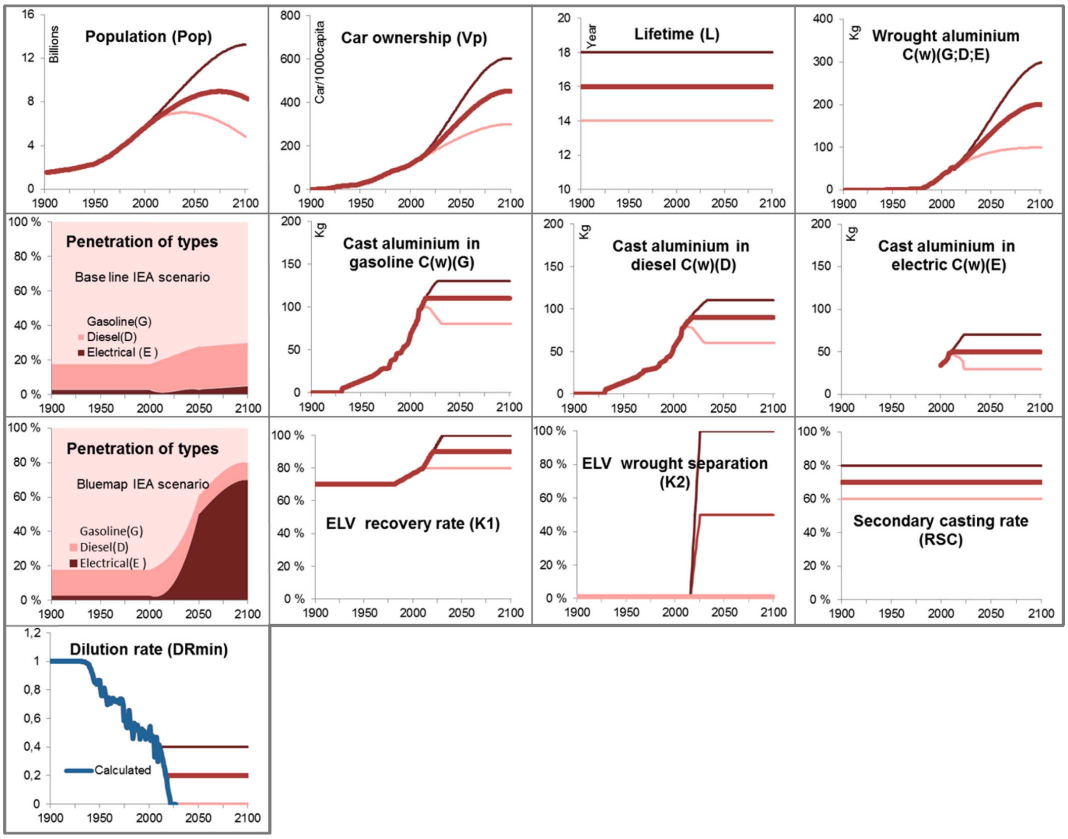

Figure 3. Input parameter estimation for base scenario (thick lines) and sensitivity analysis (thin lines).

All studies so far have been conducted at a regional scale. However, vehicles and scrap are traded on global market. A potential scrap surplus will therefore most likely manifest on a global scale, while slight regional differences might occur in case that shipment costs hinder scrap trade.

Here, we develop a dynamic model for aluminum use in passenger cars on a global scale to address the following questions: (1) How are the dynamics of the global vehicle stock shaping the boundary conditions for aluminum recycling? (2) When and under what conditions is a scrap surplus likely to occur? (3) What are the most effective interventions to ensure that all recoverable scrap will find a useful application?

2. METHODOLOGY

2.1. System Definition. Figure 1 illustrates the aluminum cycle related to passenger cars on a global scale. The system includes three processes: passenger car production, use, and ELV management. All processes are divided into three subprocesses: wrought aluminum, primary castings, and secondary castings.

Wrought aluminum, which usually has lower alloy content than cast aluminum, is mainly produced from primary aluminum (A).[7] To produce wrought aluminum from scrap (N), sorting per alloy group is needed to ensure that the alloying element concentration in the scrap fraction does not exceed the required tolerances.

Primary casting products are made exclusively from primary aluminum (B), while secondary castings are produced from a mix of ELV scrap (M) and dross, turnings, new and old scrap from other applications, alloying elements, and only in a few cases primary aluminum (C).[9] These additional resources (C) are blended or diluted with cleaner aluminum resources to meet the quality requirements.

In most cases, ELV management recovers only a single aluminum fraction (M), which is assumed to be used exclusively for secondary casting production.[16]

Losses (L) arise from incomplete collection, shredding, and sorting. For simplification, this flow is considered as arising from the ELV management process; although in reality collection losses occur in the use phase. In addition, there is also a metal loss during melting and casting[16] in the secondary casting subprocess, however, these losses are very small compared to the other losses and are therefore disregarded. The system is open due to interaction with other systems through flows C and L. The stock dynamics of the other sectors such as building, packaging, and others are out of the scope here.

Figure 2 illustrates the subprocesses and drivers of the use phase. The model distinguishes different drive technologies. Gasoline technology includes here conventional gasoline, gasoline hybrid, and plug-in hybrid gasoline; diesel technology includes diesel, diesel hybrid, and plug-in hybrid diesel; and electric vehicle technology consists of electric, hydrogen fuel cell, hydrogen−hybrid, and gas-powered vehicles.

2.2. Model Formulation. *(a). Use Phase.* To calculate inflows (D, E, G) and outflows (H, I, F), a demand driven model was constructed (Figure 2), which is an extension of the conceptual stock dynamics model developed by Müller.[17] The model distinguishes three types of vehicles (gasoline, diesel, and electrical), all of which have distinct uses for cast aluminum.

There are two steps in the model calculation. First, vehicle stocks and flows are calculated for the three vehicle technologies. Subsequently, aluminum stocks and flows are determined, differentiating wrought, primary, and secondary castings.

The parameters are as follows: population (Pop), lifestyle as vehicle per capita (V_p), vehicle lifetime (L), market penetration of vehicles types (gasoline (P^G), diesel (P^D), electric (P^E)), and aluminum content for cast ($C_{(c)}{}^{(G;\ D;\ E)}$) and wrought aluminum ($C_{(W)}{}^{(G;\ D;\ E)}$) per vehicle. All the parameters are functions of time but t is sometimes omitted for simplification.

Population and lifestyle determine the passenger car stock in use. Input of new and output of retired passenger cars is determined by a given stock development and lifetime. The lifetime is estimated assuming a normal distribution with mean τ and standard deviation σ.

The overall cast and wrought aluminum inflows for each technology are derived from the car inflow, the share of different car technologies, and the corresponding cast or wrought contents. A similar approach is used for computing aluminum scrap outflow. The only difference is that output (O) is a detailed matrix of each cohort outflow. The matrix allows for a calculation of the outflow of obsolete cars from different cohorts for any specific year.

(b). ELV Management. For simplification, collection recovery from the use phase is considered together with the shredding and sorting recovery from the ELV. All these recovery rates are denoted as K_1 and used to calculate flow M. ELV wrought aluminum separation rate (K_2) is used to calculate flow N.

(c). Passenger Cars Production. Wrought aluminum production uses both primary aluminum and wrought aluminum scrap. Primary castings are made using exclusively primary aluminum. Secondary castings are produced from ELV scrap and additional resources. The share of secondary castings in all castings is $RSC = F/(E + F)$.

If the amount of ELV scrap (M) is small, all of it is used to produce F, and C is added in order to meet total resource demand and the necessary quality by dilution. As M increases initially, C is reduced accordingly. It is assumed that scrap from other systems can be recycled for applications other than vehicles, and that, within a certain range, the necessary quality can still be reached. Although substitutions among the different aluminum sources grouped in C are likely to occur, the model does not treat them explicitly. However, the need for dilution of ELV scrap (M) with other aluminum sources (C) for quality purposes sets a boundary condition for a minimum value for C: $C \geq DR^*F$. Dilution rate is defined as $DR = (F - M)/M$. If the minimum dilution rate is reached, the dilution rate is held constant by an increase in M, and the system produces a scrap surplus.

2.3. Parameter Estimation. Detailed documentation on parameter estimation is available in the Supporting Information. Figure 3 shows all the input parameter estimations. The bold lines represent parameter estimations used for the base scenario, which uses medium options for all parameters except for ELV wrought separation, where the current level of zero is used as reference, and for technology penetration, where the baseline scenario provided by the International Energy Agency (IEA)[18] is used as a reference.

Population (Pop). Historic population data are estimated using UN national population statistics for 1900−2000.[19] The population scenarios for the period 2000−2100 are based on the UN Population Projection.[20]

Vehicle Ownership (V_p). Historic numbers for global weighted-average vehicle ownership were calculated based on individual countries. Passenger car stock data were compiled for 1900−1979[21−23] and for 1980−2005.[19] These country data were used to estimate weighted-average vehicle ownership in a global weighted average. Future scenarios for car ownership are estimated based on regional IEA projections[18] and other studies[24] for 2005 to 2050. All scenarios assume a logistic growth in car ownership with saturation around 2100. The saturation levels for the low, medium, and high scenarios were chosen to be 300, 450, and 600 cars per 1000 capita.

Lifetime (L). Based on previous studies on car lifetime from the U.S., Norway, and Japan,[15,25,26] we assume for the global level a constant lifetime approximated using a distribution function with a mean (τ) of 14, 16, and 18 years and a standard deviation (σ) of 3 years. We further assume that the lifetime of aluminum components in cars is the same as the lifetime of the cars.

Penetration of Types (P^G, P^D, P^E). The share of different technologies is derived from IEA Baseline and BLUE Map scenarios[18] for 2000−2050. In the Baseline scenario, gasoline technology remains dominant, while in the BLUE Map scenario electrical vehicles are penetrating the market effectively, from a 2% market share in 2010 to 50% in 2050. For the period 2050−2100, we assume a continuation of the growth in the adoption of electrical vehicles toward saturation at 70% market share.

Wrought and Cast Aluminum Content ($C_C{}^{(G;\ D;\ E)}$, $C_W{}^{(G;\ D;\ E)}$). Historic data for wrought and cast aluminum concentrations in vehicles were derived from estimates for the total aluminum content in vehicles and estimates for the share of wrought and cast aluminum. The use of aluminum in passenger cars began around 1930.[27] Ducker Worldwide reports the global average total aluminum content of passenger cars for the period 1978 (32 kg) to 2009 (149 kg).[28] For the period 1930−1978, we assume linear growth.

The average shares of wrought and casting alloys employed in average passenger cars are reported for Europe at 10-year intervals beginning in 1978[29] (see Table S1). We assume that these numbers are representative for gasoline vehicles in other parts of the world.

Since wrought aluminum is used for body in white (BIW) and skin, which are largely independent of the drive technology, all technologies are assumed to include the same amount of wrought aluminum. However, casting use began to differ by drive technology after 1978, when the use of aluminum engine blocks in gasoline vehicles started to become established. We assume 20% and 50% less cast aluminum use compared to gasoline vehicles[30] for diesel cars and electric vehicles,

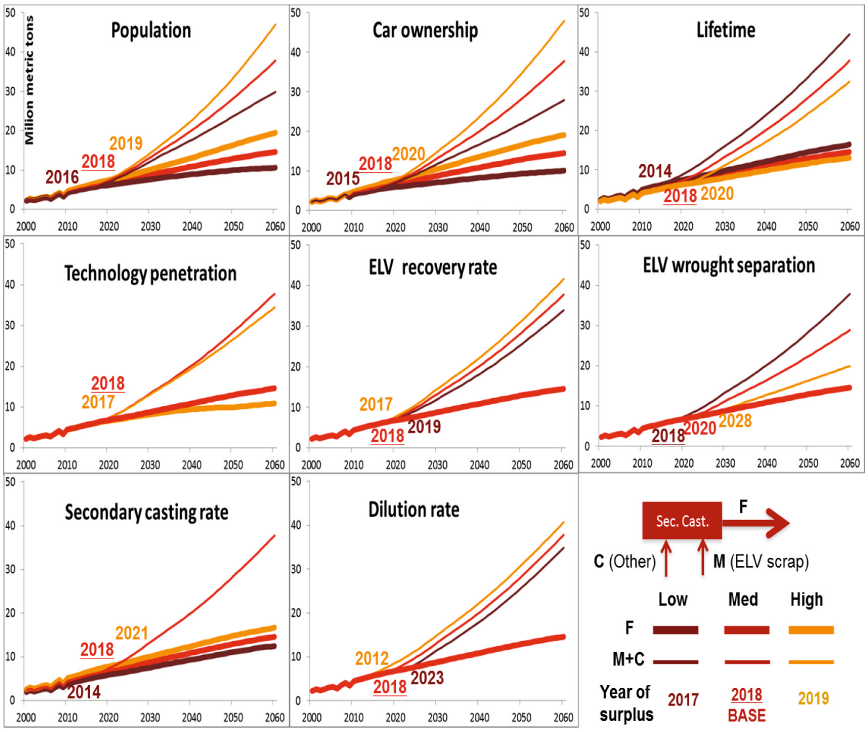

Figure 4. Sensitivity analyses of the input parameters (wrought and castings variations results are provided in the Supporting Information).

respectively. For the period 1930−1978 a linear growth in aluminum content to 32 kg is assumed. Wrought and castings share for the period prior to 1978 are assumed to be constant and equal for all technologies.

Most studies show that the growth potential for wrought aluminum in passenger cars is generally much higher than for castings, due to the high market penetration rate of aluminum in engine parts (castings) and the current low level of aluminum application in BIW (wrought).[27,31,32]

On the basis of components analysis and expert interviews, wrought aluminum growth is assumed to increase linearly from the current level of approximately 50 kg to 100, 200, or 300 kg by the end of 2100. This wide range was assumed in order to account for the high uncertainty surrounding the future use of wrought aluminum and to test the sensitivity of the model to this parameter.

Castings have a much smaller potential for growth because their application in engine components has already penetrated the market to a high extent. Based on experts' interviews, we assume saturation levels of 80, 110, and 130 kg for the low, medium, and high scenarios.

Secondary Castings Rate (RSC). Zapp et al. estimate the share of secondary castings to be about 70% of total castings use in passenger cars.[14] This level was assumed for the medium scenario, while 60% and 80% were used for the low and high scenarios.

ELV Recovery Rate (K_1). In the U.S., more than 95% of retired cars enter a comprehensive recycling system.[33] In Europe, approximately 89−95% of the aluminum in automobiles can be recovered from shredder plants.[34]

If this information is applicable globally, the current recovery rate is 85%. To be on the safe side, a current global recovery rate of 80% was assumed. The ELV recovery rate was assumed to be 70% until 1980; thereafter linear growth was assumed to meet the current rate in 2010. After 2010, three scenarios were proposed. The recovery rate in the low scenario was assumed to be constant with a value of 80%. According to the EU directive no later than 2015, for all ELVs, the reuse and recycling shall be increased to a minimum of 85% while reuse and recovery shall be increased to a minimum of 95% by an average weight per vehicle and year.[35] Therefore, in the medium scenario a linear increase to 85% in 2015 and 90% in 2020 and thereafter a constant rate was assumed. In the high scenario the recovery rate reaches 100% in 2030.

