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Aluminium use in passenger cars poses systemic challenges for recycling and GHG emissions

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ABSTRACT

The demand for automotive aluminium is expected to boom in the coming decades given current trends in the passenger car market, such as electrification, light-weighting, customers' preference for larger cars (SUVs) and growing global car ownership and population, resulting in a growing challenge for the aluminium sector to curb GHG emissions. We develop a new multilayer dynamic material flow analysis model to analyse the combined effects of those drivers on the automotive aluminium cycle and related GHG emissions. Our results show that (i) aluminium use in passenger cars is likely to quadruple towards 2050 (ii) emissions resulting from aluminium production will be a major part of the carbon footprint of cars (iii) electric vehicles require more wrought aluminium, leading to a surplus of mixed alloys and castings scrap which can only be mitigated through the introduction of alloy sorting technologies and/or an increase in vehicle lifetime (iv) given the expected fast growth in automotive aluminium demand, an overall emission reduction in the aluminium industry would require an even faster penetration of low-carbon technologies in the energy and aluminium production sectors, which may, in turn, increase aluminium demand even further.

1. Introduction

The transport sector is, besides buildings, the largest user of aluminium and its share is expected to further increase towards 2050 (CM Group 2020). Within the transport sector, passenger cars form the main application for aluminium (Cullen and Allwood 2013). The demand for automotive aluminium has historically been driven by light-weighting (Liu and Müller, 2013), followed more recently by the growing preference of customers and manufacturers for larger and heavier cars, such as sport utility vehicles (SUVs). The current electrification of the transport sector is also transforming the use of aluminium in cars. On the one hand, a lot of the aluminium used in internal combustion engine vehicles (ICEVs) consists of casting alloys used in engine parts, which are not needed in battery electric vehicles (BEVs). On the other hand, batteries also contain a significant amount of aluminium, both inside the battery (aluminium foil for cathode current collectors) and especially in the casing, a large piece often made of aluminium sheets (Løvik et al., 2021). To compensate for the extra weight of carrying a large battery, EV manufacturers tend to use even more aluminium in the body of the car. The combination of these factors have resulted in an overall increase of aluminium use in EVs compared to ICE, and a higher proportion of wrought aluminium alloys (DuckerFrontier 2020).

Last but not least, human population and car ownership are still increasing globally. These factors point towards a significant increase in aluminium demand for passenger cars in the coming decades. A concern is that this could offset some of the benefits of electrification for reducing global GHG emissions: an aluminium car component usually has a higher carbon footprint than if it was made of steel, mostly because of the energy-intensive primary production process. Still, previous studies have shown that the use of aluminium in passenger cars (including EVs) for light-weighting still had overall benefits on life cycle GHG emissions, thanks to a reduction in fuel consumption despite higher emissions in the production phase (Wolfram et al., 2021). Modaresi et al. (2014b) have found that light-weighting of passenger cars could lead to cumulative GHG emissions savings of 9 to 18 Gt CO_2-eq between 2010 and 2050. However, as the share of BEVs in the vehicle fleet is steadily increasing and the electricity mix used to charge them is expected to become greener (IEA 2021), the relative contribution of aluminium to the carbon footprint of cars will keep increasing as well. Furthermore, the most recent life cycle assessments (LCA) of battery production found the impact of cell production to be much lower than previously

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estimated, due to technological improvements and better understanding of inventory data (Emilsson and Dahllöf 2019) .

Notwithstanding, LCAs of EV batteries, such as (Q. Dai et al., 2019; Emilsson and Dahllöf 2019; Ellingsen et al., 2014) tend to focus more on the cell production and use phases, while underestimating the contribution of aluminium to Global Warming Potential (GWP). According to Conzade et al. (2021), material production already represents almost half of the total life cycle emissions of an average European EV, and this share is expected to increase with a decarbonised electricity mix. They also found aluminium to represent 35 to 50% of the material carbon footprint of an EV, compared to 10–20% for other battery materials. While other impacts of aluminium use in the automotive industry have recently come under the spotlight (Wormington et al., 2021), it is critical to better understand how current trends will affect the future aluminium demand for cars and the associated GHG emissions.

The carbon footprint of recycling aluminium is 10 to 20 lower than primary production (International Aluminium Institute 2009; IEA-ETSAP 2012; European Aluminium 2015). An obvious way to reduce the carbon footprint of aluminium in cars is to increase recycling and substitute primary aluminium with secondary resources. However, this is proving difficult for two reasons: (1) the fast growing demand for aluminium combined with the relatively long lifetimes of cars results in limited amounts of post-consumer scrap available in the short-term (Rombach 2002; Liu et al., 2013), and (2) the switch from casting to wrought alloys accelerated by the transition to EVs is challenging for recycling as wrought aluminium requires lower levels of alloying elements and impurities than what is typically found in post-consumer scrap (Rombach et al., 2012). New technologies (such as laser-induced breakdown spectroscopy (LIBS) and solid-state recycling) that enable alloy-specific sorting and recycling have been developed for more than 10 years (Cui and Roven 2010; Kelly and Apelian 2016), but they remain expensive, inefficient for complex scrap mixes, and are yet to be implemented at a larger scale. As a result, the future contribution of recycling could be limited by two seemingly contradictory effects: on the one hand, the low availability of post-consumer scrap to meet the growing demand, and on the other hand, a potential surplus of low-quality scrap that does not meet the specifications needed for future applications.

Previous studies based on dynamic Material Flow Analysis (MFA) have already exposed the risk of a future mixed scrap surplus (Modaresi et al., 2014a) and how electrification of the personal vehicle fleet might increase this problem (Hatayama et al., 2012; Modaresi and Müller 2012). Løvik et al. (2014) have used a dynamic vehicle-component-alloy-element model to discuss potential solutions to solve this problem, such as increased component dismantling and automatic alloy-sorting technologies. They also pointed out the importance of cooperation between the different actors within the system, such as primary and secondary aluminium producers, car manufacturers, and vehicle dismantlers. However, those studies suffer from some limitations to describe the current and future use of aluminium in the automotive sector, mostly as they have become partly outdated and largely omit the related GHG emissions. More specifically, they (1) underestimated the penetration of EVs compared to current data, new policies, and updated future forecasts, (2) did not have enough detailed understanding of the different aluminium needs between electric and conventional vehicles and underestimated aluminium content in cars, and (3) did not consider the surge in demand for larger cars such as SUVs.

Buchner et al. (2017) published a more recent study on this topic, with a different scope: all end-use sectors were considered, but geographically limited to Austria, which was considered as a closed system. This study provides a good overview of the potential lock-ins and synergies for scrap exchange between different sectors, but it cannot be generalised to the global level, especially since most of the increase in aluminium demand is expected to come from non-Western countries. The use of aluminium sheets in the body of vehicles for light-weighting has been examined in more details by Zhu et al. (2021). They looked at the most popular SUV models in the USA and concluded that significant amounts of scrap will be generated, offering an opportunity for recycling. Automotive manufacturers such as Ford are already introducing closed-loop recycling of manufacturing scrap (Ford 2016), but processes for alloy-to-alloy recycling of post-consumer scrap are yet to be developed. Tu & Hertwich (2021) have analysed the effects of incomplete scrap separation and sorting errors on scrap reuse rate and the consequences on lifecycle emissions for different light vehicle archetypes. However, their analysis was limited to six archetypes and they only considered one scenario for EV penetration over time in Canada. Other recent studies focusing on aluminium use in the automotive sector have been performed for China (Yang et al., 2022; Chen et al., 2022) and America (Hua et al., 2022), but not at the global level.

