Environmental Science & Technology

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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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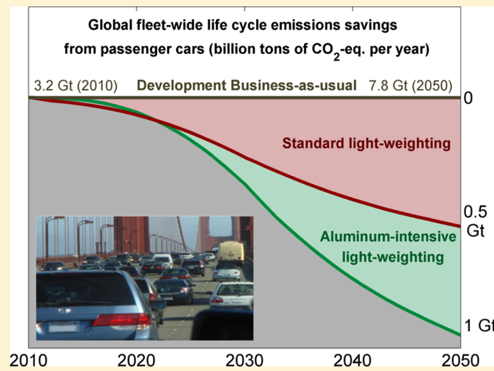
Supporting Information

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-

Received: October 31, 2013
Revised: August 9, 2014
Accepted: August 11, 2014
Published: August 11, 2014

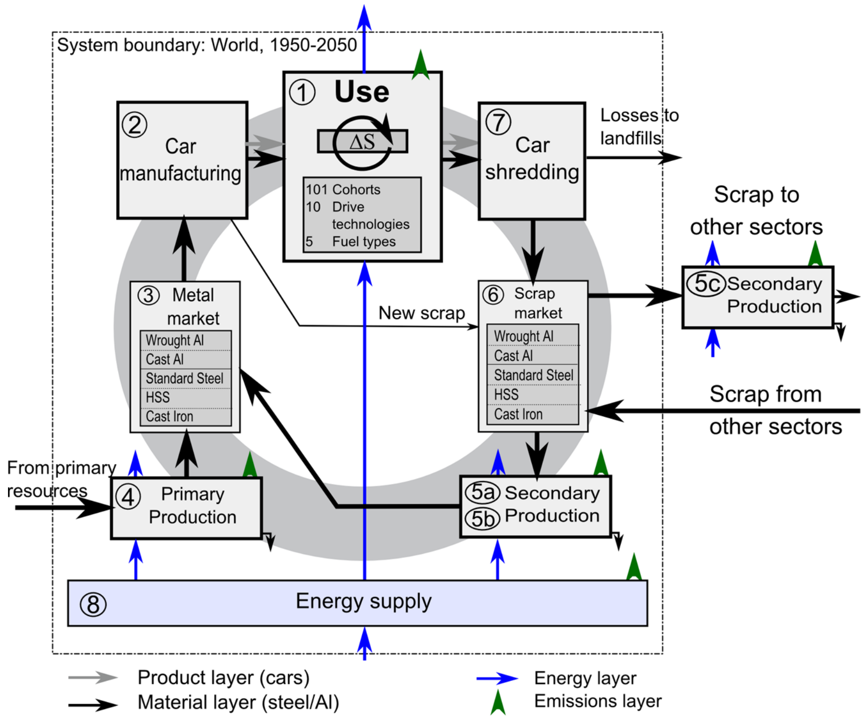


Figure 1. System definition. The model time runs from 1950 to 2010 with historical data and from 2011 to 2050 with scenario data. Car flows and stocks were divided into ten drive technologies. The model distinguishes cast iron, standard steel, high strength steel, cast aluminum, and wrought aluminum. 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%

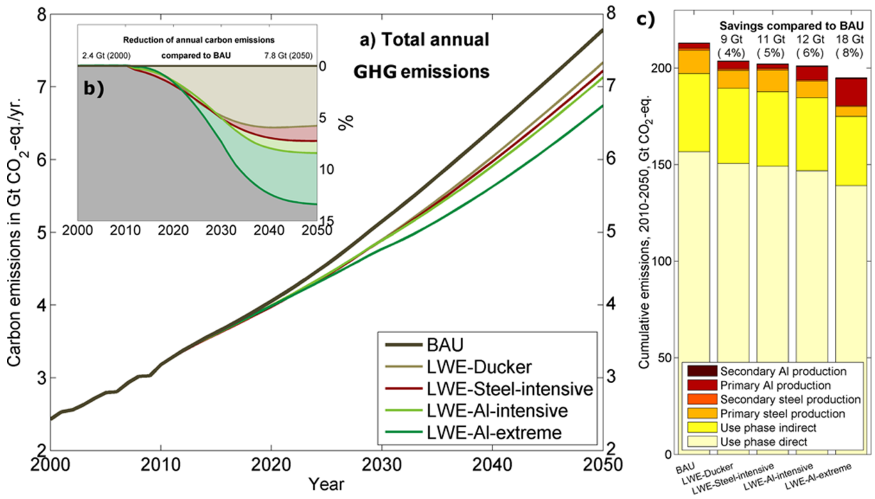


Figure 2. (a) Total GHG emissions from the system in Figure 1, including the use phase, aluminum and steel production and recycling, and energy supply for the global passenger car fleet. Five scenarios, including development business-as-usual (BAU) and four light-weighting scenarios, are shown. (b) The 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).

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.