ELV Wrought Separation Rate (K_2). Current practice in ELV management after shredding is to separate only one fraction of mixed alloy scrap from other materials. Wrought aluminum, which generally has lower alloy content, is not recovered separately. New technologies for further sorting of the mixed alloy fraction into casting and wrought aluminum fractions, as well as different alloys, are currently being developed, but have not been widely adopted. We assume 0% sorting separation for the base (low) scenario. The medium and high scenarios assume the market penetration of sorting technologies between 2015 and 2025 to reach levels of 50% and 100%, respectively, and subsequent stabilization at these levels.

Table 1. Result of Timing and Amount of Scrap Surplus in 2050, and the Level of Al Demand in the Surplus Year for the Different Input Parameters

parameter	level of input parameter	year of scrap surplus[a]	level of Al demand[a] (million metric tonnes)	scrap surplus in 2050 (million metric tonnes)
population (Pop)	low	2016	5.8	12.6
	high	2019	7.3	15.5
cars/1000capita (V_p)	low	2015	5.4	11.6
	high	2020	7.8	16.5
lifetime (L)	low	2014	6.4	17.4
	high	2020	6.4	11.4
penetration of types (P_G, P_D, P_E)	base	2018	6.5	14.0
	blue	2017	6.3	15.3
ELV recovery rate (K1)	low	2019	6.8	11.1
	high	2017	6.5	**18.3**
ELV wrought separation rate (K2)	med	2020	6.8	8.6
	high	**2028**	**8.6**	**3.3**
secondary castings rate (RSC)	low	2014	4.9	15.5
	high	2021	8.0	9.6
dilution rate (DR$_{min}$)	low	2023	7.4	11.4
	high	**2012**	**5.0**	16.6
wrought & castings (C_c, C_w), C_w)	low C_w & low C_c	2016	5.4	10.8
	low C_w & high C_c	2019	7.0	11.4
wrought & castings (C_c, C_w), C_w)	high C_w & low C_c	2016	5.4	15.8
	high C_w & high C_c	2019	7.0	16.4

[a] Last year in which surplus is 0.

Minimum Dilution Rate (DR$_{min}$). In 2002, European automotive secondary castings were produced using at least 50% feedstock from non-ELV sources consisting of 10−15% dross, 20−25% turnings, 25−30% new scrap, and 35−40% other old scrap and little amount of primary ingots.[14] Model calculations on the global level resulted in a similar dilution rate of currently about 50%, with a declining trend (see Figure 3). The lower boundaries for the dilution rate to achieve the necessary alloy qualities are difficult to estimate due to the varying alloy content of the scrap and the secondary castings, and the possibility of substituting different types of additional resources, which is not explicitly treated in the model. We therefore test the sensitivity toward this parameter by covering a wide range for the minimum dilution rate, DR_{min}, assuming for the low, the medium (base), and the high scenarios values of 0%, 20%, and 40%, respectively.

2.4. Sensitivity Analysis. The sensitivity of the system variables was analyzed with respect to change in all parameters. Parameters were changed individually, using the base scenario as reference.

3. RESULTS

All scenarios reach a point at which the sum of scrap supply from the passenger cars (M) and additional minimum aluminum resources for dilution (C) exceeds secondary castings demand. In the base scenario, scrap surplus starts in 2018 and reaches a level of 14 mmt in 2050.

The time of scrap surplus is relatively robust around 2018, depending on the specific conditions. The earliest surplus time is reached with a high dilution rate of 0.4 in 2012, and the latest occurs with a high ELV wrought aluminum separation in 2028. However, the gap between demand and supply can grow to considerably different levels of 3.3−18.3 mmt per year in 2050 according to the parameter assumptions (see Figures 4 and S4, and Table1). The lowest surplus level is reached with a high ELV wrought aluminum separation, while the highest level is caused by a high ELV recovery rate. A higher level of ELV wrought aluminum separation delays the surplus and reduces the scrap excess most effectively. A relatively small scrap surplus occurs even with perfect ELV wrought aluminum separation because of the assumed minimum dilution rate of 20%, which limits the amount of casting scrap to be used for secondary casting production.

Higher population and car ownership can delay the time of scrap surplus slightly to 2019 and 2020, however, they will create a higher scrap surplus in the long term (+10%, +18% in 2050 compared to the base scenario). An extension of the lifetime, in contrast, can slightly delay the scrap surplus (2020) and reduce the long-term excess (−18%). The market penetration of electric vehicles with lower cast-aluminum content has no recognizable effect on the timing of the onset of the surplus (2017) because the penetration level will be still very low at that point. While in a long-term, the BLUE Map scenario results in a lower demand for secondary castings as well as a lower amount of ELV scrap. An increase in the secondary casting rate delays the scrap surplus to 2021. The secondary casting rate affects only the secondary casting demand (F), but not the resource supply ($M + C$). In contrast, the dilution rate affects only resource supply, but not secondary casting demand. The minimum dilution rate has a strong impact on the timing of the scrap supply: A DR$_{min}$ of 40% results in the creation of a scrap surplus in 2012, while a rate of 0% can delay the scrap surplus to 2023. A more intensive wrought aluminum usage has virtually no impact on the timing of surplus (Figure S4), because scrap amounts arise only after a delay of the average vehicle lifetime, while the surplus is expected to occur in less than one vehicle lifetime. However, the introduction of wrought aluminum technology has the greatest effect on the potential long-term scrap surplus (about 15.8−16.4 mmt in year 2050). In contrast, more extensive market penetration of castings-based technology leads to a small delay in the onset of the surplus (2019).

4. DISCUSSION

A continuation of the current aluminum recycling strategies of downgrading and diluting alone will inevitably lead to the formation of large amounts of highly alloyed material in the next few decades which will not find an application in the automotive market. The simulation results indicate that by 2050, the annual scrap excess from passenger cars may reach 3.3–18.3 Mt or 0.4–2 kg per capita. This potential resource loss corresponds to 10–54% of the primary aluminum production of about 34 Mt in 2006,[2] or 3–18% of primary production in 2050, if primary production triples by 2050 as expected by the International Energy Agency.[18] The expected scrap surplus implies a loss of an energy saving potential of 45–240 TWh/yr, assuming an electricity demand for smelting of 14 MWh per tonne,[1] which is equivalent to the total electricity demand of a medium sized country (e.g., Denmark: 33 TWh/yr; Iran: 207 TWh/yr, Spain: 268 TWh/yr). Assuming an average emission rate of 9.5 kg CO_2/kg aluminum,[2] this corresponds to a loss in greenhouse gas saving potential of 4–19 kg per capita and year.

In contrast to the timing of the development of a surplus, the estimation of the potential absolute level of the scrap surplus (or the potential need for wrought separation to avoid the scrap surplus) in the long term is much more uncertain. There are a variety of policy options that can hinder or delay a scrap surplus and reduce its negative effects on energy use and emissions.

(a) Technologies for sorting mixed aluminum scrap into castings, wrought aluminum, and different alloy families have the highest potential for avoiding excess scrap in the medium and long-term. Such technologies have been developed (e.g., Laser-Induced Breakdown Spectroscopy (LIBS)), but advanced sorting technologies are not yet competitive [34] and further research and development is needed to reach sufficient functionality. However, the approaching of a potential scrap surplus is likely to lower unsorted scrap prices drastically, which will help to make these technologies viable.

(b) Manual sorting of alloy types is today already economically attractive in developing countries with low labor costs, such as China, India, and Brazil.[36] According to the model simulations, an excess of scrap can be avoided only if the enhanced sorting is introduced very quickly on the global scale (see Supporting Information for market penetration scenarios), which may be unrealistic given the need for further technology development. An export of mixed scrap to developing countries, combined with manual sorting in these countries, may be a realistic intermediate solution.

(c) Refining technologies for separating alloying elements and impurities from the aluminum melt (such as chlorination, electrolysis, fractional crystallization, hot crush, filtration, or floatation) are currently very costly and have significant environmental drawbacks, including a high energy demand. A major breakthrough would be needed to make these technologies economically and environmentally viable.[7,8]

(d) Design for disassembly and design for recycling—including a reduction of the number of alloys employed in automobiles—has a potential to improve the performance of both manual and mechanical sorting.[4] However, the impacts of such measures on the separation efficiency would be delayed by about a vehicle lifetime. In the medium and longer term, it might be attractive for the aluminum industry to cooperate with the automotive industry to develop new alloy systems that are adapted to the use of recycled aluminum.

(e) Scrap recovery and sorting in nonautomotive sectors (such as buildings, cans, or appliances) has a potential to immediately reduce the amount of downgraded scrap currently being absorbed by automotive secondary castings.

(f) Exploring alternative applications for mixed or casting scrap could act as additional sinks. As scrap prices can be expected to fall drastically in case of excess scrap, such applications might become viable in areas where aluminum is currently not competitive from a cost perspective. Alternative sinks could delay a scrap surplus in short-term, however, they are not a long-term solution.

(g) Mandating properties instead of composition of aluminum alloys would provide aluminum producers more flexibility in blending to develop new alloy types that meet the required qualities with a higher share of obsolete scrap. Such a measure has a potential to reduce the minimum dilution rate immediately.

(h) Additional tools for reducing the dilution rate through intelligent blending of different scrap alloys are potentially effective to delay scrap surplus. This is one of the very few measures on which the aluminum industry has direct influence. Such strategies would benefit from improved knowledge about the alloy composition of the purchased scrap categories and related uncertainties.

Current ELV regulations were presumably not designed to cope with issues of potential future scrap surplus. For instance, even a small amount of unrecyclable ELV scrap could pose a challenge to the fulfillment of the EU-wide ELV Directive, which requires that the rate of reuse and recovery must be increased to 95%, while reuse and recycling shall be increased to a minimum of 85% by average vehicle weight by 2015.[35] Through these requirements, the ELV Directive is thus excluding virtually any landfilling of excess aluminum scrap, and is thereby indirectly mandating the employment of alternative interventions discussed above.

The model's limitations are related to the resolution of the system definition and parameter assumptions. The model employs a global system definition and does not consider inter-regional trade flows. If the markets for aluminum scrap do not function perfectly, e.g. due to falling scrap prices which would make scrap trade economically less attractive, we can expect that a scrap surplus could occur in some areas earlier than in others. Further, the parameters used in the model have strongly differing uncertainties. The parameter variation showed that the results regarding the timing of scrap surplus are relatively robust: between 2012 and 2028, while they are less robust with regard to the long-term surplus level. The robustness for surplus timing can be explained partly by the fact that the expected surplus is less than one vehicle generation in the future, thus the problem is largely determined by the vehicle stock currently in use, not by hypothetical future vehicle stocks, for which uncertainties are much larger.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

More information regarding the system definition, model formulation, and parameter estimation; additional results of sensitivity analysis for the parameter of wrought and castings variations; and effect of the sorting technology penetration for ELV wrought separation. This information is available free of charge via the Internet at http://pubs.acs.org/

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Notes

The authors declare no competing financial interest.

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Paper II

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'Aluminium Recycling – Raw Material Supply from a Volume and Quality Constraint System'

Georg Rombach, Roja Modaresi, Daniel B. Müller, World of Metallurgy –
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Aluminium Recycling – Raw Material Supply from a Volume and Quality Constraint System

Georg Rombach, Roja Modaresi, Daniel B. Müller

The limited availability of energy and raw materials as well as the ambitious emission reduction targets are of big concern in the metallurgical industry as in other base materials industries. Consequently resource efficiency targets are set under EU‘s Raw Material Initiative, measures are taken to reduce GHG-emissions and there is a focus on carbon footprint of products and companies. For example legislators and stakeholders request a high recycled content in downstream products. Due to missing knowledge about the relative availability of secondary raw materials in growing markets the debate of recycling content vs. end-of-life recycling is still ongoing. In case of the European aluminium industry the remaining primary smelters suffer from high costs of energy and the emission trading system. A survival is depending on acceptable power contracts and their role as active player in the electricity grid modulation. Furthermore restructuring and consolidation of the recycling industry is not finalized. On the other hand collected aluminium scrap volumes are expected to increase significantly and therefore, remelters and integrated cast houses prepare themselves to remelt different kinds of scrap to minimize the use of primary ingots. But depending on the final product properties the chemical composition of aluminium alloys has to fulfil strict specifications. Consequently the usability of secondary raw materials can be limited or would require costly up-grading and sorting processes. In order to analyse and forecast the scrap availability the use of Material Flow Analysis gains increasing importance. A high accuracy is requested from MFA calculations when quantity and quality of particular material flows are of major concern. Applying existing models, two major issues become obvious, which are discussed in this paper on a global scale: The limited availability of end-of-life scrap and possible quality constraints of the current recycling system.

Keywords:

Aluminium recycling – Material Flow Analysis – Scrap availability – Recycled content – Quality constraints

Aluminiumrecycling – Rohstoffversorgung über ein restriktives Volumen- und Qualitätssystem

Die begrenzte Verfügbarkeit von Energie und Rohstoffen sowie die ehrgeizigen CO_2-Reduktionsziele sind Grund zur Besorgnis in der metallurgischen Industrie wie auch in anderen Branchen der Grundstoffindustrie. Folglich werden im Rahmen der EU-Rohstoffinitiative Ziele zur Steigerung der Ressourceneffizienz definiert und es werden Maßnahmen zur Treibhausgasreduktion ergriffen. Die Fokussierung auf den Carbon-Footprint von Produkten und Unternehmen führt zum Beispiel zur Forderung nach hohen Recycling-Anteilen in Produkten. Aufgrund fehlender Kenntnisse über die relative Verfügbarkeit von sekundären Rohstoffen in wachsenden Märkten ist die Debatte um die konkurrierenden Ansätze Recycling-Anteil und end-of-life-Recyclingquote noch nicht abgeschlossen. Im Falle der europäischen Aluminiumindustrie leiden die verbliebenen Primärhütten unter den hohen Kosten für Energie und Emissionshandel. Ein Überleben ist von akzeptablen Stromverträgen und ihrer Rolle als aktiver Teilnehmer in der Netzmodulation abhängig. In der Recycling-Industrie sind Umstrukturierung und Konsolidierung noch nicht abgeschlossen. Andererseits wird mit einer deutlich steigenden Menge verfügbarer Aluminiumschrotte gerechnet, so dass auch Remelter und integrierte Gießereien vermehrt Altschrotte einsetzen um die Verwendung von Primärmaterial zu minimieren. Dies muss unter Einhaltung der gleichen engen Spezifikationen geschehen. Folglich kann die Verwendbarkeit sekundärer Rohstoffe eingeschränkt sein oder erfordert teure Aufbereitungs- und Sortierprozesse. Zur Analyse und Prognose der Verfügbarkeit von Schrott gewinnt die Stoffstromanalyse zunehmend an Bedeutung. Insbesondere wenn Quantität und Qualität der Stoffströme von wesentlicher Bedeutung sind wird von den Berechnungen eine hohe Genauigkeit gefordert. Unter Anwendung bestehender Modelle werden im Folgenden zwei wichtige Fragen auf globaler Ebene diskutiert: Die begrenzte Verfügbarkeit von End-of-Life-Schrott und Qualitätseinschränkungen des derzeitigen Recycling-Systems.