Global-scale dynamic MFA models examining the future of the aluminium cycle and its associated emissions already exist, such as those developed by Liu et al. (2013) and Van der Voet et al. (2018), but they lack sufficient sector and alloy resolution to analyse scrap surplus and the drivers for aluminium demand in the automotive sector. They also tend to focus on end-of-life (EoL) while omitting upstream climate change mitigation strategies (Watari et al., 2021). More recently, Van den Eynde et al. (2022a) used a global dynamic MFA with increased alloy resolution to estimate a global Al scrap surplus of 5.4 Mt by 2030 and 8.7 Mt by 2040, but their representation of the transport sector was simplified compared with previous studies. Pedneault et al. (2022) used a more refined sector-specific bottom-up approach, linking future stocks and flows of aluminium with shared socio-economic pathways. However, their use of fragmented and constant values for aluminium content in cars is likely to lead to an underestimation of the future aluminium demand in the automotive sector. There is a lack of studies analysing the climate change mitigation potential of the global automotive aluminium cycle at sufficient resolution to capture the relevant trends and barriers related to change in alloys used.

Here, we aim at answering the following research questions:

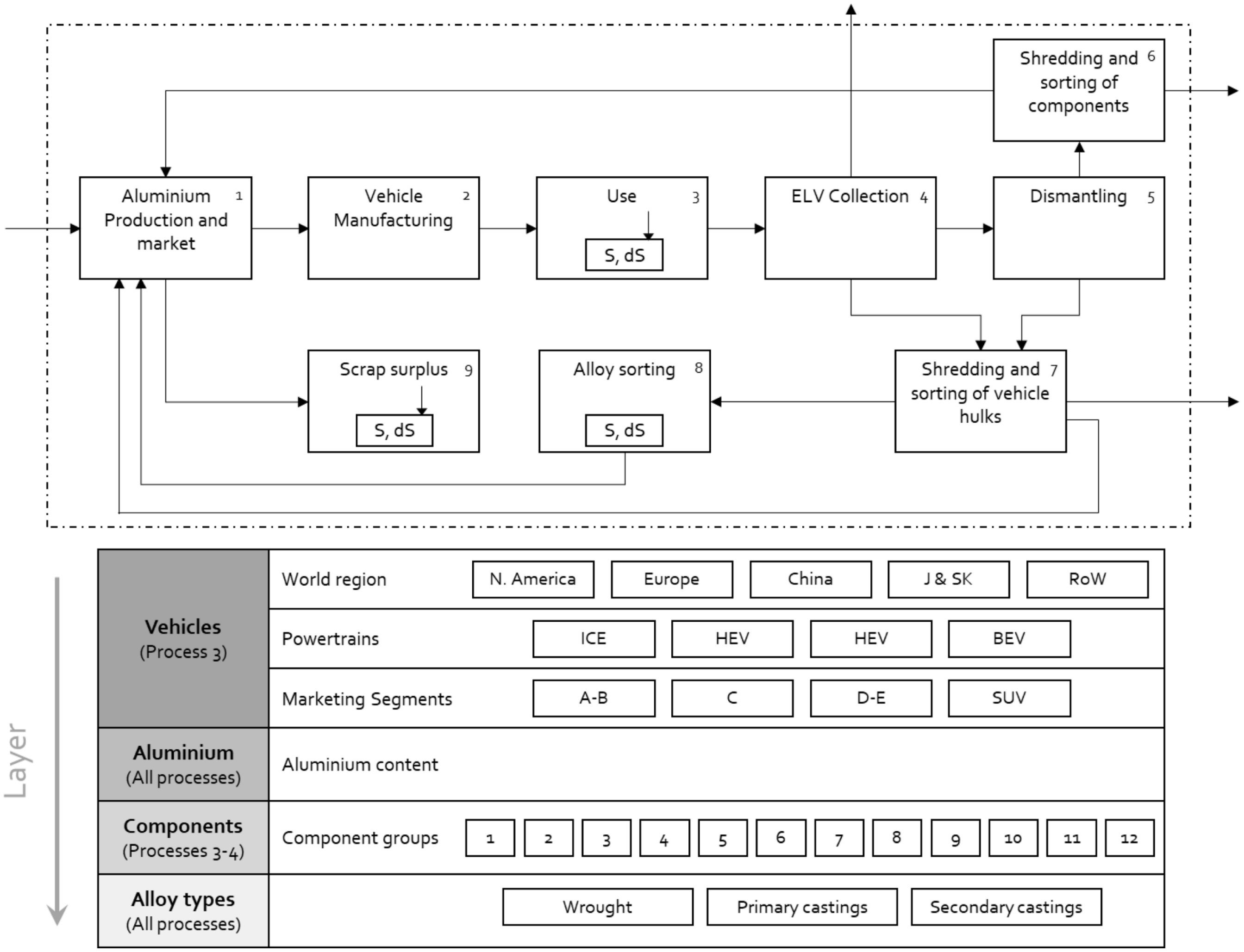
1 Given recent trends in the transport sector, what are plausible pathways for the global automotive aluminium cycle?
2 What are the implications of these trends for GHG emissions in the automotive aluminium sector?
3 What are the most effective systemic strategies to mitigate these emissions?

2. Methods

2.1. System definition

This study considers aluminium use in the global passenger cars system. As shown in Fig. 1, the system is composed of eight processes and four layers: a vehicle layer, a component layer, an aluminium layer, and an aluminium alloys layer. For the vehicle layer, five world regions are considered: Europe, North America, China, Japan and Korea, and Rest of the World (appendix 2.1). Car manufacturing is only considered at a global level and trade is out of the scope of the model; this means that the characteristics of the cars in the model are not defined by their place of production, but by the region in which they enter use. The rationale for this assumption was to avoid the complexity and data requirements of dealing with exports of new and used cars, as well as considering that characteristics are defined by consumer preferences in the region of use. 4 types of powertrains were considered: ICEV, Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV) and BEV (appendix 2.2). The definition of passenger cars varies between different countries and world region. Similarly, there is no international standard for the definition of vehicle segments. We therefore decomposed the vehicle fleet in 4 segments: A/B, C, D/E, and SUV, adapted from the European standard (see appendix 2.3).

To quantify the aluminium layer, the average aluminium alloy mass



Layer													
Vehicles (Process 3)	World region	N. America	Europe	China	J & SK	RoW							
	Powertrains	ICE	HEV	HEV	BEV								
	Marketing Segments	A-B	C	D-E	SUV								
Aluminium (All processes)	Aluminium content												
Components (Processes 3-4)	Component groups	1	2	3	4	5	6	7	8	9	10	11	12
Alloy types (All processes)		Wrought	Primary castings	Secondary castings									

Fig. 1. System Definition of the multilayer MFA system with the parameters used in the model. A more detailed description of the system definition is presented in appendix 1.

per car type and region was calculated based on recent regional studies for Europe (DuckerFrontier 2019; Løvik et al., 2021), the USA (DuckerFrontier 2020), and China (CM Group 2019). The same data was used to derive coefficients quantifying the influence of vehicle segment and powertrain on the aluminium content.

