Titre: Title:	Sector-specific scenarios for future stocks and flows of aluminum: An analysis based on shared socioeconomic pathways
Auteurs: Authors:	Julien Pedneault, Guillaume Majeau-Bettez, Stefan Pauliuk, & Manuele Margni
Date:	2022
Type:	Article de revue / Article
Référence: Citation:	Pedneault, J., Majeau-Bettez, G., Pauliuk, S., & Margni, M. (2022). Sector-specific scenarios for future stocks and flows of aluminum: An analysis based on shared socioeconomic pathways. Journal of Industrial Ecology, 26(5), 1728-1746. https://doi.org/10.1111/jiec.13321

Titre de la revue: Journal Title:	Journal of Industrial Ecology (vol. 26, no. 5)
Maison d'édition: Publisher:	Wiley & Yale University
URL officiel: Official URL:	https://doi.org/10.1111/jiec.13321
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TITLE

Sector-specific scenarios for future stocks and flows of aluminium – An analysis based on Shared Socioeconomic Pathways

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ABSTRACT

Aluminium is an energy-intensive material that is typically used as an alloy. The environmental impacts caused by its production can potentially be spread out over multiple uses through repeated recycling loops. However, inter-alloy contamination can limit the circularity of aluminium, which highlights the importance of analyzing prospective stock dynamics of aluminium at an alloy and alloying element level to inform a more sustainable management of this resource. A dynamic material flow analysis (MFA) of aluminium alloys was developed in line with the Shared Socioeconomic Pathways (SSP) framework to generate consistent scenarios of the evolution of aluminium stocks and flows from 2015 to 2100 covering 11 economic sectors in 5 world regions. A sector-specific and bottom-up modelling approach was developed. Results show no saturation of global stock per capita before 2100, reaching a range between 200 and 400 kg per capita according to different socioeconomic scenarios. For the business-as-usual scenario, the global annual inflow rises to 100 Mt in 2050 and peaks at 130 Mt in 2090, showing a saturation in total stock. Electricity-sector demand has the highest relative growth over the century, while building and construction demand saturates and decreases from 2090. No major mismatch between inflows and outflows of aluminium alloy is observed. This means that with appropriate dismantling and sorting, changes in alloy demand wouldn’t limit the implementation of a closed-loop aluminium industry. This study demonstrates the advantages of combining detailed MFAs and SSPs, both for greater consistency in circular economy modelling and for furthering scenario development efforts. This article met the requirements for a gold JIE data openness badge described at http://jie.click/badges.

1 INTRODUCTION

Aluminium, the second most produced metal after steel, is used in a wide range of forms and products such as vehicles, industrial equipment, buildings, packaging, and consumer durables (Cullen & Allwood, 2013). Aluminium is rarely used in its pure form, but rather in an alloyed form to improve specific physical properties. There are two main families of alloys: wrought alloys and cast alloys. The most commonly used alloying elements are silicon, iron, copper, magnesium, and manganese (The Aluminum Association, 2021).

The environmental profile of aluminium largely depends on the electricity mix supplying the energy-intensive electrolysis process involved in its primary production (Nunez & Jones, 2016; Paraskevas, Kellens, Van De Voorde, Dewulf, & Duflou, 2016; Pedneault, Majeau-Bettez, Krey, & Margni, 2021). Recycling aluminium reduces its energy consumption by 95% and can reduce its carbon footprint by as much as a factor of 30 in comparison to primary aluminium (Liu & Müller, 2012). Thus, reducing the environmental impact of the industry can be done by increasing the recirculation of recycled material (Liu, Bangs, & Müller, 2012; Material Economics, 2016). However, this recirculation can be limited by inter-alloy contamination. When different alloys are mixed, the alloying elements cannot then be separated due to thermodynamic parameters, aluminium's relatively low melting point, and its strong affinity for oxygen (Nakajima et al., 2010). To overcome such contamination, the recycled alloy is diluted with primary aluminium in a process called sweetening. This process lowers the concentration of tramp elements but increases the environmental impacts of recycled aluminium (Cullen & Allwood, 2013). Downcycling wrought alloys into cast alloys is commonly done in the industry because the latter can typically accommodate a larger percentage of alloying contamination (Cullen & Allwood, 2013; Løvik, Modaresi, & Müller, 2014). Downcycling practices could generate a potential future mismatch between secondary aluminium composition and overall demand due to the accumulation of tramp elements over repeated recycling cycles (Liu, Bangs, & Müller, 2011). The reduced demand for cast aluminium arising from the electrification of transport (Hatayama, Daigo, Matsuno, & Adachi, 2012; Modaresi, Løvik, & Müller, 2014; Rombach, Modaresi, & Müller, 2012) may also consequently lead to a surplus of low-grade recycled aluminium (Bertram et al., 2017; Hatayama, Daigo, Matsuno, & Adachi, 2009; Rombach et al., 2012). These potential issues highlight the importance of understanding not only the dynamics of aluminium stocks dynamics, but also those of its different alloys and alloying elements to improve the management of aluminium resources and to support the transformation of the industry towards a more sustainable and circular economy (Lauinger, Billy, Vásquez, & Müller, 2021).

Material flow analysis (MFA) is widely used in industrial ecology and circular economy to systematically quantify the flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2005; Müller, Hilty, Widmer, Schluep, & Faulstich, 2014). To assess the evolution of stocks and flows over a given time interval, a dynamic material flow analysis (dMFA) is preferred (Chen & Graedel, 2012).