Schlüsselwörter:

Aluminiumrecycling – Stoffstromanalyse – Verfügbarkeit von Schrott – Recycled Content – Qualitätseinschränkungen

Recyclage d‘aluminium – approvisionnement en matières premières à partir d‘un système soumis à des contraintes concernant le volume et la qualité

Reciclaje de aluminio – suministro de materias primas a partir de un sistema restrictivo de volumen y calidad

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1 Global material flow models

Since 2002 there is a common approach of the aluminium industry to develop and up-date material flow models in the Global Aluminium Recycling Committee (GARC) [1], supported by the International Aluminium Institute (IAI) and the Organisation of European Remelters and Refiners (OEA). The most known and communicated result is the yearly update of the global aluminium cycle shown in Figure 1.

The global material flows of aluminium show the order of magnitude of the overall metal demand as well as scrap supply from production and end-of-life. In 2010 about 45 Mt of aluminium entered the use phase as finished products. In the same year 11 Mt of end-of-life scrap were collected for recycling. Aluminium is used mainly in long-life applications like building, transport and engineering, only packaging material has a short lifetime. Consequently about 31 Mt of aluminium products were added to the global metal stock. Over the decades an inventory in use of about 700 Mt has accumulated, accounting for 75 % of the ever produced primary metal (Figure 2). This metal stock is the future potential of raw material and energy we have invested in.

In order to evaluate the raw material availability and the efficiency of the product recycling various quotas and other indicators have been developed. The most widely used definitions were proposed by the European Association of Metals, Eurometaux in Brussels. Following two main indicators are distinguished [3]:

1. End-of-life recycling efficiency rate = recycling rate

Recycled aluminium produced from old scrap as a percentage of aluminium available from old scrap sources. It consists of:

- The end-of-life collection rate.
  Aluminium collected from old scrap as a percentage of aluminium available for collection from old scrap sources.
- The end-of-life processing rate.
  Recycled aluminium produced from old scrap as a percentage of aluminium collected from old scrap sources.

From a metals industry point of view the "end-of-life" recycling rate is the only meaningful way to evaluate the suc-

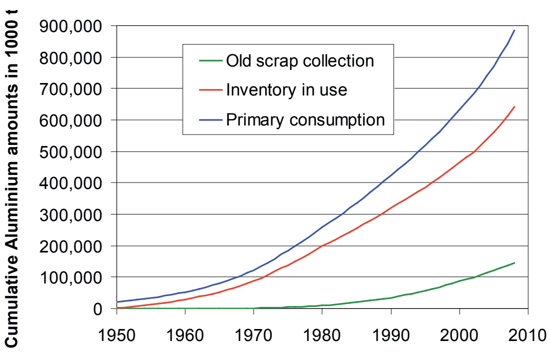
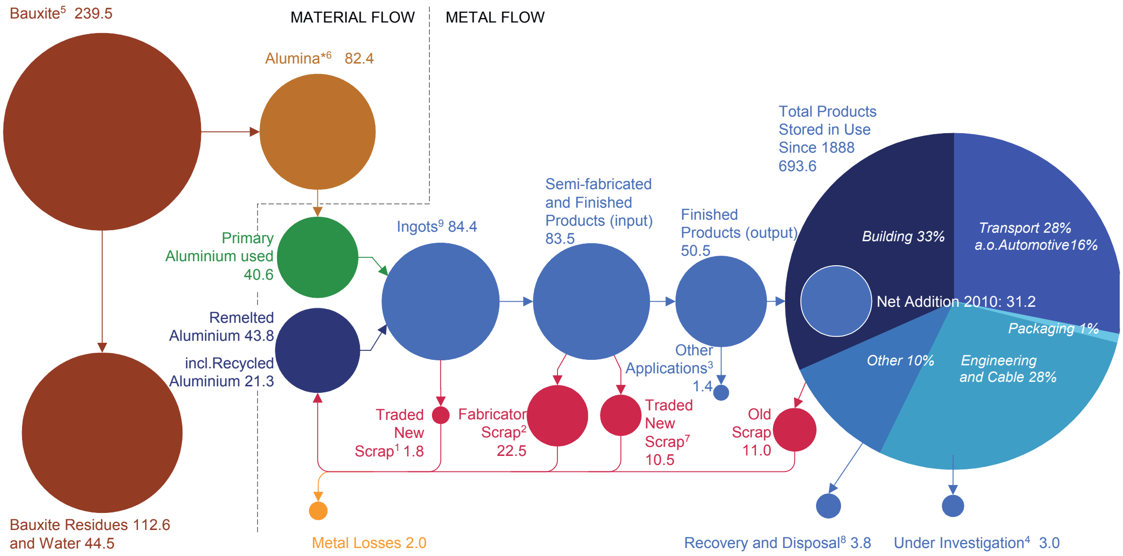


Fig. 2: Cumulative aluminium inventory, scrap collection and production [1]



Values in millions of metric tonnes. Values might not add up due to rounding. *Change in stocks not shown
1 Aluminium in skimmings; 2 Scrap generated by foundries, rolling mills and extruders. Most is internal scrap and not taken into account in statistics; 3 Such as deoxidation aluminium (metal property is lost) 4 Area of current research to identify final aluminium destination (reuse, recycling, recovery or disposal); 5 Calculated based on IAI LCI report - update 2010. Includes, depending on the ore, between 30% and 50% alumina; 6 Calculated. Includes on a global average 52% aluminium; 7 Scrap generated during the production of finished products from semis; 8 Either incinerated with/without energy recovery, material recovery or disposal; 9 Estimated stock decrease 890,000 tonnes.

Fig. 1: Global aluminium cycle 2010 [1]

cess of recycling activities. It is based on the actual achieved primary metal substitution by collection, processing and remelting [2]. The result can be given as the recycling quota, which consists of the above mentioned collection quota and the technical recycling quota. The latter represents the metal yield of the processing and melting operation. This separation clarifies the different systematic levels of the recycling chain and represents a basis for a resource-oriented view of the recycling efficiency.

2. Recycling input rate = recycled content

Recycled aluminium produced from traded new scrap and old scrap as a percentage of total aluminium (primary and recycled sources) supplied to fabricators.

Calculating the global recycled content based on post-consumer scrap only would result in 22 % for 2010. In other words, less than one quarter of current aluminium demand comes from used products!

If applying Eurometaux's definition of the recycled content the result is 37 %, because a certain amount of fabricator scrap is counted, too. Of course remelting of this material, which is often contaminated and/or thin gauged, is an important part of the process chain, but from a product point of view such a new scrap recycling does not contribute to raw material, energy or CO_2 savings. In contrary, trying to increase the recycled content by fabricator scrap would base a credit for recycling on a process-caused inefficiency, which leads to higher energy use and CO_2 emissions.

Even more problematic is the use of the recycled content as criteria for recycling performance. The recycled content of aluminium products is not low because of inefficient recycling but because of the strongly increasing demand of long-life applications, driven by the necessity of using its outstanding metallic properties. One example is the building sector in Europe. In 2010 the old scrap amount is only able to supply 23 % of the metal demand even though the end-of-life recycling rate is above 95 % [4]. Consequently growth and lifetime determine the recycled content globally; trade influences the regional results additionally.

In the meantime the recycled content of products has, despite all criticism, become the most used criteria of "green" products for many customers and policy makers. Already today customers require a high recycled content and it could well be that EU legislation will favour the recycled content for green labelling. Main concern of the metals industry is, if using the recycled content as criteria for regulation, that the future potential of recycling for raw material supply is overestimated whereas the actual performance of end-of-life recycling is not credited. Regulations should aim at improving the overall performance of the system, which usually benefits from increased end-of-life recycling efficiency, in particular the collection of used products [5, 6]. As aluminium is a relatively young material the aluminium stock growth is in a leaping phase and needs time to reach saturation. Therefore, recycled content shows a much lower amount than for many other metals.

Evaluating the statistical data from IAI confirms the dominant influence of yearly growth in aluminium production on the resulting recycled content (based on EOL-scrap) in the last decade (Figure 3). Especially during the financial crisis the recycled content increased significantly due to the lower production volume related to an unaffected end-of-life scrap supply.

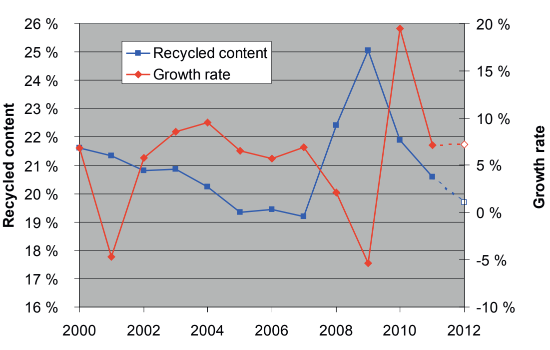


Fig. 3: Evolution of growth rate of Aluminium production and its recycled content based on collected end-of-life scrap from 2000 to 2011, 2012 values are estimated

Recent scenario calculations show that if the growth rate of aluminium demand will remain at an average of 4 % not more than 25 % recycled content will be reached (Figure 4). Even assuming a decrease of growth down to 0 % until 2050 the global recycled content will not exceed 40 % assuming constant collection rates.

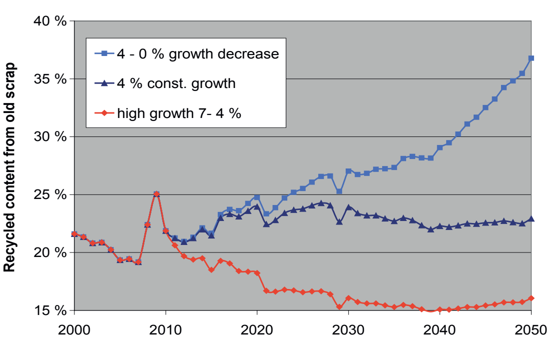


Fig. 4: Long-term development of average recycled content (old scrap based) of aluminium for different growth scenarios

Looking to the use of metals from an inventory perspective offers a much better possibility to focus on the benefits of materials in use (e.g. energy saving by lightweight construction) and the demand and supply of raw materials of such a system. Furthermore the link between materials and energy or CO_2 becomes obvious and the need for integral approaches of optimization.

2 Development of MFA of metals

So far Material Flow Analysis (MFA) is mainly used to assess a defined status (e.g. on annual basis), which results from a historic development. Even in this case the calculation results are sometimes difficult to interpret due to varying data quality or numerous assumptions. Main sources of uncertainty are product lifetime, fabricator scrap rates (customer utilisation), trade of parts and finished products, end-of-life collection rate, etc. If a top-down approach is used for MFA calculation a danger of misinterpretation exists, because no information about the accessibility and physical condition of the scrap volumes is given. A high scrap potential in packaging material is for example limited by user behaviour, collection logistic, technology, waste incineration, etc. Bottom up studies could provide the missing data, but the high efforts even increases with expanded regions.

2.1 MFA today

Looking from past and present also to the future, MFA can be used as a tool to forecast the development of scrap availability and composition. Combined with scenario calculation it can be used to estimate the scrap availability in different ways: Regional or global amounts, old and new scrap shares, scrap quality dependent on lifetime and application are some possible results. Despite the unknown accuracy of such calculations with respect to regional distribution of material, lifetime or growth rates, highly valuable information can be generated to support the business strategy development. Here recycling capacity planning, site and equipment selection, and scrap pre-treatment requirements are important aspects to be mentioned. MFA today usually

- considers material flows as mass or metal flows without quality information;
- the calculation of metal stocks and scrap availability is assumed to be driven by production flows;
- theoretical scrap amounts, based on products shipments and lifetime are used for quota calculation.

Nevertheless, a description of the magnitude of secondary raw material supply for different stakeholders is possible.

Current developments aim at the understanding of stocks (product inventories in use, so-called “urban mines”) as dynamic consumer and application determined systems, which consider lifetime distribution, trade and per capita “consumption” of materials as drivers of the metal cycle. In such models the accessibility of secondary raw materials in terms of collection probability at the end-of-life point is still missing. The collection rate could for example be extended by an accessibility factor to estimate the amount of available material. From a methodological point of view efficiency indicators for metal recycling must overcome the disadvantage of long-life applications caused by the time-depending material gap in growing markets.

2.2 Metallurgical limitations

Unfortunately, production and use of metals are more complex in reality. In some cases metal recycling cannot be treated as an alternative production route achieving the original properties and chemical composition of primary material. And, as a result of its electrochemical behaviour, each metal cycle looks completely different compared to any other.

Gold, silver, and copper for example are metals for which the original purity and therewith basic material properties can be reproduced from all kinds of secondary raw materials, independent of their metal content or the alloying element concentration. In this case the metal refining takes place after the melting step and almost all higher electronegative elements can be removed.

For aluminium and magnesium the opposite is the case. Refining has to be done before the primary metal is produced (pure alumina or magnesium chloride for the electrolysis). For recycling it means that the scrap has to be upgraded and sorted before remelting takes place. Nevertheless the properties of pure aluminium or magnesium cannot be recovered since nearly all alloying elements stay dissolved in the metal. Furthermore only very few closed-loop recycling systems for metal containing products exist.

Consequently we need to include metallurgical information in MFA models to determine how much scrap we actually can use in closed recycling cycles before reaching limits in terms of castability, formability, physical properties and surface appearance etc. Dynamic models are required because both, the chemical composition of the scrap and the specifications are changing over time.

2.3 Quality consideration in MFA

In above described models the scrap accessible is determined in terms of collection rate and defined recycling loops. Besides volumes the need for disaggregated quality information of collected material is increasing. Another aim is to evaluate the condition in which the individual part/material/alloy/element is present (e.g. gallium in PV cells or 6063 aluminium profiles in ELV shredder fractions). This “metallurgical accessibility” at element or alloy level defines the requirements for material up-grading or sorting processes and if possible for metal refining. Consequently, the achievable purity before the melting step determines the recyclability and the metallurgical limitation determines the scrap value for the target application.

Long-term goal should be a “quality constraint material availability modelling”. Based on the approach of a dynamic stock modelling with the understanding of alloy qualities and limited refining possibilities following questions could be investigated:

- element accumulation in metal cycles (alloying elements and trace elements);
- scenario calculations for material demand and scrap supply with increased quality resolution.