The components and alloy types layer were derived using data on aluminium content and alloy composition per 12 component groups (appendices 4 and 5) from Modaresi et al. (2014a), which was updated to reflect the recent evolution in composition of EVs. Alloys were separated in 3 groups: wrought alloys, primary castings and secondary castings. In the end-of-life system, it was assumed that only dismantling before shredding (processes 5 and 6) or alloy-sorting technologies (process 8) after shredding in bulk could enable separation by alloy groups (and potential alloy-to-alloy recycling). Otherwise, mixed shredder scrap was assumed to be only suitable for the production of secondary castings. The passenger car sector has historically been a sink for post-consumer scrap from other sectors, thanks to the low-quality requirements of secondary castings alloys used for the production of engine blocks (Modaresi et al., 2014a). However, we assumed that all scrap from other sectors will be recycled within their sectors to reduce cascading and the risk of scrap surplus. Therefore, scrap flows to/from other economic sectors are not considered. Pre-consumer scrap is also not considered explicitly: we assumed that current technologies make it possible to reuse close to 100% of this scrap in a closed-loop system. Finally, we did not consider regional disparities in scrap surplus: aluminium scrap is a globally traded commodity, so we assumed that if a regional surplus were to occur, international trade flows would balance it out. Overall, these assumptions are quite optimistic about the ability of the system to recycle all the scrap, meaning that our forecasts for scrap surplus are conservative and might underestimate it.

2.2. *Dynamic MFA model*

A dynamic MFA model was computed from years 2000 to 2050, with some input data starting as far back as 1900 to initialize values. Demand for cars is computed using a lifetime-stock-driven model (Müller 2006; Lauinger et al., 2021). The in-use stock of cars per year and world region is determined by multiplying the population by the car ownership per capita over time.

Future scenarios were developed using eight independent parameters (Table 1). For each of those parameters, several future projections were analysed. Population per region per year was derived from the United Nations (2019) Low, Medium and High projections. Car ownership per capita over time has been estimated from historic data and a logistic regression (Pauliuk et al., 2012) with Low, Medium and High levels of saturation. Vehicle lifetime per region has been estimated from existing sources and modelled using a normal distribution. Scenarios for the speed of electrification of the vehicle fleet and subsequent changes in powertrain splits were taken from the IEA scenarios Stated Policies, Sustainable Development and Net Zero. A Constant scenario assuming a

Table 1
List of parameters used to build future scenarios.

Parameter	Scenarios	Comments
Population per region (Appendix 6.1)	Low Medium High	Derived from UN Population by country scenarios
Car Ownership per region (Appendix 6.2)	Low Medium High	Determined using historic data and Gompertz logistic regressions with different saturation levels per region.
Vehicle Lifetime per region (Appendix 6.3)	Low Medium High	Average vehicle lifetime per region, using a normal distribution. The three scenarios start with historic mean lifetime values for the different regions, close to 15 years. They stay constant in the Medium scenario, or converge to 10 years (Low) or 20 years (High) for all regions in 2050
Powertrain split per region (Appendix 6.4)	Constant	Constant 2020 values (included for reference)
	Stated Policies (STEP)	IEA STEP Scenario
	Sustainable Development (SUS)	IEA SUS Scenario
	Net Zero (NZE)	IEA Net Zero Scenario
Segment split per region (Appendix 6.5)	Small cars	Increasing share of A/B cars
	Constant	Constant 2020 values
	SUV	Increasing share of SUVs
Aluminium Content per region (Appendix 6.6)	Low Medium High	Average aluminium mass per vehicle per region, assuming a constant 2020 powertrain and segment split. This parameter represents the intensity of aluminium use for lightweighting.
Penetration of Alloy-sorting Technologies per region (Appendix 6.7)	Low Medium High	Share of mixed shredder scrap that is further sorted using LIBS or similar alloy-sorting technologies. Low corresponds to no implementation, Medium up to 50% in 2050, High up to 80% in 2050
Carbon Footprint of Aluminium Production (Global values) (Appendix 6.8)	BAU	Constant 2020 values
	Medium	Average reduction effort
	Below 2 Degrees (B2DS)	Based on the International Aluminium Institute B2DS Scenario, including primary production with Net-Zero electricity and inert anodes, Carbon Capture Utilisation & Storage (CCUS), electrification of casthouses and refineries, and increasing yields and collection rates for recycling.

constant 2020 powertrain split was included as a reference. The influence of a change in vehicle segment split was analysed with three scenarios: one with constant 2020 values, one in which the average size of cars is reduced with an increase of the share of the A/B segment, and one with a larger penetration of SUVs. Future levels of light-weighting with aluminium were represented with Low, Medium, and High scenarios for the average aluminium content per vehicle. Three scenarios are considered for the penetration of alloy-sorting technologies, from no alloy-sorting in the Low scenario to 80% penetration rate in 2050 in the High scenario. Finally, future GHG emissions due to the production of aluminium in cars were estimated using three scenarios for the global average carbon footprint or primary and secondary aluminium production. The BAU scenario is assuming a continuation of the last 20 years trend with a stagnation at current levels, where the benefits of technology improvements are offset by changes in the electricity mix. The Below 2 Degrees scenario (B2DS) is taken from a roadmap from the International Aluminium Institute (International Aluminium Institute 2021) and is representative of an optimistic industry roadmap to meet the sector's decarbonisation goal. The Medium scenario is a middle of the road scenario where about half of the decarbonisation effort of the B2DS scenario is achieved in 2050.

The model also contains fixed parameters, such as yields and transfer coefficients (appendix 3). Their value can change over time depending on the data and assumptions made, but they are not used further to build scenarios and in the sensitivity analysis, contrarily to the scenario parameters.

2.3. *Explorative sensitivity analysis based on parameter variation*

The combinations of all unique possibilities for the scenario parameters listed in Table 1 results in a total of 8748 future scenarios, all of which were analysed in separate model runs. A sensitivity analysis by parameter variation between 2020 and 2050 was conducted for 7 parameters for the quantity of mixed scrap surplus, and 8 for the carbon footprint of aluminium in cars. This explorative approach is using the stock-driven dynamics MFA model to identify which potential drivers have the most impact on the system, as well as setting boundaries for possible future outcomes.