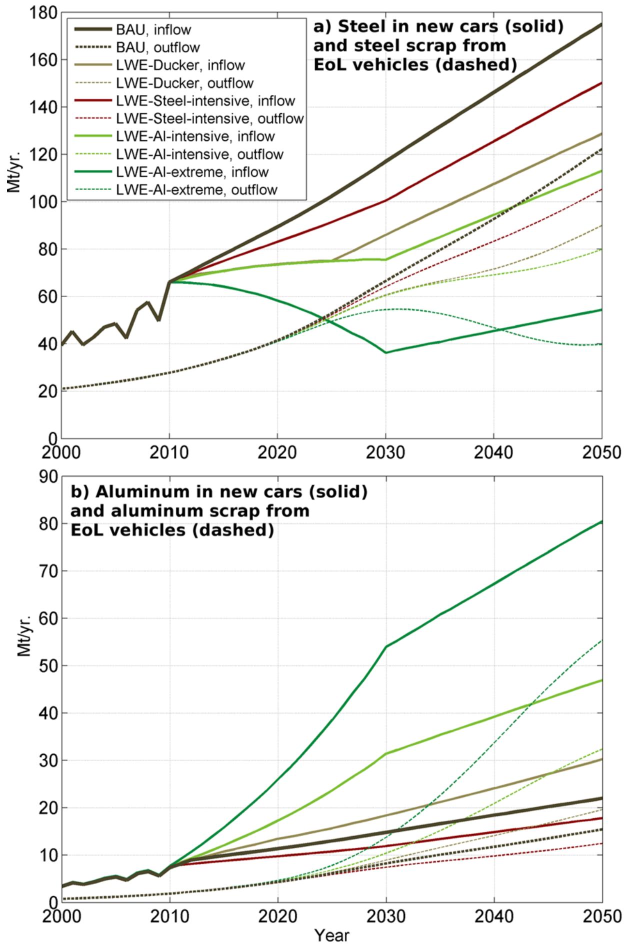


Figure 3. (a) Steel entering and leaving the global passenger car fleet in new and end-of-life vehicles, respectively. (b) Aluminum entering and leaving the global passenger car fleet in new and end-of-life vehicles, respectively. Results are shown for development business-as-usual (BAU) and the four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

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;

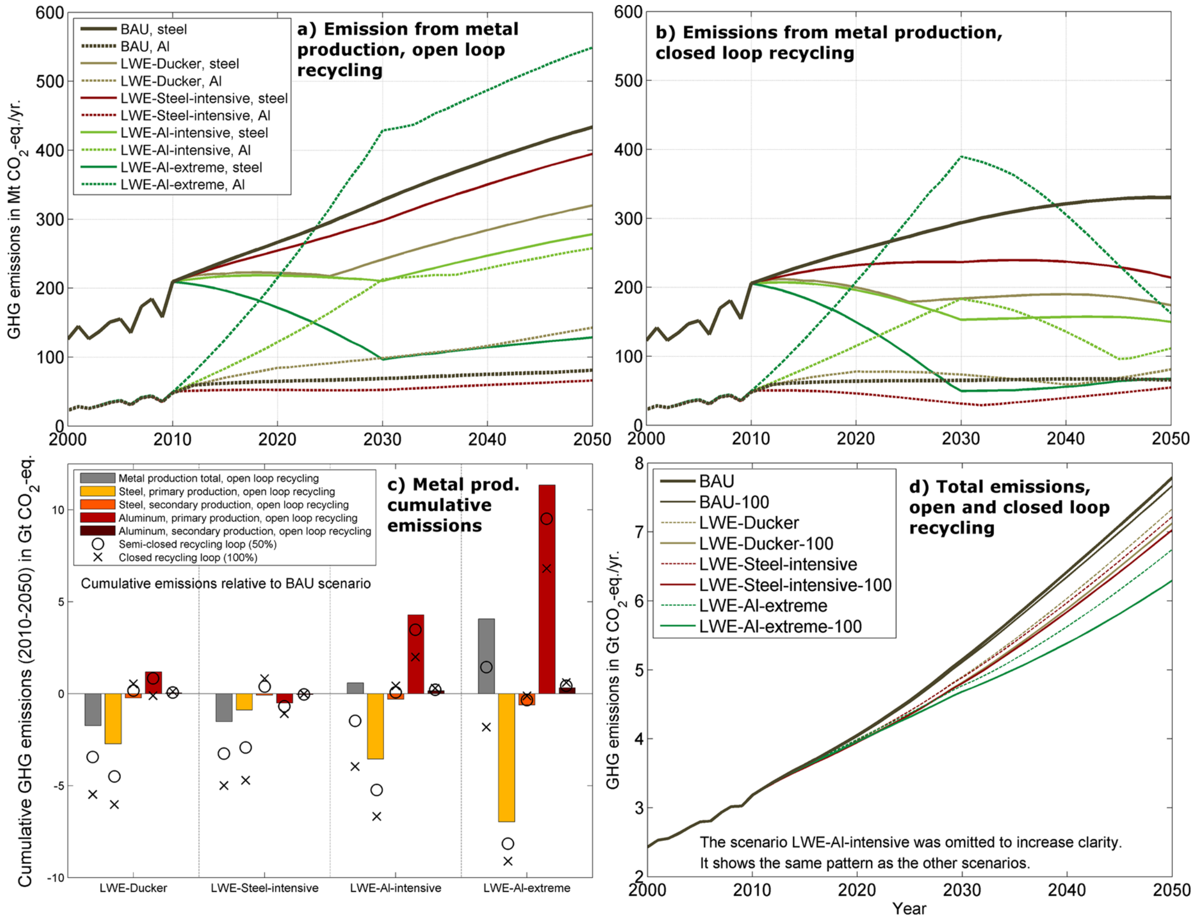


Figure 4. (a) Emissions from steel and aluminum production for passenger cars for development business-as-usual and the four light-weighting scenarios. The open loop recycling system includes cascading of end-of-life vehicle scrap. (b) The same figures, but for closed loop recycling without cascading. (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.

■ ACKNOWLEDGMENTS

The work of Stefan Pauliuk was funded by the Research Council of Norway under the CENSES Project (grant number 209697).

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■ NOTE ADDED AFTER ASAP PUBLICATION

This paper was originally published ASAP on September 2, 2014, with incorrect dates in the Abstract. The corrected version was reposted on September 3, 2014.