3 Automotive casting as a bottleneck for recycling

As the amount of old scrap is increasing quality constraints are becoming more relevant. Although the overall average recycled content of aluminium is expected to grow only moderately over the coming decades, this varies significantly for different applications. Due to the limitations of refining and the high costs of separating different alloys and impurities, old scrap is currently often used to pro-

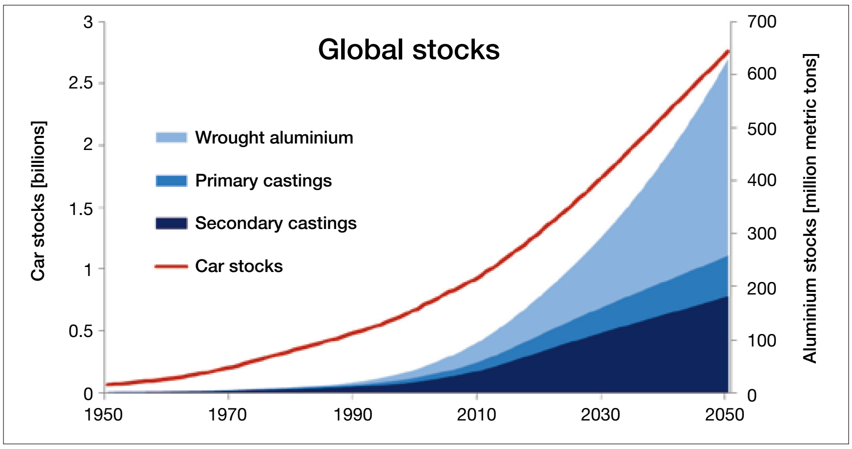


Fig. 5:
Global passenger car stock and embodied aluminium stock, divided into secondary and primary castings, and wrought alloys. The future passenger car stock is based on estimates of medium population, car/capita growth and lifetime (base scenario in Modaresi & Müller 2012 [9]).

duce secondary castings, which require larger amounts of alloying elements and are more tolerant towards impurities. Secondary casting alloys are predominately used for the fabrication of automotive components such as engine blocks, transmission parts, etc. [7, 8], which form a so-called bottom reservoir of the apparent alloy cascade in open recycling chains. In addition to secondary castings, automobiles embody also a growing amount of primary castings and wrought aluminium (Figure 5), mainly to reduce vehicle weight and increase fuel efficiency. As aluminium scrap from end-of-life vehicles (ELVs) is mostly recovered in a mixed fraction of these alloys, both sheets and extrusions are not recycled in their specific alloy group. Consequently the usability of this material becomes limited by increased element concentration.

The current recycling system based on blending and dilution of different scrap qualities is economically attractive and ecologically sensible, because it saves sorting costs as well as alloying elements, which would need to be added from other sources. However, the current recycling system relies on a constant growth of secondary castings. Model simulations of the global vehicle stock [9] have shown that the old scrap from ELVs is likely to exceed the demand for secondary castings already about 2018±5 (see Figure 6 for a simplified visualization). A continuation of the current recycling practice would thus lead to a growing scrap surplus that will not find a market in automotive secondary castings, with corresponding losses in energy saving potential. Sensitivity analyses demonstrated that the computed timing of the scrap surplus is relatively robust, because the vehicles causing the scrap surplus – which is expected in about 2018 – are already on the road, and the timing thus depends largely on the development of the use of secondary castings in new vehicles over the coming years, a market with limited growth potential. However, the size of the potential longer-term scrap surplus is much more uncertain due to the large, but uncertain growth potential of wrought aluminium in body-in-white applications.

Simulation results further demonstrate that a scrap surplus can only be avoided with a fast implementation and high penetration of scrap sorting technologies. Due to the large number of alloys used for automotive cast and wrought aluminium, these sorting technologies need to be capable not only to differentiate cast and wrought scrap, but also key alloy groups within these categories. Furthermore, Figure 6 shows that within the automotive sector an ad-

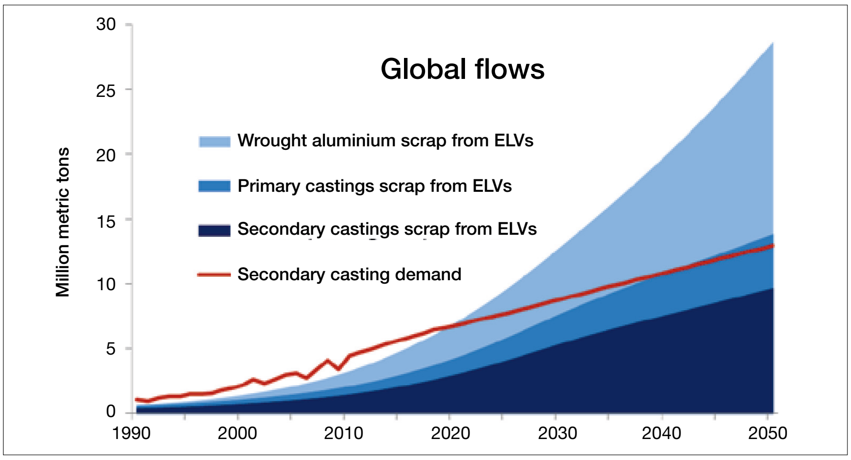


Fig. 6:
Simulation of secondary casting demand (red) and aluminium scrap from ELVs (blue). Aluminium scrap from ELVs will exceed the demand for secondary castings by about 2019. Note that this visualization does not account for losses due to incomplete collection and recycling, additional downgraded scrap from non-automotive sources, and the need of clean aluminium resources (e.g., dross, turnings, new scrap, or primary aluminium) for dilution purposes. For further details see [9].

ditional sorting of different casting alloys will be necessary around 2040. Here mixing of high and low silicon containing castings as well as copper and magnesium concentrations should be avoided. As aluminium scrap from several sources other than automobiles are currently finding a second life in automotive castings too, a saturation of this application would cause implications for the entire aluminium recycling system, and improved sorting technologies will be required also in other sectors, such as buildings.

Alternative mitigation options involve the development of new applications for cast aluminium. As scrap prices can be expected to decrease in case of approaching a scrap surplus, secondary castings of aluminium are likely to become more attractive. However, although such additional casting markets would delay the scrap surplus, they could not prevent over the longer time to create their own recycling challenges. Secondly, the complexity of alloy application is also caused by the product design. Possibilities to reduce the material complexity or design options with more compatible parts should be considered as an important development target [10].

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Paper III

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'Component- and Alloy-Specific Modeling for Evaluating Aluminum Recycling Strategies for Vehicles'

Roja Modaresi, Amund N. Løvik & Daniel B. Müller, JOM, The Journal of The Minerals, Metals & Materials Society (TMS), Vol. 66, No. 11, 2014,

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Paper IV

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'Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements'

Amund N. Løvik, Roja Modaresi, and Daniel B. Müller, Environmental Science and Technology 2014, 48, 4257−4265, dx.doi.org/10.1021/es405604g

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Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements

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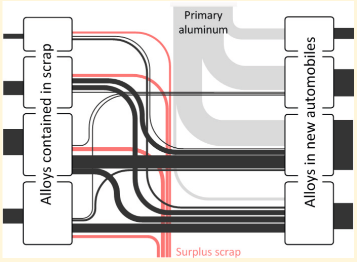
Supporting Information

ABSTRACT: Aluminum recycling currently occurs in a cascading fashion, where some alloys, used in a limited number of applications, absorb most of the end-of-life scrap. An expected increase in scrap supply in coming decades necessitates restructuring of the aluminum cycle to open up new recycling paths for alloys and avoid a potential scrap surplus. This paper explores various interventions in end-of-life management and recycling of automotive aluminum, using a dynamic substance flow analysis model of aluminum and its alloying elements with resolution on component and alloy level (*vehicle-component-alloy-element* model). It was found that increased component dismantling before vehicle shredding can be an effective, so far underestimated, intervention in the medium term, especially if combined with development of safety-relevant components such as wheels from secondary material. In the long term, automatic alloy sorting technologies are most likely required, but could at the same time reduce the need for magnesium removal in refining. Cooperation between the primary and secondary aluminum industries, the automotive industry, and end-of-life vehicle dismantlers is therefore essential to ensure continued recycling of automotive aluminum and its alloying elements.



1. INTRODUCTION

Aluminum production is energy intensive and causes significant greenhouse gas emissions, recently estimated to 1.1% of world total (CO_2 eq.).[1] Material flow models have shown that scrap availability will increase, enabling industry to meet demand with a higher share of postconsumer scrap than today's ~20%.[1−3] An increased share of secondary production can significantly reduce energy use and emissions, but poses a challenge for the industry with regard to material quality because of the large diversity of aluminum alloys and the limited number of applications that can currently absorb end-of-life scrap.[4,5]

Dynamic material flow models are ideal for investigating such problems because they can be used to forecast future availability and demand of different types of scrap as well as qualitative changes within each type. Early models with a focus on scrap quality, developed for the European market, indicated that scrap supply would increase faster than the demand for traditional secondary alloys, thus pointing at a potential problem with scrap utilization.[6,7]

Hatayama and colleagues[8] applied a regional model of aluminum use and recycling to China, Europe, Japan, and the United States, making assumptions about the alloys used in the relevant sectors (*sector-alloy-element* model) to find the chemical composition of scrap flows. They connected this to an optimization procedure for blending of different raw materials that determines the maximum scrap utilization, and concluded that a regional scrap surplus in the United States and Europe may be absorbed in Japan and China through trade of scrap today, whereas in 2050 the four regions together will be a net exporter of scrap. In a follow-up study,[9] a similar model was used to show that introduction of electric and hybrid-electric vehicles can intensify the regional scrap surplus by lowering the demand for secondary cast alloys.

Gaustad and colleagues developed a dynamic material flow model with chemical element resolution and an optimization procedure,[10] and use this to demonstrate the importance of scrap segregation for a case of aluminum recycling from three sectors (beverage cans, buildings and automotive) in the United States. However, this study uses a simplified representation of aluminum use by including only selected components. For example, automobiles are represented as three parts (castings, bumpers and body sheet), with no attempt to quantify the relative share of these, and assuming a single alloy used for each of them. Although indicating a problem, the conclusions from these models[6−10] regarding scrap surplus are limited by the regional system boundaries: rapidly developing regions such as India, South-East Asia, or Latin America, could absorb the surplus scrap and thereby delay the problem. To make statements about the timing, it is necessary to use a global system boundary.

Modaresi and Müller[11] developed a dynamic model of aluminum in automobiles worldwide, distinguishing between wrought, primary cast, and secondary cast aluminum. Maximum

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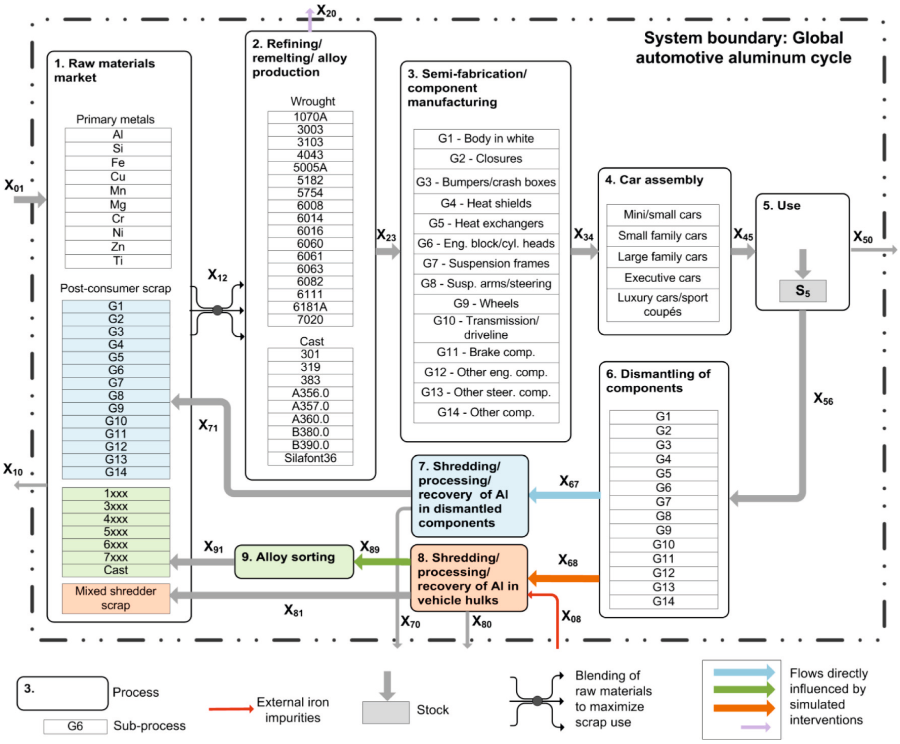

Figure 1. System definition of the global use, production and recycling of aluminum and its alloying elements in automobiles. A layered model tracks aluminum and the most common alloying elements through the use and recycling of alloys and components in vehicles. Detailed flows, for example, which alloys are used in specific components, are not shown, but included in the model.

scrap use was estimated by assuming that up to 56% of the mass of cast alloys is scrap (70% of cast alloys are secondary, and they contain up to 80% old scrap). They found that without any intervention, aluminum scrap supply from automobiles is likely to exceed demand in the same sector between 2014 and 2023, where the variation in timing is due to different assumptions for the model drivers and key parameters such as population, vehicle ownership or scrap dilution rate. This indicates a strong need to restructure recycling paths, since automotive castings function as the bottom reservoir in a recycling cascade that includes all aluminum products. However, the model lacks the component level resolution which is needed to simulate alternative strategies, as well as the chemical element resolution necessary to quantify the capacity for scrap use in other applications than the traditional secondary castings.

These previous material flow studies were mostly concerned with problem identification, which is reflected in the architecture of the models. Automotive aluminum was represented in a simplified way: as a collection of alloys,[6,8,9] as example components made of single alloys,[10] or as cast/wrought material.[7,11] In reality, aluminum is used in a very wide range of components.[12] The choice of alloy for a given application depends on material property requirements, which in the case of automotive components leads to an extreme diversity in chemical composition. Under the assumption that all automotive aluminum enters the same scrap stream through shredding of the vehicle hulk, the component level becomes irrelevant since it has no influence on the average composition of the scrap. However, dismantling of selected components before shredding enables segregation of scrap streams with different compositions, determined by the alloys used in these components. To be able to assess interventions in end-of-life vehicle management, it is therefore necessary to include a component level in the model. Moreover, some component groups have a much larger growth potential than others: By relating the alloy use to components, it is possible to create a more realistic forecast of future alloy demand and scrap quality.

These issues were recently addressed with a model for forecasting global scrap availability from vehicles in 14 different component groups and 7 alloy types (*vehicle-component-alloy* model), as well as the demand for these in new vehicles.[13] Although giving a detailed understanding of future alloy demand and scrap supply from automobiles, the model still lacks chemical element resolution and a procedure to quantify possible scrap surplus, and cannot fully assess the effect of interventions, or identify alternative recycling paths.