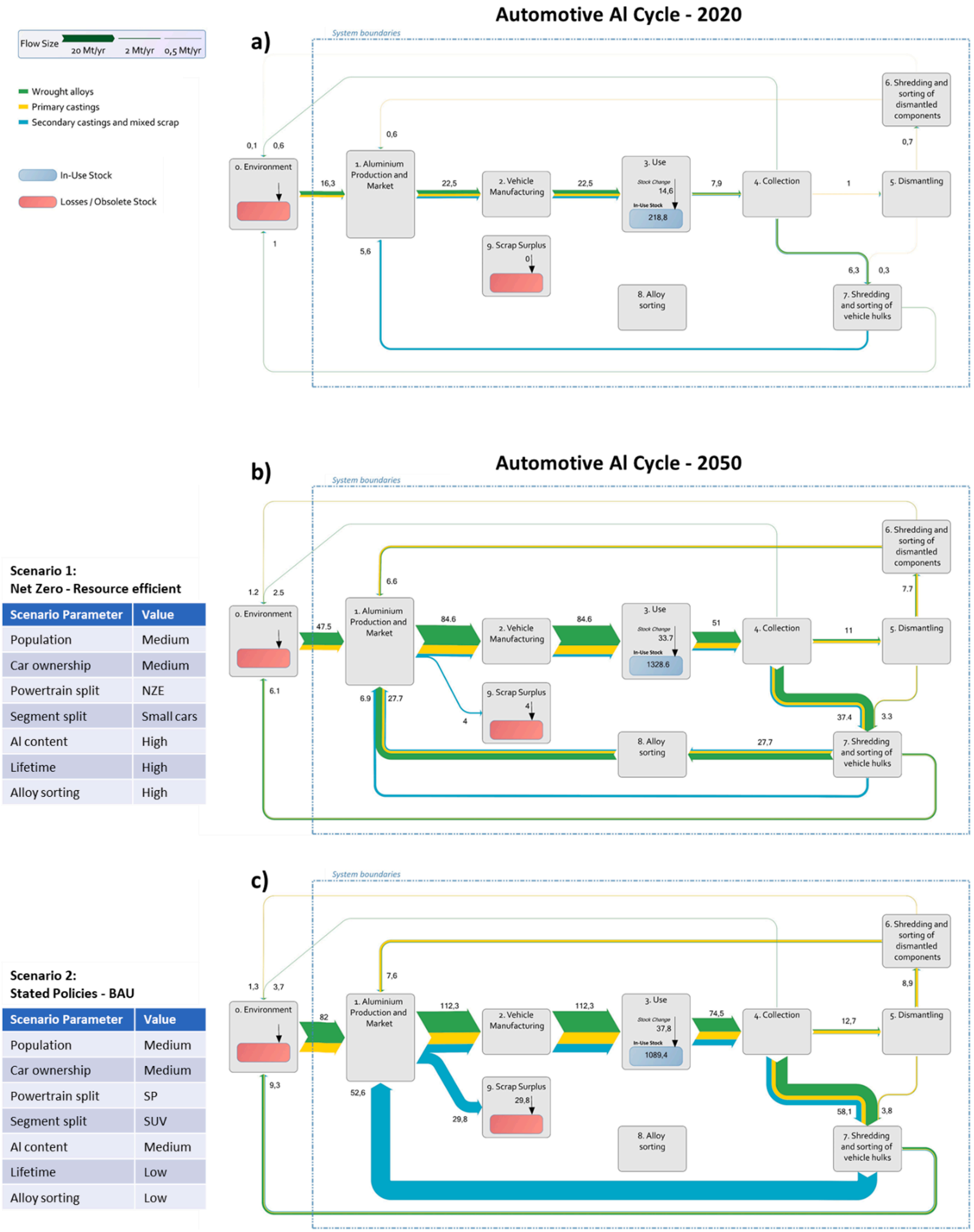
The model used in this study is based on the ODYM software (Pauliuk and Heeren 2020). The code and additional interactive visualisations are available in the following repository: https://www.doi.org/10.5281/zenodo.7041497

3. Results

3.1. *Global passenger car Al system in 2050*

Fig. 2 shows the quantified system of global aluminium use in passenger cars in 2020 and in 2050, under two possible scenarios out of the 8748 computed. The scenario 1 *Net Zero - Resource efficient* (Fig. 2b) is a possible future in which the consequences of a fast electrification and increased lightweighting on the aluminium cycle are partly compensated by the use of smaller cars, a prolonged vehicle lifetime and the penetration of alloy-sorting technologies. Conversely, the scenario 2 *Stated Policies - BAU* (Fig. 2c) depicts a future with lower ambitions for electrification and lightweighting, but in which aluminium demand is kept high by the growing preferences for SUVs and a shorter vehicle lifetime. In both scenarios, the Medium projections were used for population and car ownership.

Compared to the system in 2020, in 2050 all flows have increased in size independently of the chosen scenario, especially the flows from the end-of-life subsystem as the global stock of passenger cars starts to stabilize. However, the large volumes of post-consumer scrap available do not result in a reduction in primary aluminium demand, which goes up to 47.5 Mt/yr in the scenario 1 compared to 16.3 Mt/yr in 2020. Indeed, the need for primary production is mainly driven by the demand for



Scenario 1:
Net Zero - Resource efficient

Scenario Parameter	Value
Population	Medium
Car ownership	Medium
Powertrain split	NZE
Segment split	Small cars
Al content	High
Lifetime	High
Alloy sorting	High

Scenario 2:
Stated Policies - BAU

Scenario Parameter	Value
Population	Medium
Car ownership	Medium
Powertrain split	SP
Segment split	SUV
Al content	Medium
Lifetime	Low
Alloy sorting	Low

Fig. 2. Global cycle of aluminium production, use and disposal in passenger cars, quantified for 2020 (a) and 2050 under two example scenarios. The example scenario 1 represented in b) allows for the highest penetration of EVs and increasing lightweighting, while keeping primary Al demand and scrap surplus limited thanks to smaller cars, an increasing vehicle lifetime and a high penetration of alloy sorting technologies. Conversely, the example scenario 2 represented in c) has fewer EVs and limited lightweighting, but the primary Al demand and scrap surplus are higher due to the high penetration of SUVs and a shorter vehicle lifetime combined with less efficient recycling technologies.

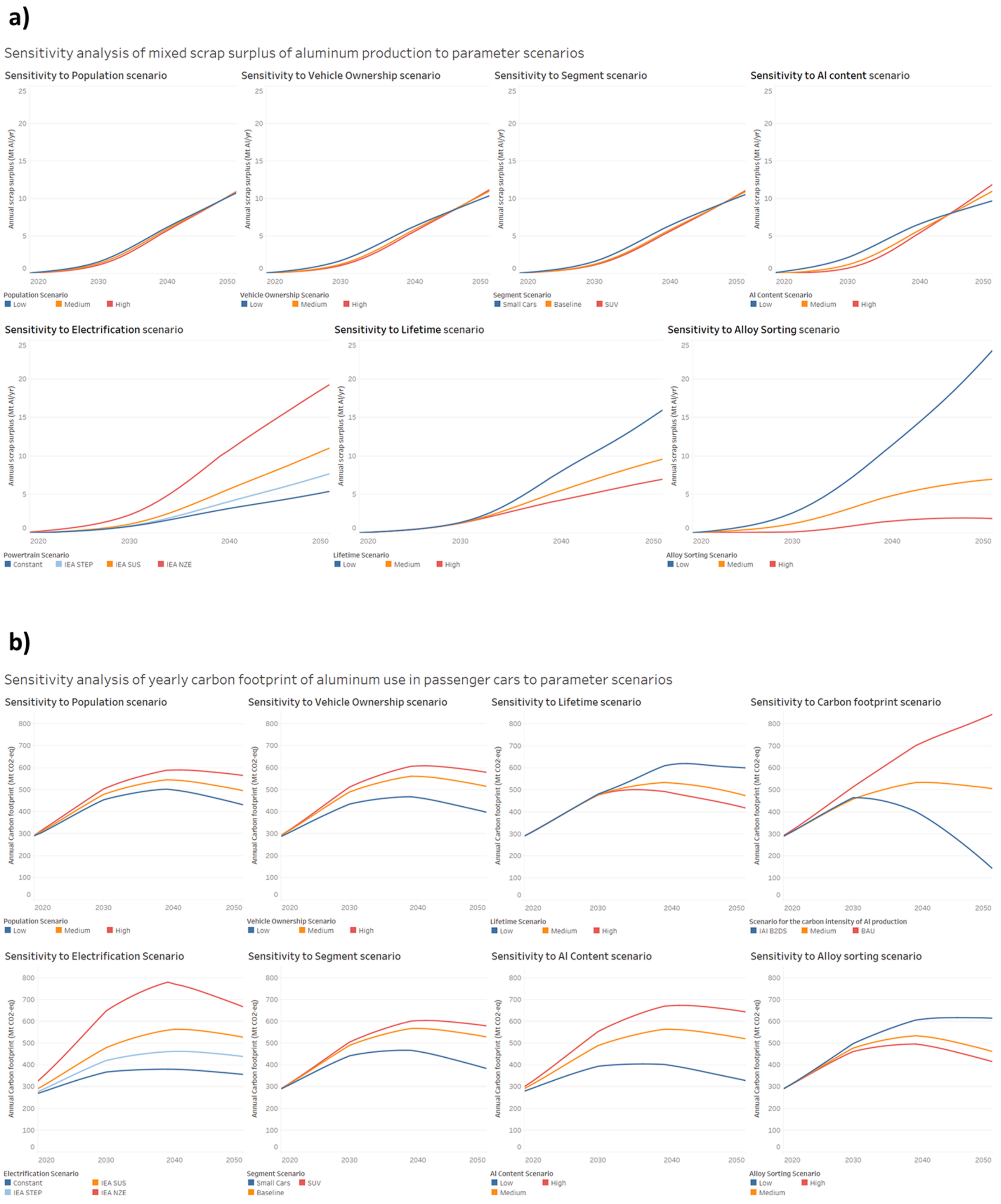


Fig. 3. Sensitivity analysis over time by parameter variation for the size of the mixed scrap surplus (a) and the carbon footprint associated with aluminium use in passenger cars (b).