The chemical element resolution is needed because the possibility of utilizing scrap ultimately depends on its chemical composition, and due to thermodynamic limitations there is a lack of viable refining options for all alloying elements except magnesium.[14,15] Magnesium is often removed from molten

Table 1. Conditions Explored in Model Simulations

condition	description	implemented
low dismantling	representing current level of component dismantling (e.g., 100% of wheels, 10% of closures, 50% of bumpers and crash boxes, 0% of heat shields, 50% of engine blocks and cylinder heads, 0% of other engine components).	yes
high dismantling	representing a maximum level of dismantling with current technology (e.g., 100% of wheels, 80% of closures, 75% of bumpers and crash boxes, 50% of heat shields 100% of engine blocks and cylinder heads, 75% of other engine components).	no
alloy sorting	sorting of mixed shredded aluminum into 8 categories of alloys with 90% success rate.	no
recycled material used in safety-relevant cast parts	end-of-life scrap used in the production of safety-relevant cast parts (*body-in-white, suspension frame, suspension arms and steering, wheels, brake components, other steering components, other components*)	no
demagging used	magnesium removal during refining is used.	yes

aluminum to achieve the low levels required in the most common secondary cast alloys, typically by injecting a mixture of an inert gas and chlorine gas into the melt.[16] Because of the high value of magnesium, costs associated with the process, and chlorine emissions[17] it is desirable to reduce the extent of this practice.

In the present work we attempt to overcome the aforementioned limitations with a newly developed model that integrates: (1) a global dynamic material flow model of aluminum in automobiles; (2) component-level resolution; (3) alloy resolution; (4) chemical element resolution of alloys and scrap, combined with optimization procedure to quantify the scrap surplus and recycling paths under maximum scrap utilization. We focus on the automotive subsystem, because it has been identified as the most critical sector,[4,8,11] being both the main scrap sink in the system and largest source of it. The architecture of the model (*vehicle-component-alloy-element*) allows for a more realistic representation of interventions based on component characteristics, whereas the optimization procedure determines the quantitative impact of them and can point out new recycling paths for the industry by indicating alloys and components that could function as intermediate reservoirs in the cascade. By analyzing model simulations for different conditions and interventions in end-of-life treatment and recycling, we address the following questions: (1) What recycling paths of alloys and components are likely under current practice in ELV management and auto manufacturing? (2) Which interventions or combinations of interventions can most effectively open up new recycling paths and thus mitigate scrap surplus in the long term?

2. MATERIALS AND METHODS

We used a layered material flow analysis framework to evaluate the future recycling potential and pathways of aluminum scrap within the automotive subsystem. An implicit assumption is that other sectors of use, such as buildings or consumer durables, can absorb their own scrap in the future, but have a limited capacity to utilize scrap from automobiles. This is likely due to the large variety of alloys in the automotive sector and the presence of cast alloys with high concentrations of alloying elements, whereas for example the vast majority of extruded building products are made from a few quite similar alloys of the 6xxx series and can easily be separated from other types.[18] The first place to look for improvements is therefore within the automotive subsystem itself.

We track aluminum as components, alloys, and chemical elements through the global system of vehicle use, production and end-of-life management, as illustrated in Figure 1. The core of the stock-driven model, developed in previous works,[11,13] gives a forecast of the aluminum components entering and leaving use through historic data and future projections of world population and car ownership. By constructing a recipe for the alloys used in various components we arrive at a range of material compositions that needs to be produced by proper blending of primary aluminum and alloying elements with the scrap materials available at end-of-life. For each year, the model determines: (1) stock of vehicles in use, S_5, from population and vehicle ownership; (2) vehicles leaving use, X_{56} and X_{50}, by lifetime distribution and production in previous years; (3) demand for new vehicles in five segments, X_{45}, from a balance equation of stock change and outflow; (4) aluminum metal in new components, X_{34}, and alloys needed for these, X_{23}; (5) availability of scrap of different compositions, X_{71}, X_{81} and X_{91}, by past alloy use and ELV management criteria; (6) optimal blending of scrap and primary metals to produce the alloys needed and the exact composition of alloys in X_{12}, by a linear program. The linear program minimizes the use of primary aluminum and alloying elements, and does not consider the difference in price between scrap types or the balancing of supply and demand through price changes. The quality of scrap and the amounts available in a given year are decided by the historic aluminum use in different components, the simulated utilization (blending) of scrap in the past, and the current practice in ELV management. Along the chain there are losses due to: incomplete collection, X_{50}; shredder dust and incomplete sorting from other materials, X_{80} and X_{70}; oxidation during remelting and magnesium removal, X_{20}. In addition, there may be a loss from the system due to surplus scrap, X_{20}.

Forming and manufacturing scrap were excluded from the model, because closed loop recycling of new scrap into the same alloy or very similar alloy is something that is either done already, or could relatively easily be achieved in the future by scrap segregation at source or automatic sorting technologies.[19,20] We do not consider this one of the main limitations for the system in the future. If we assume closed loop recycling of all new scrap, this flow will have no influence on the system's capacity to absorb end-of-life scrap, and including it in the model will only introduce unnecessary calculations in the optimization procedure. A complete description of the system definition, mathematical model formulation, parameter estimation and data sources is in the Supporting Information (SI).

The timing and magnitude of a potential scrap surplus depend on many factors, including but not limited to future population growth, vehicle ownership, and the market penetration of electrical vehicles. Previous work has indicated that a scrap surplus is likely to occur within a wide range of scenarios for these parameters.[11] Therefore, we focus on interventions in the industry (end-of-life vehicle management, secondary aluminum industry, component manufacturers), which may enable increased scrap utilization in the future.

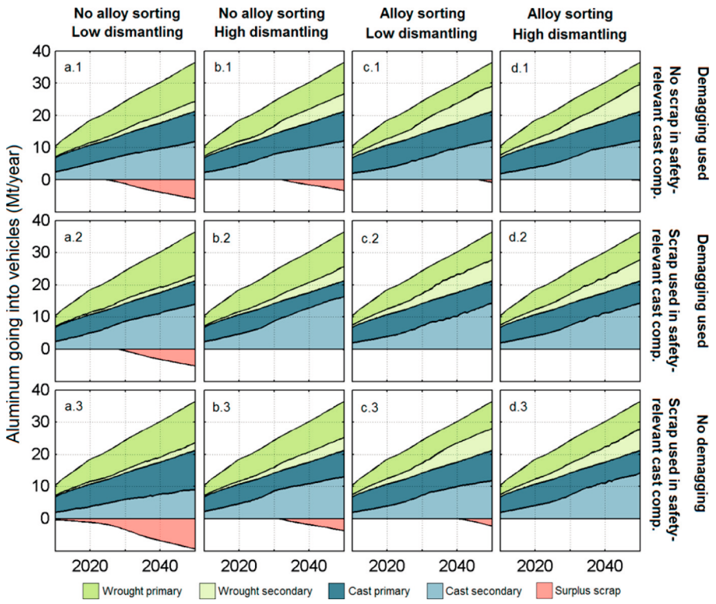

Figure 2. Simulated future production of wrought and cast aluminum for vehicles, and the relative share covered by primary and secondary sources under combinations of interventions in ELV management and scrap sorting (columns) and restrictions in aluminum/auto manufacturing industry (rows). A combination of better scrap segregation and recycling into safety-relevant cast components is necessary to avoid surplus scrap until 2050 (b.2, c.2, d.2−3). Increased dismantling combined with alloy sorting eliminated the need for magnesium removal during refining (d.2).

The model was run for different scenarios of ELV management and alloy production, assuming that the whole industry will adapt a given strategy. This can shed light on the ultimate potential of interventions, though in reality they would only be implemented gradually. The interventions include: (1) different levels of component dismantling before shredding; (2) advanced alloy sorting of mixed shredded aluminum by laser-induced breakdown spectroscopy (LIBS); (3) with and without recycled material in safety-relevant cast components; (4) with and without magnesium removal during refining. An overview of interventions can be found in Table 1, and details are in the SI.

Dismantling is already being done for some component groups, mainly for the purpose of reuse or remanufacturing of parts,[21] but can also be an effective way of segregating scrap of different qualities by taking advantage of the component-specific use of alloys. We assume that components, once dismantled, are kept apart from each other to obtain separate scrap streams. It is also assumed that dismantled aluminum parts are completely separated from particles of other metals. Assumptions regarding current and possible future levels of dismantling are based on a comprehensive evaluation by industry experts for a project with the European Aluminium Association and the International Aluminium Institute.[13,22]

LIBS sorting is a promising technology that enables high-speed automatic sorting of aluminum particles based on their chemical composition, but so far only being used on a small scale with production scrap.[19,20] We assume that alloys can be identified by the series they belong to (1xxx, 3xxx, 4xxx, 5xxx, 6xxx, 7xxx, cast low Cu, cast high Cu) with a 90% success rate, and that the failed 10% are distributed evenly between the other categories.

Safety-relevant cast components, such as wheels or space frame nodes, must have a combination of high strength and ductility to be able to withstand impacts. This requires a very low level of impurities, especially iron, which can only be achieved using primary metal.[23,24] We consider a widespread use of old scrap in such components as a separate intervention because it will require extensive testing, possibly adjustment of company-specific alloy specifications, and substantial coordination between refiners, foundries and auto manufacturers.

Finally, the possibility of reducing the practice of magnesium removal (demagging) in parallel with recycling into safety-relevant components was investigated as a separate strategy by running the model without the option of magnesium removal in the refining/remelting process.

3. RESULTS

The flows of primary- and recycled aluminum into the stocks of cast and wrought automotive components in use are shown for all simulations from 2010 to 2050 in Figure 2 together with the available scrap which could not be utilized due to material composition constraints. Simulation a.1, representing current practice, resulted in a scrap surplus from 2025 that grows to 28% of available scrap in 2050. An increased level of dismantling (b.1) delayed the surplus until 2033, and reduced the magnitude to 16% of available scrap in 2050. Alloy sorting of the mixed shredded fraction gave similar results for both levels of dismantling (c-d.1): the surplus was further delayed until 2047 (low dism.) and 2048 (high dism.). In these simulations (a-d.1), recycling into safety-relevant cast components was excluded. By lifting this constraint (a-d.2), an increased amount of scrap could be utilized and surplus was avoided for the whole time period in the simulations with

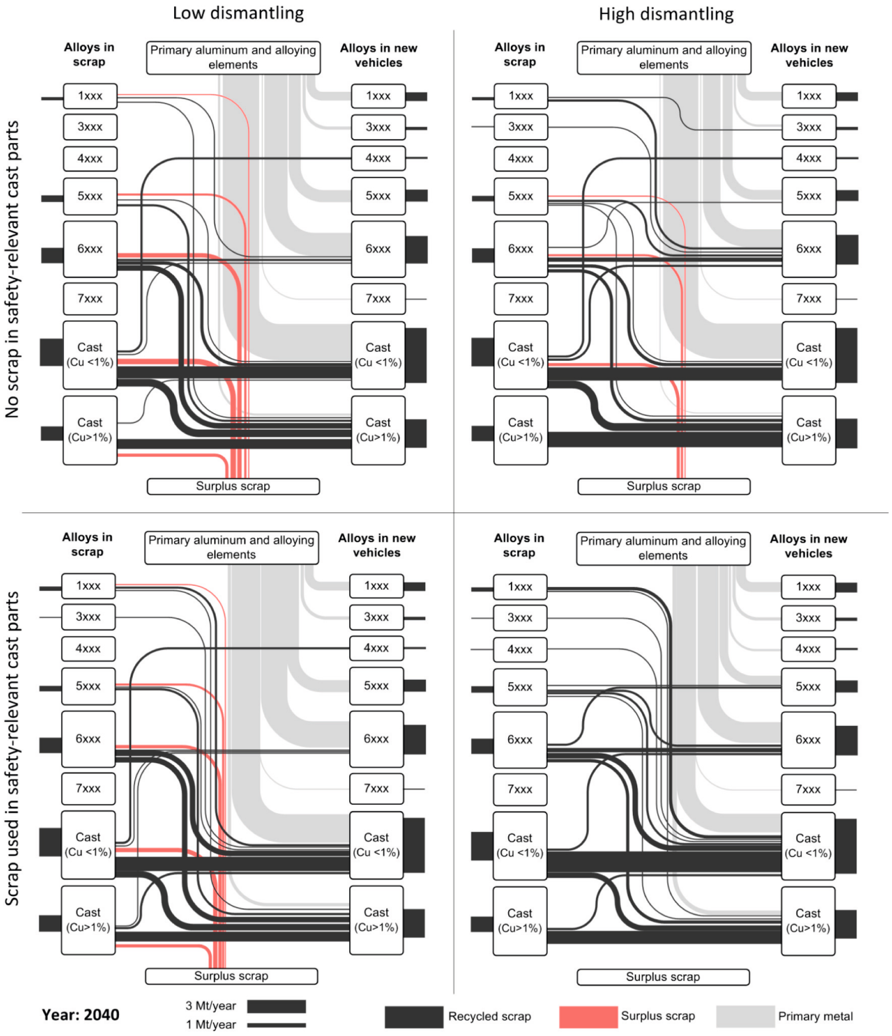

Figure 3. The automotive aluminum recycling cascade illustrates the pathways of alloys contained in scrap as they are recycled into new alloys in 2040. A "closed loop" is not achieved in most cases because of incomplete separation at end-of-life. By utilizing intermediate scrap reservoirs (low-Cu cast and 6xxx) and taking full advantage of dismantling as a scrap segregation measure, surplus may be avoided (bottom right). Flows smaller than 0.5% of the total are not shown.

increased dismantling and/or alloy sorting. The third row shows the results when magnesium removal during refining was excluded. Here, scrap surplus was avoided only by combining alloying sorting and increased dismantling (d.3).

Alloys and their compositions were tracked throughout the system. Scrap streams, such as dismantled engine blocks, wheels or the mixed shredded fraction, contain a variety of alloys. Because of this mixing, it is often not possible to recycle a scrap alloy into the same. For example, all 1xxx alloys that are contained in the mixed shredded scrap will necessarily be transformed to a lower purity alloy upon recycling. This leads to a "cascade" of recycling where some alloys absorb most of the scrap, and others act as sources of scrap only. Figure 3 visualizes this cascade in 2040 for four of the simulations by showing the pathways taken by the main alloy groups through recycling. The high-Cu cast alloys act as the bottom reservoir in the system. They absorb large amounts of scrap from all other alloys, but cannot in turn be used as a source for other alloys. As seen from the lower half of the figure, the system's performance is improved by allowing recycling into safety-relevant cast components. Scrap with the right composition is available in large amounts due to the high dismantling rate for wheels and the low variation in alloys used for that purpose. Redirecting this scrap to an intermediate reservoir frees up capacity in alloys with a high tolerance for impurities to absorb more of the mixed scrap. When combined with a high level of dismantling (lower right of Figure 3), the 6xxx alloys and low-Cu cast alloys both act as intermediate reservoirs, thereby slowing down the cascading behavior of the system. In all simulations, the surplus occurred mainly for the mixed shredded scrap, such that the relative magnitudes of the red flows in Figure 3 always reflect the constituents of this scrap. Many of the wrought alloys (1xxx, 5xxx, 6xxx) are pulled out of the system as "passengers" in mixed shredded scrap because of limited dismantling, instead of being used to produce these alloys again. There is low utilization of scrap in wrought alloys, the only significant absorber being the 6xxx alloys.