aluminium in new cars, which would increase 3.75 times in 2050 compared to 2020, limiting the role of recycling in the overall picture. Under the scenario 2, both the total and the primary aluminium demand would increase by a factor 5. The significant mixed scrap surplus (29.8 Mt/yr compared to 4 Mt/yr in the scenario 1) is greatly reducing the potential to substitute the primary demand by post-consumer scrap, further illustrating the inability of the system to run on secondary production only.

3.2. *Sensitivity analysis of scrap surplus and carbon footprint*

The sensitivity analysis allowed us to explore further the impact of the different scenario parameters on critical characteristics of the system. The risk of scrap surplus (Fig. 3a) is mostly sensitive to three parameters: electrification speed, penetration of alloy sorting technology, and vehicle lifetime. Other parameters were found to have almost no effect on scrap surplus, apart on the timing: for instance, higher population and vehicle ownership increase the aluminium demand, which tends to slightly delay the occurrence of scrap surplus in the short term, only to lead to a larger surplus towards 2050.

For carbon footprint (Fig. 3b), the situation is different: all parameters included in the sensitivity analysis have a significant effect. This was anticipated, as they all influence the overall aluminium demand in one way or another. However, the parameter with the strongest effect is by far the carbon footprint of aluminium production.

3.3. *Future scenarios for aluminium demand*

Projections for the total future aluminium demand for passenger cars for all 8748 scenarios are shown on Fig. 4a). All model runs lead to a significant increase of automotive Al demand, but the speed and scale of this increase shows large variations between scenarios. As shown in Fig. 4b), 50% of the scenarios considered result in a demand within the range of 55.1 to 98.5 Mt/yr in 2050, with a median of 74.3 Mt/yr. For the three IEA electrification scenarios (excluding the Constant scenario used for reference), the median increases to 80.1 Mt/yr, almost a 4 times increase compared with 2020. Electrification has a clear effect on aluminium demand: the fastest electrification scenario (represented in red) leads to an average additional increase of 37 Mt/yr in 2050 compared with a constant powertrain split.

Fig. 5 allows us to dig deeper into the consequences for the automotive aluminium cycle by separating between alloy types. Indeed, the increase in demand is not spread evenly: wrought alloys show a stronger increase to become the dominant alloy family in 2050, while the need for secondary castings remains limited. More interestingly, fast electrification scenarios exacerbate this difference: due to the different requirements for battery casings and extra light-weighting, they show the largest increase in wrought alloys and to a lesser extent primary castings, while their secondary casting demand is lower than in low electrification scenarios due to the lower need for internal combustion engine parts.

When it comes to scrap generation, the same patterns can be observed with some delay, corresponding to the rather long lifetimes of vehicles. This is creating several challenges for the circularity of aluminium in the automotive sector. On the one hand, fast electrification scenarios require much more wrought aluminium than what can be produced from scrap, increasing the need for primary production, even if optimal collection and recycling systems were in place. On the other hand, the lower demand for secondary castings alloys while significant scrap volumes will be generated from retired ICE leads to a situation where it becomes difficult to find a use for all the scrap. The bottom right graph in Fig. 5 shows that the demand for secondary castings remains higher or equal to the scrap generated apart in a few extreme scenarios, indicating that a secondary castings scrap surplus could theoretically be avoided with perfect separation, sorting, and recycling technologies.

3.4. *Risk of scrap surplus*

However, a scrap surplus is likely to take place long before scrap generation is exceeding demand, due to the current cascading nature of the automotive aluminium recycling system. Indeed, Fig. 6 shows that without the deployment of alloy sorting technologies, all scenarios lead to a scrap surplus starting in the coming years and increasing to more than 10 Mt/yr in 2050, highlighting the need for such technologies to support the transition to electric mobility. As identified by the sensitivity analysis (Fig. 3a), the risk of mixed scrap surplus is directly linked to the transition to EVs, a faster transition increasing the potential size of a

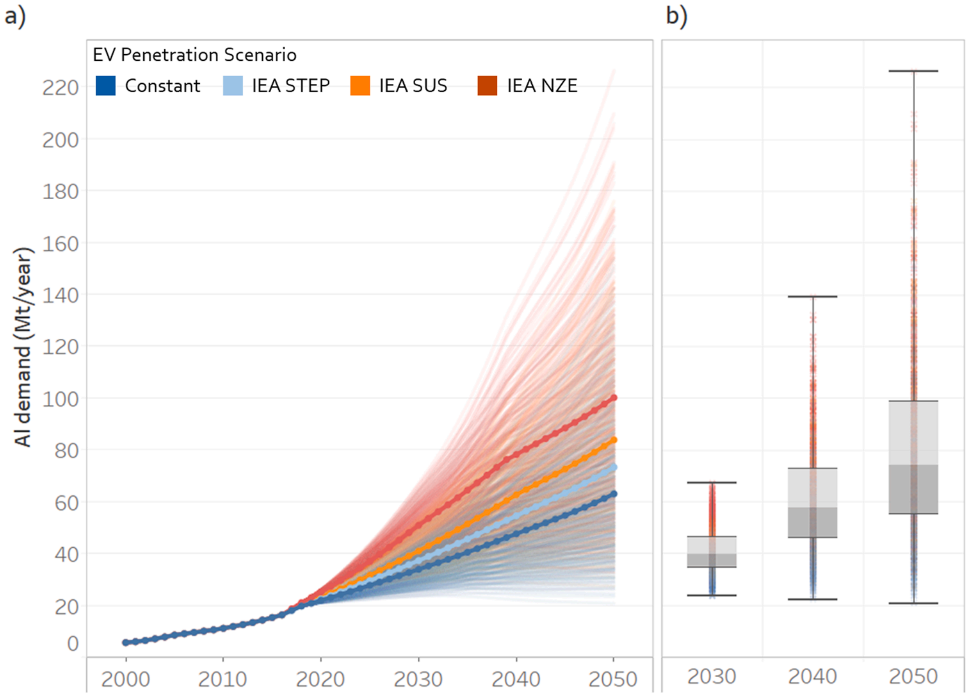


Fig. 4. Yearly global aluminium demand for passenger cars
a) Each line represents a model run for every unique combination of model parameters.Thick dotted lines represent the average of all scenarios for a given electrification scenario (dark blue: Constant, light blue: STEP, orange: SUS, red: NZE).
b) Box and whisker plot showing the statiscal distribution of aluminium demand computed for all scenarios in 2030, 2040, and 2050. Each colour dot represents one scenario. For each year, the box indicates the mean quartiles (the demand lies within the box for 50% of the scenarios): the bottom of the box is the lower quartile, the separation in the middle the median and the upper of the box the upper quartile. The whiskers represent the extreme data points.