The chemical composition of mixed shredded scrap is expected to change significantly within the coming decades as shown in Figure 4. Three major trends were observed: (1) decreasing silicon concentration, (2) decreasing copper concentration, and (3) increasing magnesium concentration. This reflects the recent and expected future penetration of wrought aluminum, which on average contain less silicon and copper, but more magnesium. Increased dismantling will amplify the trend, since it has a larger potential for cast than wrought components. The concentration of copper shows the largest change, down from almost 1% in 2010 with low dismantling to 0.2% in 2040 with high dismantling.

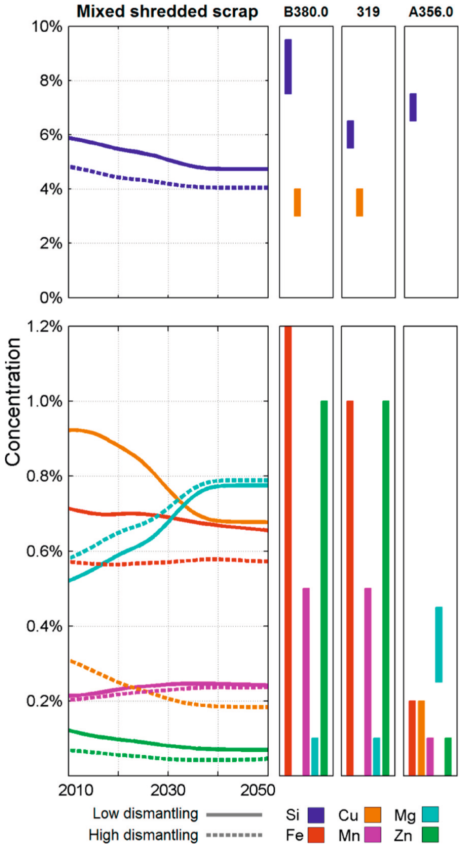

Figure 4. Simulated future chemical composition of mixed shredded automotive aluminum scrap under different degrees of component dismantling (left), and composition limits for some important cast alloys (right). The concentration of magnesium increases, while silicon and copper decreases, due to increased penetration of wrought components. The composition of mixed scrap is diverging from the specifications of traditional secondary alloys (B380.0, 319) but is still very far from typical primary cast alloys (A356.0). This trend is amplified by increased dismantling, because it mostly targets the secondary cast components.

4. DISCUSSION

Scrap surplus is a consequence of the dynamics of in-use stocks and complexity in the recycling system. Mixing of different materials prevents closed-loop recycling and leads to a recycling cascade where alloys play different roles as sources or sinks of scrap. Such systems depend on growing in-use stocks of the sinks to ensure sufficient scrap demand. Parameters in the model may be divided into two groups based on whether they influence (1) the growth rate of the in-use stocks, or (2) the complexity of the system. In group (1) are the drivers such as population, vehicle ownership and the lifetime of cars which determine the in-use stock over time and the number of vehicles entering and leaving use. Because scrap surplus is closely related to stock saturation, these factors have a large influence on the timing of the problem. However, it was found in a previous study the effect is small within a wide range of future scenarios due to the amount of aluminum already existing in use and the relatively slow rate of change for the drivers.[11] Increased growth rate of population or vehicle ownership, or longer lifetime, may delay the problem but not permanently solve it due to the eventual saturation of in-use stocks. Similarly, large-scale penetration of electrical cars may reduce the demand for secondary cast components, and thus intensify the problem and the need for better scrap segregation.[9,11] Other sectors of use were not included in the model, while in reality some scrap from these sectors is being absorbed by the secondary cast alloys for automobiles. Due to large in-use stocks, it is expected that scrap supply from these sectors, particularly buildings, also increases in the future.[25] It is therefore unlikely that the system can be reversed so that these sectors absorb scrap from automobiles. In group (2) are the number of alloys, the chemical composition limits of these, their relative use in various components, all the parameters that influence scrap segregation at end-of-life (e.g., accuracy of alloy sorting technologies), and the contamination rate for external impurities such as free iron or copper. Changes in these parameters may influence the time and magnitude of scrap surplus as well as the effectiveness of dismantling and alloy sorting. For example, a large diversity in alloys for closures will make dismantling of these a less effective option. Because complexity in the recycling system is a cause of surplus, most model simplifications can inherently lead to more optimistic results. One important limitation of the model is that although 26 different alloys were used, the specifications found in industry standards are relatively wide and there is a significant degree of overlap between them. Typically, a lower and upper limit is defined for 1−3 of the alloying elements, while for the rest, only the upper limit is given and the lower limit is zero. Nevertheless, these minor alloying elements are often added. Examples include iron for improved high-pressure die casting process, titanium or boron for grain refining, zirconium to influence recrystallization and antimony or strontium for modification of the microstructure.[26,27] Moreover, each company has its own internal alloy specifications with stricter impurity limits. Hence, the real diversity of automotive aluminum alloys is larger than what is captured by the model. Another important simplification is that the relative use of different alloys for a given component was assumed to be constant over time. For most components this reflects reality well given the resolution of the model (e.g., cast 3xx.x wheels have always been the dominant technology for this component), but there are exceptions: bumper technology has moved from 7xxx sheet to 6xxx extrusions.[28] Such changes may inhibit recycling if the alloys become obsolete before they are recycled.

Only one external impurity, iron, was included in the model, and it was assumed that it only enters the system through shredding of the vehicle hulk. Other contaminations in the mixed shredded scrap, such as copper, zinc or nonmetallic inclusions may further inhibit recycling, but were not included due to a lack of quantitative estimates. Moreover, dismantled parts will contain impurities to varying degrees. One important future limitation to closed-loop recycling of wrought alloys may be the use of steel rivets, which are difficult to separate from aluminum sheet during recycling.[29] An increased concentration of iron leads to lower formability of the sheet material,[30] which is currently a limiting factor for aluminum use in more complex closures such as doors and liftgates. [31]

The model does not consider the relationships between scrap supply, demand and prices; in other words the simulations reflect a situation where both scrap supply and demand are price inelastic. A surplus of scrap will lead to significantly lower prices and have repercussions throughout the system of ELV management, scrap processing, recycling and component manufacturing, potentially increasing the competitiveness of secondary aluminum versus other materials. However, the short-run price elasticities of scrap supply and demand have been shown to be very low, which confirms the validity of the model.[32]

Most of the model limitations lead to an underestimate of alloying element and impurity concentrations in scrap, or idealize scrap blending possibilities; hence the conclusions drawn here regarding interventions must be regarded as best-case results. Nevertheless, it is possible to point out some directions in which the system must develop to facilitate aluminum recycling in the future.

In simulation a.1, representing current European ELV management, scrap surplus occurred from 2025, which is 7 years later than in the base scenario of our previous model.[11] Maximum recycled content was previously fixed as 56% and 0% for cast and wrought alloys respectively. In the current model, where maximum recycled content is determined by the chemical composition of scrap and alloys, maximum recycled content was found to be 51% and 13% for cast and wrought respectively in 2025 (Figure 2, a.1), increasing to 55% and 19% in 2040. The increased recycled content in wrought alloys and an updated population scenario are the main reasons for delayed scrap surplus compared to the previous model. This result shows that current dismantling practice can already alleviate some of the pressure on the traditional scrap absorbers by liberating components which can be recycled into wrought alloys. In the long term however, additional measures are needed to ensure full utilization of scrap.

An increased level of dismantling delayed the scrap surplus until 2033 (Figure 2, b.1). As can be seen in the upper part of Figure 3, a higher level of dismantling enables significant recycling into the 6xxx alloys (41% recycled content). However, because of the restriction of not using scrap in safety-relevant cast components such as wheels, this measure has little effect on the recycled content in cast alloys, which is already close to 100% for the high-Cu alloys. Alloy sorting delayed the surplus until 2047 and 2048 with low and high level of dismantling respectively, by enabling a recycled content of about 50% in 5xxx and 64% in 6xxx alloys. The results indicate that advanced alloy sorting of mixed shredded scrap is more effective than intensified dismantling. However, such sorting technologies — although promising — have yet to be proven effective for sorting of dirty end-of-life scrap.[20]

The use of recycled material in safety-relevant cast parts had a large impact on the results, and is a key development that needs to take place to avoid scrap surplus in the long term. However, it is only effective when combined with better scrap segregation to reach sufficient quality. Again, impurities not included in the model, for example, attached to dismantled parts, may cause problems in practice. For example, iron levels below 0.2% are usually required to achieve sufficient ductility in cast wheels or nodes used in space frames.[24] Current recycling of used wheels into steering system parts by Nissan is a first step toward development of intermediate scrap reservoirs.[33]

The results showed that the removal of magnesium during refining is a necessary element of the current recycling system (Figure 2, a.3), without which there would already be a surplus of scrap today. Due to the increased penetration of wrought alloys, the concentration of magnesium in mixed scrap is expected to increase to about one and a half times its current level (Figure 4). Hence, it is likely that efforts to reduce chlorine emissions from demagging must be intensified in the future. Because of such emissions and the value of magnesium as an alloying element, it is desirable to keep this element in the cycle. With the most ambitious strategy for scrap segregation, scrap with magnesium can be redirected to applications where it has a value, and removal is no longer needed for full scrap utilization (Figure 2, d.3).

The results confirm that the automotive aluminum sector may go from being a net scrap consumer to a net scrap producer in the coming decade. Based on model simulations, we suggest a tentative list of priorities to enable increased recycling within the sector in the coming decades: (1) increased dismantling of components before shredding, in conjunction with a strategy to develop high-volume applications of 6xxx alloys with a high recycled content; (2) closed-loop recycling of safety-relevant cast parts (mainly wheels); (3) development of technologies for automated sorting of shredded scrap. While the need for such interventions comes from the aluminum industry, the realization of them depends on agents elsewhere in the system.

In the current situation, with a low price difference between primary and secondary material, there is limited economic motivation for investments in scrap segregation technologies or for a wider use of postconsumer scrap. A higher availability of scrap will lead to lower prices and incentivize such new developments. However, in the case of dismantlers, it is unlikely that prices of scrap will have a large influence on how they operate; a study from France showed that about 95% of their revenue comes from selling dismantled components for reuse or remanufacture, and only about 4% comes from selling the vehicle hulk which contains the majority of the aluminum.[34] Sorting technologies such as LIBS are not yet efficient for end-of-life scrap.[20] A larger price difference between scrap types will motivate companies to develop the technology, but only after the surplus has occurred. Increased scrap use in safety-relevant components may require relaxing the composition limits of alloys. Recent research has shown that the same material properties can be achieved with a higher level of trace elements by modifying the production route.[35] Currently, agreements between refiners and their customers are based on compositional specifications rather than material properties. New developments can only happen through cooperation to define new alloy standards, which will demand extensive material testing. Early recognition of these challenges and collaboration between the different players to explore new technical solutions are essential to ensure that aluminum and its alloying elements are effectively recycled in the future, with associated energy use and emissions reductions.

■ ASSOCIATED CONTENT

Supporting Information

Detailed description of system definition, mathematical model formulation, parameter estimation and data sources. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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■ ABBREVIATIONS

ELV end-of-life vehicle

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Paper V

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'Global Carbon Benefits of Material Substitution in Passenger Cars until 2050 and the Impact on the Steel and Aluminum Industries'

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Global Carbon Benefits of Material Substitution in Passenger Cars until 2050 and the Impact on the Steel and Aluminum Industries

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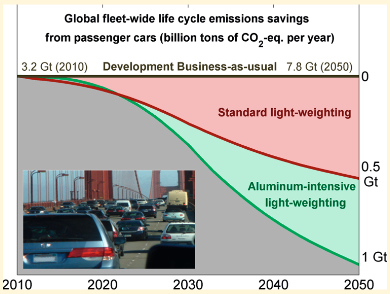
Ⓢ *Supporting Information*

ABSTRACT: Light-weighting of passenger cars using high-strength steel or aluminum is a common emissions mitigation strategy. We provide a first estimate of the global impact of light-weighting by material substitution on GHG emissions from passenger cars and the steel and aluminum industries until 2050. We develop a dynamic stock model of the global car fleet and combine it with a dynamic MFA of the associated steel, aluminum, and energy supply industries. We propose four scenarios for substitution of conventional steel with high-strength steel and aluminum at different rates over the period 2010−2050. We show that light-weighting of passenger cars can become a "gigaton solution": Between 2010 and 2050, persistent light-weighting of passenger cars can, under optimal conditions, lead to cumulative GHG emissions savings of 9−18 gigatons CO_2-eq compared to development business-as-usual. Annual savings can be up to 1 gigaton per year. After 2030, enhanced material recycling can lead to further reductions: closed-loop metal recycling in the automotive sector may reduce cumulative emissions by another 4−6 gigatons CO_2-eq. The effectiveness of emissions mitigation by material substitution significantly depends on how the recycling system evolves. At present, policies focusing on tailpipe emissions and life cycle assessments of individual cars do not consider this important effect.



1. INTRODUCTION

1.1. The Need for a Systems Approach To Assess Emissions Reductions from Passenger Transport. Climate change mitigation requires absolute and sustained reduction of global greenhouse gas (GHG) emissions.[1] The question to what extent the different end-use sectors should contribute to emissions reduction has proven to be difficult to solve and is still open.[1] One reason for this difficulty is that the different sectors are coupled. Decreasing emissions in one sector may come at the expense of increasing emissions in other sectors, for example, via the use of more emission intensive materials.

Current policies for greenhouse gas (GHG) emissions reduction in the transportation sector avoid this problem; they consider only tailpipe or direct emissions. EU regulations, for example, set the target for new cars to 130 g of CO_2-eq per kilometer (g/km) from 2015 on,[2] and the U.S. Corporate Average Fuel Economy (CAFE) standard sets the 2025 direct emissions intensity target to 102−133 g/km.[3] Strategies to achieve these targets include increases in engine and power train efficiency, a shift in drive technology,[4] vehicle downsizing, or light-weighting by material substitution (henceforth called light-weighting or LWE).[5−10]

Car weight and specific fuel consumption are strongly coupled: a weight reduction of 10% results in a reduction of specific fuel consumption of 3−7% while maintaining the same functionality.[8,9] This is the main motivation for vehicle light-weighting.