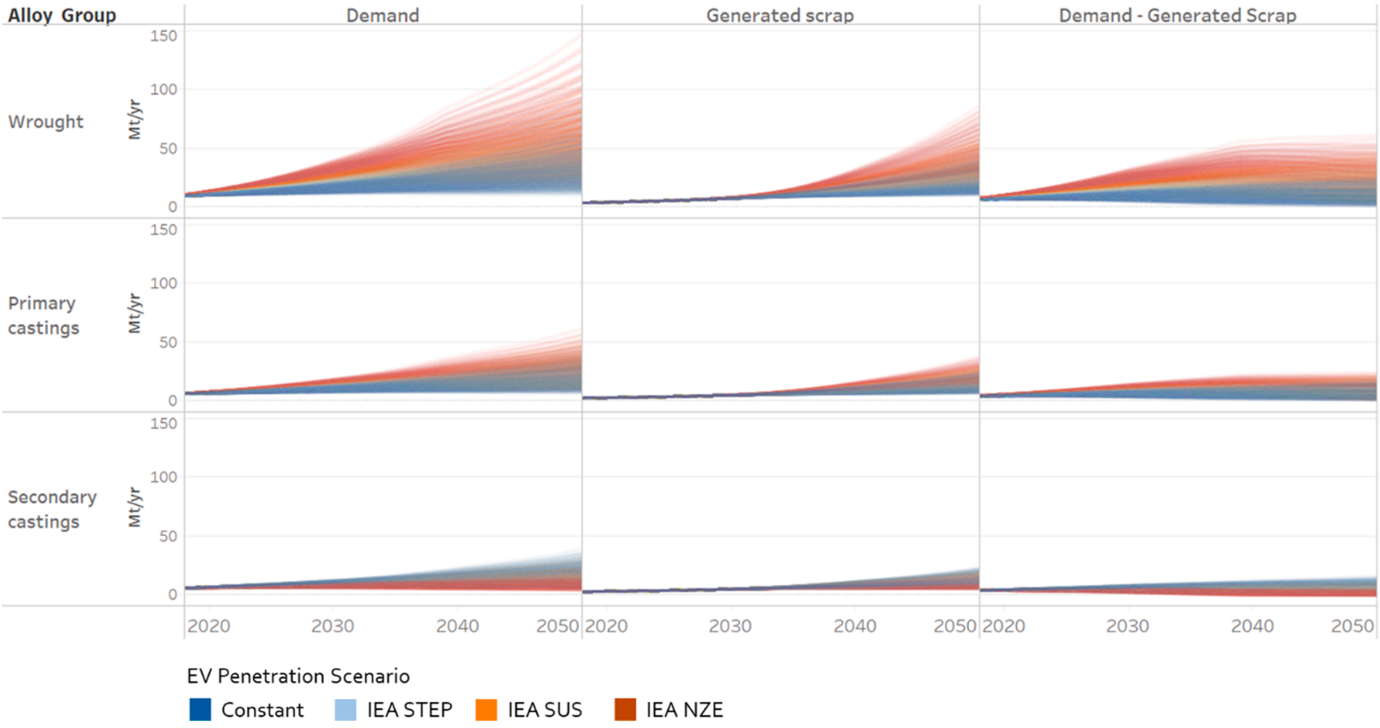


Fig. 5. Aluminium demand for passenger cars and end of life scrap by alloy type from 2020 to 2050 according to all scenarios. Projections for future powertrain shares are represented in different colors, from dark blue (constant 2020 values) to red (more and faster electrification).

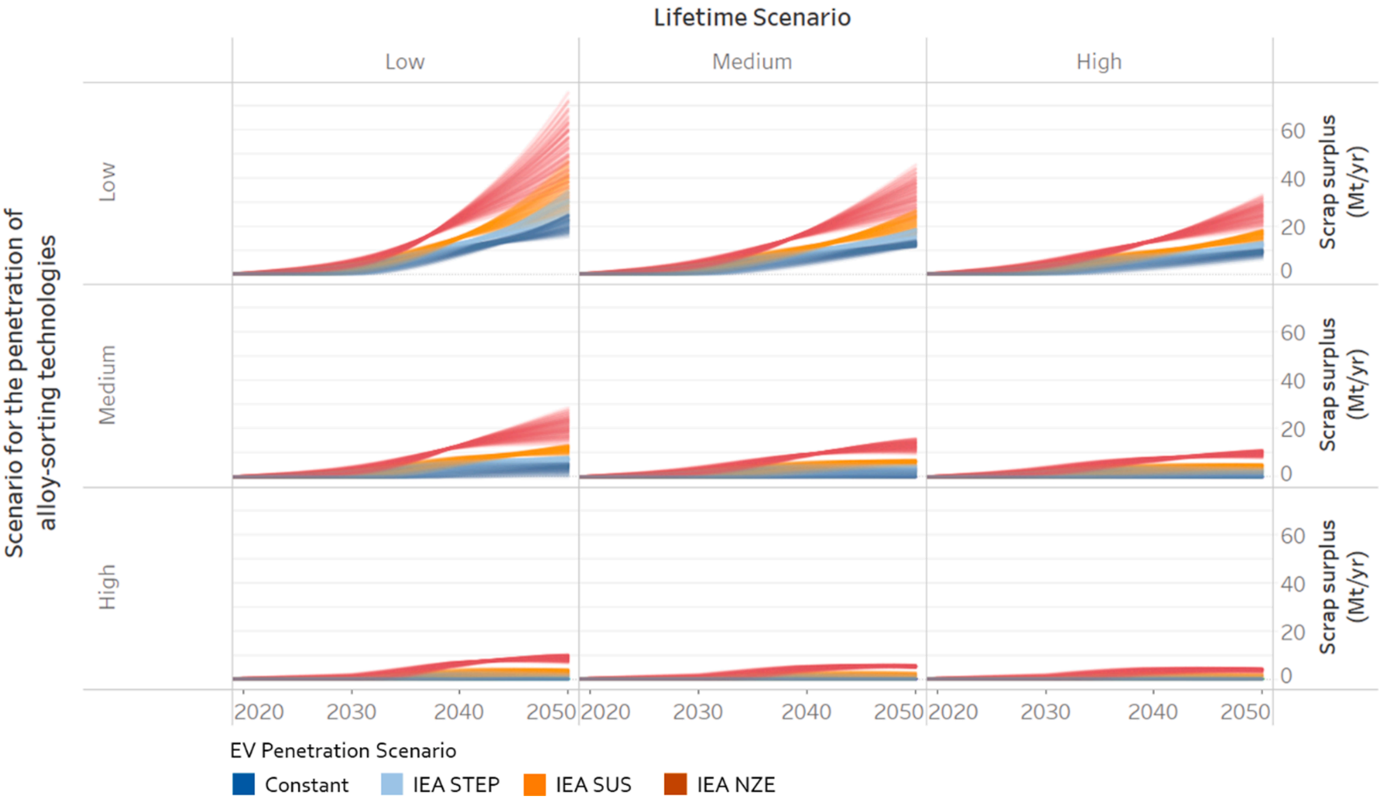


Fig. 6. Evolution of the size of scrap surplus under different electrification, vehicle lifetime, and alloy sorting scenarios. Each line represents a model run for every unique combination of model parameters. Columns correspond to different vehicle lifetime scenarios, rows to different alloy sorting scenarios. Projections for future powertrain shares are represented in different colors, from dark blue (constant 2020 values) to red (more and faster electrification).