Material substitution involves the use of aluminum, high-strength steel (HSS), magnesium, plastics, or polymer composites as alternatives for cast iron and steel.[6,7,10] Material selection is determined by economic viability at large production volumes, the weight savings potential,[6] physical properties such as strength, stiffness and formability,[7,8] safety performance, and anticipated environmental benefits.[11] Among the candidates for light-weighting, aluminum and HSS are more cost-effective in large scale production than their competitors and their use is expected to increase in the future.[6,7] They also comply well with vehicle safety and performance requirements[12] and are relatively easy to recover and recycle.[10] Material substitution involves redesign at the component level to optimally utilize the specific properties of the new material. In addition, secondary weight reductions can be achieved as subsystems such as engine and drive train can be down-sized as a consequence of the primary weight savings.[6]

Light-weighting often leads to higher emissions from materials production,[8] and policy makers and engineers need to make sure that light-weighting creates an overall or system-

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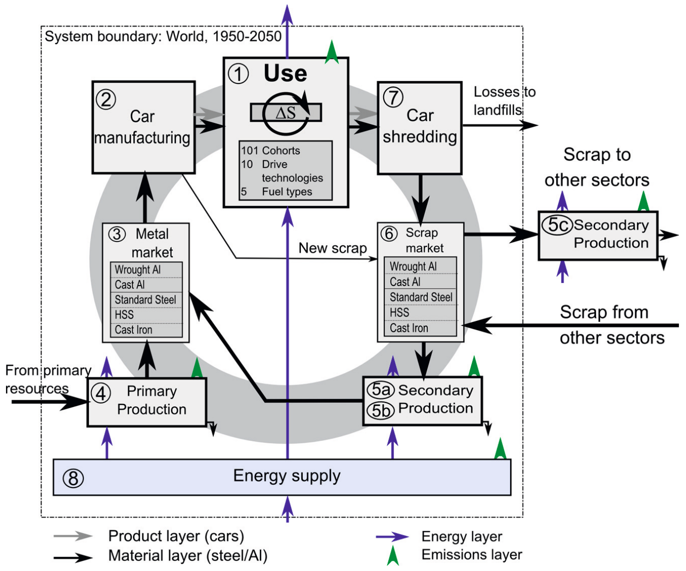

Figure 1. System definition. The model time runs from 1950 to 2010 with historical data and from 2011 to 2050 with scenario data. Car flows and stocks were divided into ten drive technologies. The model distinguishes cast iron, standard steel, high strength steel, cast aluminum, and wrought aluminum. Six energy carriers were considered: gasoline, diesel, coal, electricity, natural gas, and hydrogen.

wide benefit rather than merely shifting the environmental burden to other sectors. Understanding which LWE strategies may be most beneficial in the long run requires a systems approach that not only covers all life cycle stages of the vehicles at high level of detail, but that also considers system-wide dynamic effects including technological change and the changing overall potential for material recycling.

1.2. State of the Art of Environmental Assessment of Vehicle Light-Weighting. Life cycle assessment (LCA) is the predominant tool for assessing vehicle light-weighting.[8,12−20] A recent review of 43 LCA studies finds that for conventional vehicles, material production accounts for 3−20% of life cycle energy demand.[8] It also states that under different light-weighting scenarios, this share may increase up to 55%.[8] Both aluminum and HSS have significant potential to reduce life cycle energy demand and GHG emissions.[8,12,14,16] Geyer et al.[14] use a different indicator and find that using aluminum or HSS may reduce lifecycle GHG emissions by 5−8 kg CO_2-eq per kg of replaced material.

The LCA studies in the review consider only single vehicles and a static background economy throughout the vehicles' life cycle. To assess the possible contribution of light-weighting to reducing global emissions over the next decades, it is not sufficient to simply scale up LCAs of single vehicles for the following three reasons. (i) The vehicle stock is composed of different age-cohorts with an average lifetime of about 16 years,[21−23] which means that there is a delay between the latest technology and the fleet average. (ii) Technological change in vehicles and the material and fuel supplying industries needs to be considered. (iii) Changing material composition and a growing fleet will gradually change the recycling system. This can affect the recycled content of new cars and hence reduce embodied emissions.

Dynamic models of the entire vehicle fleet, combined with life cycle impact assessment, are an alternative to single-product LCAs. This dynamic fleet approach can overcome the three limitations.[23−25] Only few studies with a fleet approach to material recycling and substitution exist. Field et al.[26] and Das[27] showed that single-car LCAs and fleet approaches can lead to very different results. Their fleet models, however, assume a steady state and thus do not capture technological change over time. The same holds for the GREET model.[28] Bastani et al.[29] estimate fuel use and GHG emissions from the U.S. vehicle fleet until 2050. They consider improvements in vehicle fuel efficiency, reduced vehicle size and weight, and the deployment of alternative vehicles and clean energy sources. Emissions from metal production and recycling are not included. Cheah[7] developed a fleet-based LCA of light-weighted vehicles to capture the effects of changing material and fuel use in the U.S. vehicle fleet, but she does not consider the changing potential for material recycling over time. A dynamic fleet approach to assess the system-wide global emissions reduction potential of vehicle light-weighting, and which includes indirect emissions and a dynamic recycling system, is still lacking.

1.3. Scope and Research Questions. We used a dynamic model of the global passenger car fleet and the steel, aluminum, and energy supply industries to analyze four ambitious light-weighting scenarios based on high-strength steel and aluminum. The following questions were addressed using scenario analysis:

(1) What is the global GHG emissions reduction potential of passenger car light-weighting by material substitution until 2050?
(2) What is the impact of steel- and aluminum-intensive light-weighting of passenger cars on the steel and aluminum industries?
(3) How does the carbon footprint of the steel and aluminum industries change under different light-

weighting scenarios and assumptions about material recycling?

2. METHODOLOGY

2.2. System Definition and Model Description. We developed a dynamic stock model of the global passenger car fleet with age-cohorts and 10 different drive technologies (process 1 in Figure 1), and coupled it to process models of car manufacturing (2), end-of-life management of vehicles (7), primary and secondary production of steel and aluminum (4 and 5), and energy supply (8). The model is fully documented in the Supporting Information (SI1), where we also present many additional results. Here, we describe only those features and parameters that are central to understanding the main results. Model simulations were run from 1950 to 2050 using time series for each model parameter. Historic data starting in 1950 was used to determine the age structure of the stock in the base year 2010. Inflows and outflows from the use phase (process 1 in Figure 1) were obtained from an age-cohort-based stock model driven by population and car ownership scenarios.[30] The vehicle fleet was divided into ten drive technologies (conventional gasoline, gasoline hybrid, conventional diesel, diesel hybrid, plug-in hybrid gasoline, plug-in hybrid diesel, electric, natural gas, H_2 combustion, and H_2 fuel cell) and five different fuel types were considered (gasoline, diesel, electricity, natural gas, and hydrogen). Annual kilometrage and age-cohort-technology-specific fuel efficiency were used to determine total fuel demand. The material layer includes a dynamic MFA of the key automotive elements steel (divided into cast iron, standard steel, and high strength steel) and aluminum (divided into cast and wrought aluminum). Primary metal production and recycling are modeled separately. The level of production meets total metal demand (process 3 in Figure 1) while at the same time, the scrap markets are cleared (process 6 in Figure 1). Secondary material production is divided into three technically identical processes: Process 5a recycles scrap from other sectors such as machinery for use in automobiles (used only for aluminum and steel castings); process 5b recycles automotive scrap for use within the automotive sector, and process 5c recycles automotive scrap for use in other sectors, e.g., construction. For each process, energy demand is determined and connected to the common energy supply (process 8). GHG emissions are divided into direct emissions from fuel combustion and process emisisons. Indirect emissions from fuel supply are accounted for in process 8.

2.2. Parameter Estimations by Process. *2.2.1. Car Stock (1).* The global car stock is determined by multiplying projections on global population with scenarios for the car ownership rate.[23,24] UN population scenarios were used as estimates of the future world population.[31] Three scenarios for the global car ownership rate were taken from a previous study with global scope;[23] they were derived from various sources.[5,32,33] In this work, we use the medium scenarios for population and car ownership, where global population increases from 6.9 billion in 2010 to 9.5 billion in 2050, and global average car ownership increases from 124 in 2010 to 275 cars per 1000 people in 2050.

2.2.2. Car Manufacturing (2). We used the following yield loss rates in car production: 18% for wrought aluminum, 3% for cast aluminum,[34] and 27% for standard steel and HSS.[35] Yield loss reductions were not considered.[36]

2.2.3. Material Production (4–5). We compiled a detailed process inventory of the emissions and energy requirements of the major production routes of the five materials, using different data sources (cf. SI1).[34−40]

2.2.4. EOL Management (7). The scrap in End-of-Life (EOL) vehicles is classified as remeltable into the same material (recycling), remeltable into other material types (cascading), or loss to landfills. This information is stored in form of a recovery matrix. In all scenarios, we assume that the recovery rate of steel and aluminum from vehicles, which in 2010 is around 85%,[34,41] will increase to 95% in 2050.[41] The present situation, reflected by the BAU scenario, can be described as open-loop recycling, as all recovered wrought aluminum from end-of-life vehicles is cascaded into cast aluminum[23,42] and steel scrap into construction steel.[35,39,43,44] To study the impact of closed loop recycling on emissions, two alternative scenarios were developed: Assuming better separation of the metals in end-of-life vehicles will be feasible in the future, we defined that by 2050, gradually, 50% of all recovered EOL material will be recycled in a closed loop in the *closed50* recycling scenario, and 100% for *closed100,* respectively.

2.2.5. The Markets for Metals and Scrap (3 and 6). The market matches material demand from car manufacturers with primary and secondary metal production. In all scenarios, secondary material from automotive scrap—if available—was the preferred material choice for all material types (match between processes 5b and 3). Excess secondary material was exported to other sectors (5c). The remaining material demand of the car industry was satisfied by either primary (4) or secondary production from scrap from other sectors (5a), according to the industry's current material input mix.

2.2.6. Energy Supply (8). The GHG emissions intensity of fuel production and supply ("well-to-tank") were taken from a compilation of LCA studies[9,45] and assumed to be constant over time in the BAU case.

2.3. Properties of Passenger Cars. In line with our previous studies, the vehicle **lifetime** was assumed to follow a normal distribution with a mean of 16 years and standard deviation of 5 years.[23] The default value for the **annual kilometrage** was 15 000 km/yr, which was modified during model calibration (cf. 2.4).[46] Ten **drive technologies** were distinguished (cf. above) and the market shares of the different drive technologies and their respective **fuel efficiency** were taken from the BAU scenario from IEA's Energy Technology Perspectives.[5]

2.3.1. Car Weight and Scenarios for Light-Weighting. Data for the U.S. on average car weight by type for 1975−2008 were taken from an EPA report[47] and scaled down to fit European average car weight trends[48] to better reflect the global average. The average weight of a new passenger car in 2010 was about 1400 kg.[49] We compiled component-level and drive-technology-specific data on the content of the five materials from various sources.[48,50−52]

Four scenarios for vehicle light-weighting, each starting in 2010, were developed. All scenarios are technologically feasible according to our best knowledge, but we do not make any statement regarding the likelihood of their implementation or the costs associated with the different light-weighting options.

The BAU scenario serves as reference. It assumes that material composition of vehicles and their average mass remains the same as in 2010.

The assumptions behind the light-weighting scenarios were informed by a number of case studies for steel and

Table 1. Material Composition for 2030 Average Gasoline Vehicles by Scenario

name	standard steel (kg)	HSS (kg)	cast iron (kg)	cast aluminum (kg)	wrought aluminum (kg)	others (kg)	total vehicle mass (kg)	weight saving compared to BAU
BAU	581	235	111	76	33	348	1382	
Ducker	349	226	99	91	57	441	1265	8%
LWE-steel-intensive	289	400	103	62	32	346	1232	11%
LWE-Al-intensive	282	207	100	115	137	341	1183	14%
LWE-Al-extreme	199	33	38	134	301	322	1028	26%

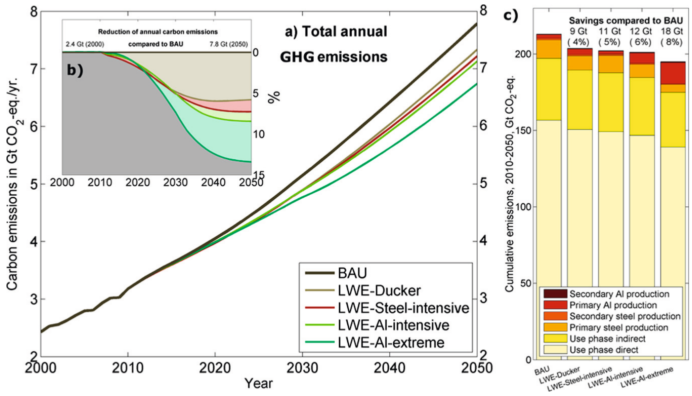

Figure 2. (a) Total GHG emissions from the system in Figure 1, including the use phase, aluminum and steel production and recycling, and energy supply for the global passenger car fleet. Five scenarios, including development business-as-usual (BAU) and four light-weighting scenarios, are shown. (b) The same figures as in part (a), but shown as change compared to BAU in percent. (c) Cumulative emissions (2010−2050) for the five scenarios, and savings compared to BAU in Gt CO_2-eq and percent.

aluminum.[7,12,48,53] In practice, both materials are combined to achieve light-weighting in specific applications and components.[7,8,53]

The *Ducker* scenario is directly based on a study by Ducker[49] that estimates the future material mix for North American light vehicles until 2025. It takes into account technology, cost, material availability, and fuel economy regulations. We extrapolate the U.S.-specific material mix to the global level.

The *LWE-steel-intensive*, *LWE-Al-intensive*, and *LWE-Al-extreme* scenarios are our own developments; they assume that significant light-weighting is achieved by replacing standard steel and cast iron with either high-strength steel or aluminum. They were developed in six steps: (1) The 2010 average vehicle mass was broken down into 6 material groups (standard steel, HSS, cast iron, cast aluminum, wrought aluminum, other materials) and 4 component groups (body and closures, chassis and suspension, powertrain, interior, and miscellaneous). (2) A literature study on the component-specific material substitution potential was conducted to quantify possible primary weight reductions (see for example refs 54 and 55). (3) Assumptions were made regarding the amount of standard steel and cast iron replaced in each component group by 2030, and regarding the replacement material. (4) The new material composition and the resulting average vehicle mass were calculated using the component-specific substitution factors. (5) Secondary mass savings from downsizing the powertrain and other relevant components were estimated for each component group using the decompounding coefficients by Alonso et al.[56] This leads to secondary weight savings that are comparable to the primary weight savings. (6) It was assumed that the full light-weighting potential will be seized by 2030, and linear interpolation was used to define vehicle material composition between 2010 and 2030.

The *LWE-steel-intensive* and *LWE-Al-intensive* scenarios represent a continuation of the current trend in material substitution for light-weighting. This trend mainly targets body and closure components.[55] It was assumed that all standard steel in body and closures, and 25% of standard steel in chassis and suspension will be replaced with HSS (*LWE-steel-intensive*) or aluminum (*LWE-Al-intensive*) by 2030. The *LWE-Al-extreme* scenario involves extensive substitution by aluminum also in powertrain and interior components. Chapter S1−1.2.3 in SI1 contains a full description of the scenario development including the literature review on current material composition and substitution factors. Table 1 summarizes the material composition of new vehicles in 2030 for the different scenarios.

A consistent set of estimates of the weight-fuel relation for different drive technologies[9] was used to determine the effect of light-weighting on fuel efficiency.

2.4. Model Calibration.

With all other parameters remaining equal, our original value for the annual kilometrage, which we have only weak data support for, was adjusted so that the modeled global use phase emissions in 2010 were equal to the reported emissions of 2.1 Gt CO_2-eq.[5] The so-obtained effective annual kilometrage was about 14 000 km/yr.

3. RESULTS

3.1. Global Carbon Impact of Passenger Car Light-Weighting.

Annual GHG emissions increase from 2.4 Gt in 2000 to 7.8 Gt in 2050 for the BAU scenario (Figure 2a).

Moderate light-weighting of passenger cars could save about 0.5 Gt CO$_2$-eq annually (*Ducker*, *steel-intensive*, *Al-intensive*), and both the steel and the aluminum-intensive moderate light-weighting scenarios lead to similar emissions reductions. For *Al-extreme*, savings would be about twice as high (1 Gt/yr). For 2050, this translates into a reduction of emissions of 6–14% compared to BAU scenario (Figure 2b). Cumulative emissions savings for 2010–2050 are between 4 and 8% or 9–18 Gt CO$_2$-eq (Figure 2c).

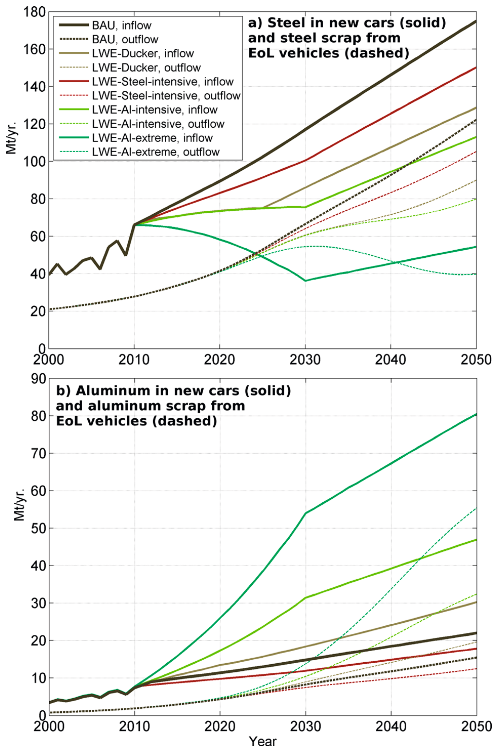

Figure 3. (a) Steel entering and leaving the global passenger car fleet in new and end-of-life vehicles, respectively. (b) Aluminum entering and leaving the global passenger car fleet in new and end-of-life vehicles, respectively. Results are shown for development business-as-usual (BAU) and the four light-weighting scenarios.

3.2. The Impact of Passenger Car Light-Weighting on the Steel and Aluminum Industries. Light-weighting of vehicles entails significant change for the aluminum and steel industries (Figure 3). For all scenarios except *LWE-Al-extreme*, total automotive steel demand increases from present levels, but at different rates: For the light-weighting scenarios, steel demand in 2050 is between 20 and 70% lower compared to the BAU scenario. For the *LWE-Al-extreme* scenario, automotive steel demand will stay at about today's level. Even in the *LWE-Steel-intensive* scenario, total automotive steel demand will be about 20% lower than BAU because of the shift from conventional to high strength steel. Supply of automotive steel scrap will at least stay at about today's levels in the *LWE-Al-extreme* scenario; however, it may triple if material composition follows the BAU track.

Total automotive aluminum demand increases in absolute terms for all scenarios; however, the relative changes between scenarios are much more significant for aluminum than for steel. While aluminum demand increases 2.5-fold in the BAU scenario, it increases by a factor 10 in the *LWE-Al-extreme scenario* over the period 2010–2050. Between 2014 and 2050, the flow of aluminum scrap from end-of-life vehicles will increase at least by a factor of 6 for *LWE-steel-intensive*; but the increase may be more than 20-fold for *LWE-Al-extreme*.

3.3. The Impact of Recycling on the Carbon Footprint of the Steel and Aluminum Industries. Figure 4a,b shows the effect of recycling on material production emissions for steel and aluminum for the different light-weighting scenarios. There is a general trend upward due to growing production numbers. The more Al-intensive the scenario, the faster emissions from aluminum production rise. They may even surpass emissions from automotive steel production, which stagnate or even decline for the Al-intensive scenarios. Figure 4a,b shows that the degree of closure of the recycling loop has only little impact on emissions before 2030. Only after 2030 does closed loop recycling have significant potential to reduce the carbon footprint of the automotive metal industries, especially for the aluminum intensive scenarios. Compared to the substantial rise in emissions from primary aluminum production to build up stocks in the vehicle fleet, the effect of recycling is delayed by about the lifetime of cars, and therefore becomes significant only after 2030.

Figure 4c shows the cumulative GHG emissions from the material cycles over the period 2010–2050 for the different light-weighting scenarios and BAU, semiclosed, and closed-loop recycling. The recycling system has significant impact on the carbon footprint of the metals industries, and it determines whether their total cumulative footprint will increase or fall compared to development BAU. While cumulative emissions from the steel industry are smaller for all light-weighting scenarios than for BAU, cumulative emissions from aluminum production may rise significantly for the aluminum-intensive scenarios. For open loop recycling, cumulative emissions during 2010–2050 may be higher than BAU emissions for the Al-intensive scenarios. This trend can be reverted by closing the recycling loop, which leads to reductions of cumulative emissions by 4–6 Gt CO$_2$-eq

Figure 4d is a refined version of Figure 2a; it shows the impact of closed loop recycling on total GHG emissions for different LWE scenarios. Closing the material loop for steel and aluminum in passenger cars can increase the system-wide GHG emissions savings of passenger vehicle light-weighting by ca. 30%.

4. DISCUSSION

4.1. Carbon Impact of Light-Weighting and Metal Recycling. Light-weighting of passenger cars by material substitution can be a "gigaton solution":[57] ambitious material substitution could save between 9 and 18 Gigatons of CO$_2$-eq between 2010 and 2050. These figures represent an upper limit for several reasons: Their realization requires the following:

(i) a very rapid penetration of aluminum or other light-weight materials to the technically feasible potential until 2030;
(ii) full utilization of the secondary mass savings potential;

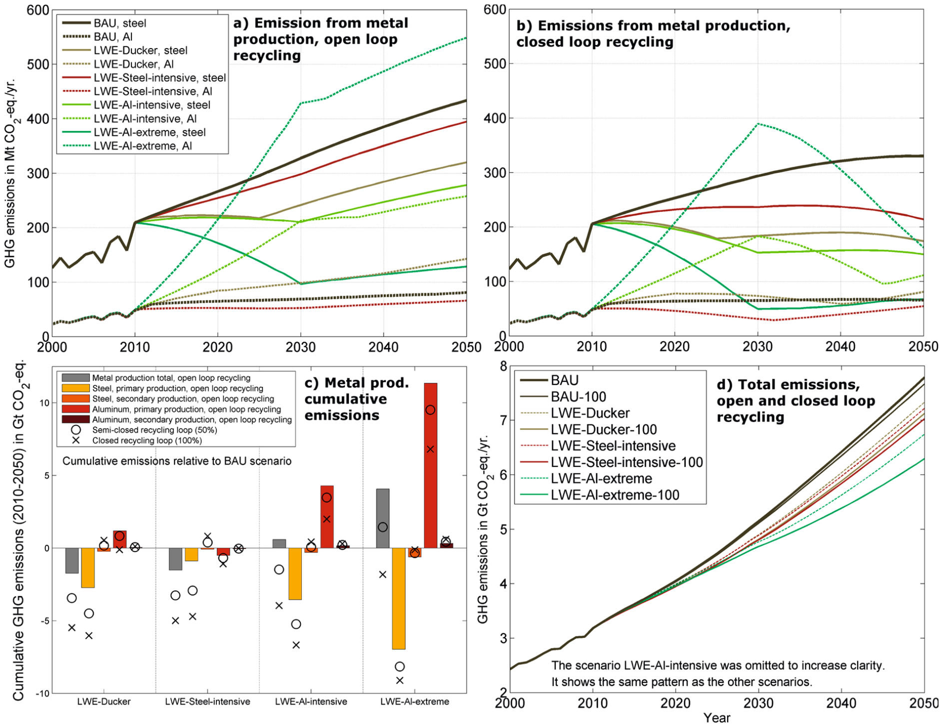

Figure 4. (a) Emissions from steel and aluminum production for passenger cars for development business-as-usual and the four light-weighting scenarios. The open loop recycling system includes cascading of end-of-life vehicle scrap. (b) The same figures, but for closed loop recycling without cascading. (c) Changes in cumulative GHG emissions (2010−2050) relative to the BAU scenario for the four light-weighting scenarios. Results are shown for three degrees of closure of the recycling loop: open loop recycling (with material cascading, solid bars), a semiclosed recycling loop where 50% of the secondary material is recycled within the same quality group (o), and a fully closed loop without cascading (x). (d) Total emissions from the use phase, steel and aluminum production, and energy supply for open and closed recycling loop. This plot shows how the results shown in Figure 2a change when the recycling loop is closed.

(iii) the absence of counter-effects, such as an increase in the mass of other vehicle components due to higher safety standards or more luxurious features in the cars.

As with all new technologies, it can take several decades before the full benefits of light-weighting become apparent. This is because several delay mechanisms act in the system: Light-weighting technology needs time to develop and affect all new vehicles, and even after full market penetration, it takes another decade or two before the whole stock of cars is replaced by lightweight vehicles. These general observations are consistent with the findings of earlier fleet-based studies.[24,26,27] In addition, the full benefit of recycling can only be realized after more than two decades from now, when a large in-use stock of aluminum will be stored in the fleet. Light-weighting may entail drastic changes in metal demand, scrap availability, and emissions from metals production. The effect of recycling on emissions is more important for aluminum than for steel, because relative savings are higher for aluminum. Before 2030, total emissions from metal production rise for all scenarios. This is because of the growing global fleet, which requires large initial “investments” in energy- and emission-intensive primary aluminum and steel. When looking only at the near future, it may seem of less importance which material is chosen for light-weighting, but in the long run, aluminum seems to have a potential to reduce emissions beyond what is achievable with HSS.

This advantage of aluminum can be amplified by closed-loop recycling. The technical and economic challenges of closed-loop recycling are discussed in detail in the literature.[23,39,43,58−60] Closed-loop recycling of steel has a similar, but smaller effect on emissions than closed-loop recycling of alumium. If closed loop recycling is not implemented, then it may happen that other sectors cannot absorb the large amounts of aluminum scrap resulting from intensive light-weighting.[23] The development for steel is less constrained, because buildings and constructions are very large sinks for lower quality secondary steel.[35]

4.2. Policies for Material-Intensive Low-Carbon Technologies.

Current policies, such as CAFE in the U.S. and the European regulations, aim at reducing tailpipe emissions of new vehicles. Previous research has pointed out the importance of taking a life cycle or systems perspective on individual cars to avoid merely shifting the burden from direct emissions in the use phase to emissions in other sectors. An LCA with a single-car-perspective, however, cannot capture changes in the recycling system, which we found to have substantial impact on total industrial emissions. We therefore suggest that ultimately, one should move beyond single-product LCAs and consider the entire vehicle fleet, its development over time, and its connection to the material industries. Only by assessing emissions reduction strategies on the full scale and over time, the future impact of emergent phenomena, such as material recycling, can be correctly estimated. This allows for coupling policies on use phase emissions reductions to those addressing emissions in material producing industries. The dynamic fleet-recycling approach allows us to model the impact of current consumption on the future recycling potential. It can be used to anticipate future challenges in end-of-life vehicle management, which again can inform policy design.[61]

4.3. Benefits and Critique of the Approach. The scenario results represent futures that are *technically possible* according to our best knowledge. Next to the uncertainty regarding the actual implementation of these strategies in different world regions, there is some uncertainty connected to our choice of technological parameters. This includes IEA's estimates of the fuel efficiency of future vehicles, the substitution factors for different components and materials reported in literature, and the extent of secondary weight savings. In addition, the results in the paper do not illustrate the uncertainties related to socioeconomic input data such as population, car ownership, lifetime, etc. These are covered in the sensitivity analysis in the SI.

Dynamic fleet-recycling models allow us to assess specific technologies in a global setting. They connect population estimates, lifestyle choices, and utilization parameters to inventories of specific drive technologies and material production processes. We showed that the relative success of a certain emissions mitigation strategy compared to development BAU is strongly influenced by system-wide emergent effects, such as the potential for material recycling. It is not possible to capture such effects by simply scaling up assessments of individual vehicles prototypes with fixed assumptions on the underlying material cycles. The environmental performance of a material cycle depends on a large set of factors (the recycling loop closure degree being only one), which are controlled by different actors within society. Not only material and vehicle producers, also car users, waste management industries, and regulators play an important role in determining the eventual recycling opportunities and resulting emissions pathways.

Models like the one applied here can help to design emissions mitigation strategies that connect product-specific strategies to sector-specific emissions reduction targets. Focusing on one sector only, as we did here, represents a severe limitation, however: Passenger cars account for only about 8%[35] and 18%[62] of global steel and aluminum use, respectively. We did not consider the impact of scrap supplied to or sourced from other sectors, or different options for allocating carbon footprints from metal processing. Dynamic models of metal cycles that consider all major applications of metals will be needed to help breaking down global emissions reduction targets into different sectors and industries. These models can help to reconcile the potential rise of emissions in the material producing industries with the subsequent carbon benefits from using these materials. Such models should include both energy and material supply, energy and material efficiency, and lifestyle changes.

Dynamic fleet-recycling models have a potential to complement both static LCA studies with high process resolution but small-scale scope, and integrated assessment models (IAM). The latter are dynamic large-scale models of society's metabolism that currently have only limited coverage of material flows, stocks, and recycling systems.

We see our model as dynamic MFA of the global passenger car fleet and the connected metal industries, but one could also argue that it is a fleet-wide dynamic LCA with scenarios for future development. We believe that this type of modeling forms a bridge between MFA and LCA research, as it allows practitioners from both fields to tackle new research questions with unprecedented comprehensiveness.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Detailed data input for used for the dynamic fleet-recycling model; (S1) system definition and model documentation; (S2) data gathering and treatment; (S3) additional results; and (S4) additional references. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ NOTE ADDED AFTER ASAP PUBLICATION

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