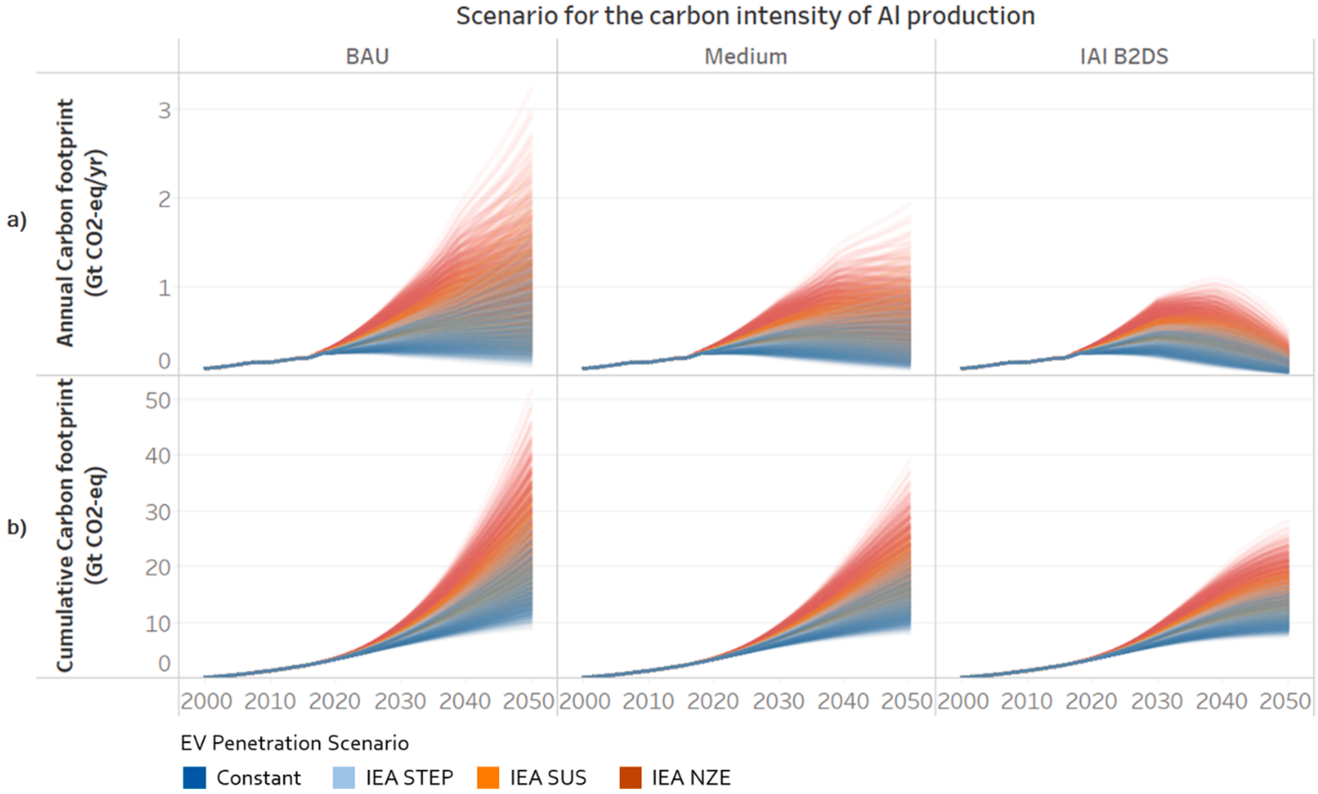


Fig. 7. Yearly (a) and cumulative since 2000 (b) carbon footprint under different scenarios for the decarbonisation of the aluminium production industry (Constant: same average carbon footprint as 2020, Medium: linear decrease from 16.8 to 10 kg CO_2-eq/kg Al in 2050 for primary production, IAI_B2DS Below 2 Degrees Scenario form the International Aluminium Institute). Each line represents a model run for every unique combination of model parameters.Thick dotted lines represent the average of all scenarios for a given electrification scenario (dark blue: Constant, light blue: STEP, orange: SUS, red: NZE).

future scrap surplus. Indeed, fast penetration of electric vehicles in the global fleet has the potential to double the size of the scrap surplus, compared with a scenario where powertrain shares stay constant at their 2020 values (dark blue curves). Due to the lack of historical data and the uncertainties associated with the development of a new technology, little is known about the effect that electrification will have on the average value of vehicle lifetime. However, our model shows that the lifetime of cars can have a great impact on the scrap surplus: longer lifetimes (right column in Fig. 6) result in postponing and reducing the scrap surplus, while shorter lifetimes intensify it (left column in Fig. 6).

3.5. *Yearly and cumulative carbon footprint*

Fig. 7a demonstrates a clear link between the scale and speed of the EV transition and the increase of the total carbon footprint of aluminium in cars. Decreasing the carbon intensity of aluminium production is a major strategy to mitigate this increase in emissions. The model results show that the most ambitious roadmap for technology development and electricity decarbonisation in the aluminium industry (right column in Fig. 7a) enables the total annual carbon footprint in 2050 to decrease back to 2020 levels in most scenarios. However, this technology transition takes time: an increase in the annual carbon footprint up to 2030 seems unavoidable, making it hard to mitigate the increase in cumulative emissions (Fig. 7b), the most relevant metric for measuring the contribution of the sector to climate change.

4. Discussion

4.1. *The future of aluminium use in passenger cars*

Forecasting the development of the global passenger car stock is a daunting task. Most of the stock growth is expected in China and RoW regions, the regions with the highest data uncertainty. However, the large number of scenarios examined in the model allowed us to quantify a wide range of future stock developments and their effect on the aluminium cycle, which leads to the conclusion that current trends in the transport sector will lead to a significant increase in aluminium demand, especially of wrought alloys.

It is however possible for the demand to be smaller than anticipated, for instance if policies and new business models limit the growth of car ownership. Systemic changes in the way personal transportation is organised, e.g. with autonomous vehicles combined with car sharing, has the potential to provide a similar service to the population with a smaller vehicle fleet (PTV and COWI 2019). Nevertheless, increasing the intensity of use of the cars might reduce their lifetime (Amatuni et al., 2020), requiring more frequent replacement and making the effect on material demand more uncertain (Roca-Puigròs et al., 2022). A modal shift to public transportation, or a reduction of the transportation demand (e.g. due to the generalisation of remote offices) could reduce material demand, provided that they actually result in a lower car ownership.

Using aluminium is not the only way to reduce the weight of cars. The most obvious solution would be to reduce the average size of car and the range of EVs to limit battery weight (Ellingsen et al., 2017), but the industry has taken an opposite direction in recent years. Other materials exist for light-weighting, such as advanced high-strength steel (AHSS), advanced composites, plastics, or multi-material solutions (Taub et al., 2019). However, they all come with their own production, cost, carbon footprint, and recycling challenges. The automotive industry still seems to favour aluminium, at least in the near future (WardsAuto 2017; DuckerFrontier 2020).

4.2. Influence on the future carbon footprint of cars

If current trends continue, the contribution of aluminium to the carbon footprint of EVs will largely exceed the one from battery materials (such as Ni, Li, Co, Mn) and assembly. This fact is often overlooked in existing LCA studies: indeed, while different electricity mixes are usually considered for the use (European Parliament 2018) or cell production (Ellingsen et al., 2014) phases, this is not the case for material production, where European or American emissions factors are usually used for aluminium smelting, resulting in a much cleaner electricity mix than the world average. For instance, Dai et al. (2019) used a factor of 7.41 kg CO_2-eq/kg Al, which is much lower than the global average of 16.5 kg CO_2-eq/kg Al from Nunez and Jones (2016) and the International Aluminium Institute (2022), and the global median value of 18.4 kg CO_2-eq/kg Al estimated with a parametric approach by Manjong et al. (2021). Correcting their values by using the world average, aluminium would represent 32% of the GWP in an average EV battery, compared to the 17% they assumed. When adding the even larger aluminium fraction contained in the rest of the car (usually not included in LCA studies focusing on batteries only), the GWP from aluminium exceeds that of the rest of the battery. This gap will keep growing with the forecasted increase in aluminium use and improvements in battery cell production.

4.3. Strategies to limit scrap surplus

Our results show that increasing the lifetime of cars is an effective way to reduce and postpone a mixed scrap surplus. The vehicle lifetime depends on many factors, including car manufacturers, consumers, market prices, regulatory environment. It is still unknown whether the transition to electric mobility will lead to a change in average car lifetime. EVs could potentially have a longer lifetime than ICEV, thanks to the reduction in moving parts and the relative simplicity of an electric engine compared to ICE, but this could be compensated by issues related to battery lifetime and consumers' preferences for the newest technologies. A generalisation of battery replacements to increase the lifetime of vehicles (Aguilar Lopez, Billy, and Müller 2022) can have both positive and negative effects on aluminium demand and scrap surplus. Several policies currently in place in different countries provide incentives to lower the vehicle lifetime, especially for ICEVs: (i) limiting the use of older ICEVs through low emission zones (Amundsen and Sundvor 2018), (ii) accelerating their replacement through scrapping subsidies (Grigolon et al., 2016), and (iii) reducing the price of new EV models through subsidies or tax reduction but not on replacement parts and batteries (Thorne et al., 2021). Since ICEVs have the highest content in secondary castings, an unwanted consequence of these policies could be to considerably increase the problem of mixed scrap surplus.

The results have shown that a scrap surplus cannot be avoided with current practices. Dismantling and/or alloy-sorting technologies such as LIBS need to be developed at the same pace as electrification to limit the scrap surplus during this transition. Nevertheless, there is currently no large-scale implementation of these methods, mostly because of the added cost that these processes add to the recycling operations. Besides, if trials have been successful for manufacturing scrap such as sheet stamping (Y. Dai et al., 2021; Noll et al., 2014), this technology has proved less successful for the sorting of mixed post-consumer scrap, whose surface is typically more contaminated with impurities (Gaustad et al., 2012; Van den Eynde et al., 2022b).

This situation might change in the future, as a scrap surplus will increase the premium between lower and higher scrap qualities, creating new economic opportunities. However, the speed and scale of the coming scrap surplus make it very challenging for these new technologies to penetrate the market fast enough. Besides, even if alloy-sorting is implemented, the accumulation of alloying elements and impurities ultimately limit closed-loop recycling (Løvik and Müller 2014). New research is trying to address this problem, with the development of processes like solid-state electrolysis for upcycling of mixed automotive Al scrap to high purity aluminium (Lu et al., 2022). Aluminium companies are also working on this topic (Alcoa 2021) but as of today little is known about the practical feasibility of these technologies, the main concern being the energy use, which is estimated to be much higher than for classical remelting or refining.

Another solution is to challenge the current alloy system to use more casting components and alloys with looser specifications whenever feasible to allow for an increase in recycled content. Some car manufacturers are already trying to reduce the number of alloys used in vehicles, while developing new casting alloys with better structural and electrical properties (Palanivel et al., 2019), especially for battery casing, could help maintaining the alloy composition of new vehicles closer to the one of old vehicles to facilitate recycling. This is facilitated by new fabrication processes, such as new joining designs to make dismantling and/or sorting easier, or big castings (Kallas 2019) that could help reducing the number of parts and hence the need for dismantling. It is however difficult for individual automakers to change the whole system; more coordination is needed between the different actors to define standards, and recyclers need to be involved to create a reverse value chain for the collection and processing of aluminium scrap. The aluminium industry is already aware of these needs, which require further development and knowledge spreading in the automotive industry (The Aluminum Association 2021).

4.4. Impact of current and future policies on the carbon footprint of aluminium in cars

New transport policies are also needed to ensure that the increasing impacts of material production will not outweigh the benefits of electrification and light-weighting. Fuel efficiency measures and stringent emissions limits are useful and have played an essential role in incentivizing manufacturers to improving the environmental performance of cars over time. However, current policies tend to focus exclusively on use-phase emissions, which could be at the expense of the material footprint of cars. For instance, g CO2/km targets such as the ones in place in the EU (European Commission 2020) are incentivising manufacturers to use more lightweight materials, especially in vehicles such SUVs which are intrinsically less energy efficient. Advantageous fuel consumption calculations (Plötz et al., 2022) also push car manufacturers who historically tend to sell bigger or more luxurious models to aggressively promote sales of large PHEV cars to leverage their expertise in ICEs and maintain their position on those lucrative higher ends markets (IEA 2022), with the side effect of strongly increasing overall material use.

After the first wave of early adoption, the transition to EVs will render these targets obsolete: the next generation of targets will need to better account for the totality of the life cycle of cars and promote a more sustainable use of energy intensive materials. Ultimately, policies should go beyond individual cars footprinting and also consider systemic impacts on material cycles, in order to encourage a reduction in overall emissions of the larger system. This is not an easy task: for example, France has introduced an additional tax on vehicles whose curb weight exceeds 1800 kg (JORF 2020), with the aim of limiting the increase of the share of SUVs in new sales. However, this also gives car manufacturers an incentive to use more aggressive light-weighting to keep selling those vehicles, hence increasing further the use of aluminium and the carbon footprint. BEVs and PHEVs with more than 50 km or electric range are exempted from this weight tax, which also encourages the production of heavy EVs. Similarly, the dual-credit policy in place in China (Ou et al., 2020) provides incentives to buy BEVs or PHEVs with higher battery range. Conversely, the Norwegian Government (2022) proposed to reduce tax exemptions for the most expensive EV models, which might limit the sales of EVs from the SUVs and D/E segments.

New policies are being introduced to limit the material footprint of EVs, mainly focusing on batteries. For instance, the new European regulatory framework for batteries will introduce recycled content targets for some critical battery materials, such as cobalt, nickel, manganese, and lithium (but not aluminium) and progressive carbon footprint requirements (Halleux 2022). However, this is not sufficient to address the carbon footprint of aluminium since it is used both in the battery and the rest of the car: more focus on the wider car system is needed. Furthermore, due to the position of aluminium as a major metal used in many products and industries, strict carbon footprint standards with limited product and geographical scope could result in carbon leakage to other countries or industries: low carbon footprint aluminium could be used in areas covered by the legislation, while “dirty” aluminium will still have other uses elsewhere, providing little benefits for mitigating global emissions.

The transition to electric mobility hence needs to be discussed in a holistic perspective, to address challenges and opportunities for other industries. Scenario analysis based on dynamic MFA provides policy makers and industries with simulation tools to anticipate this new development. There is a paradox in the fact that accelerating the EV transition is key to mitigate transport emissions, but at the same time likely to increase the emissions from the automotive aluminium cycle. As shown in Fig. 7, even under the most optimistic industry roadmaps, the carbon intensity of aluminium production is unlikely to decrease fast enough to compensate the additional emissions associated with a rapidly increasing demand for automotive aluminium. Besides, a fast transition can create a lock-in effect: due to the long lifetime of industrial assets, if the additional aluminium production capacity is built with current standards, this will highly compromise the possibility of a successful mitigation of the sector in the medium-to-long term. This issue highlights the importance of supporting the electrification and lightweighting of the transport sector with comprehensive measures to secure the large investments needed to increase the sustainability of material cycles.

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CRediT authorship contribution statement

Romain G. Billy: Conceptualization, Methodology, Software, Validation, Data curation, Visualization, Writing – original draft. **Daniel B. Müller:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data and code are available at: https://zenodo.org/record/7,041,497

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Supplementary materials

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