Two main dMFA modelling approaches exist: top-down and bottom-up. In the top-down approach, or inflow-driven approach, material stocks are calculated using annual time series for material production, economic input–output tables, and lifetime distributions of end-use products in a society (Hirato, Daigo, Matsuno, & Adachi, 2009). The top-down approach provides a good overview of the system, but it also has the disadvantage of being disconnected from the service provided by the stock. Conversely, in the bottom-up, or stock-driven, approach, the material content in every product or end-use sector contributes to the in-use stock (Müller et al., 2014). The dynamics of the inflows and outflows are then obtained from the evolution pattern of the in-use stock and its turnover as products reaching their end-of-life must be replaced (B. Müller, 2006). However, the in-use stock used as a proxy for the level of service is an oversimplification of the real system, which could introduce systematic errors (Lauinger et al., 2021). The selection of the appropriate modelling approach depends on the purpose of the model, the objective of the study, and data availability.

Projections of aluminium stocks and flows already exist, but they are either restricted to a single specific sector, too aggregated to capture the evolution of the different alloys or disconnected from the relation between the service and the stock itself. Some dMFA use a bottom-up approach to understand the material dynamics of some specific sectors, like the automotive (Modaresi & Müller, 2012) or the housing (Hatayama & Tahara, 2016) sectors, but are too specific to offer a comprehensive portrait of the whole aluminium industry. On the other hand, some global projections of major metals (including aluminium) are made using an inflow-driven approach based on the GDP evolution (Watari et al., 2020) or extrapolated from past data (Elshkaki, Graedel, Ciacci, & Reck, 2018; Van der Voet, Van Oers, Verboon, & Kuipers, 2018). Those aggregated projections are not based on an estimation of the services rendered by the stocks and cannot capture potential dematerialisation or resource scarcity dynamics. Other studies focussing on the whole aluminium industry typically use a sigmoid curve projection of stock per capita with scenarios varying the saturation levels and times to saturation (Dai, Wang, Chen, & Liu, 2019; Liu et al., 2012) or GDP evolution per capita. Saturation of stock means that stocks reach a plateau, and no further net accumulation of stocks occurs. It implies that expansion flows decline to zero while only maintenance and replacement flows are needed for maintaining the stock at its saturated level (Wiedenhofer et al., 2021). In those cases, in-use stocks are used as a proxy for the level of service (Lauinger et al., 2021) and are based on the belief that the stock of aluminium per capita will saturate within the time frame of the study. As no evidence of stock saturation has yet been observed for aluminium in industrialised countries, except possibly for the USA (Bleischwitz, Nechifor, Winning, Huang, & Geng, 2018), it is challenging to estimate a saturation level. In addition, actual aluminium in-use stock and stock per capita (IAI, 2020a) levels are already higher than most of the saturation levels originally projected by these studies. This kind of modelling is also very sensitive to assumptions as to the expected time required to reach saturation. A too early saturation timing would overestimate how rapidly downcycling would become problematic, while an excessively late saturation timing could avoid capturing downcycling dynamics altogether.

In prospective dMFA, scenario modeling is often used as a scientific tool to explore what types of futures we could encounter (Kriegler et al., 2014) without trying explicitly to predict the future. Yet, scenario definition comes with some limitations in terms of credibility and compatibility. As stated by Fishman et al. (2021): “Scenarios are often formulated on an ad hoc, case-specific basis, to answer a certain study’s research questions, with little common ground with other studies scenarios. This fact hinders comparability between results, the potential for follow-up studies, and synthesis of findings, all of which are crucial for informing policy”. A common scenario modelling approach within the scientific community would help reduce this incompatibility between scenarios across studies.

The shared socioeconomic pathways (SSP) constitute a framework used by the climate change research community to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (Riahi et al., 2017). This framework also allows assessments of future natural resource levels with greater comparability (Schandl et al., 2020). The SSPs are developed around a set of five narratives, each of them describing plausible and internally consistent developments in societal aspects such as demographic, economic, technological, social, governance and environmental factors according to different levels of challenges to climate mitigation and adaptation (O’Neill et al., 2017). SSP1 (*Taking the green road)* describes a gradual but pervasive shift towards a more sustainable path. SSP2 (*Middle of the road)* projects the evolution of society without a marked shift from historical trends. SSP3 (*A rocky road)* is characterized by regional rivalry and international fragmentation, while environmental concerns are not prioritized, and consumption remains materially intensive. SSP4 *(A road divided)* describes a world with high inequalities both across and within countries. SSP5 (*Taking the highway*) is a techno-optimistic pathway driven by economic success leading to high energy and resource consumption.

The SSPs can serve as a common basis for prospective studies in the research community (O'Neill et al., 2017; Riahi et al., 2017). The framework has been recently used to assess material dynamics and overall demand for phosphorus in agriculture (Mogollón, Beusen, van Grinsven, Westhoek, & Bouwman, 2018) and metals in electricity generation technologies, cars, and electric appliances (Deetman, Pauliuk, Van Vuuren, Van Der Voet, & Tukker, 2018).

The present research aims to model prospective aluminium alloys stock, demand, and end of life flows at a regional and global scale. To do so, we developed explorative scenarios in line with the SSP framework. This type of scenario aims to explore situations or developments from a variety of perspectives (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006). We're proposing a simulation model in line with SSP rather than an optimization model under constraints (Watari et al., 2020).

Methodologically, to overcome the oversimplification of a top-down saturation per capita level, a sectorial bottom-up approach is developed. This allows for the evaluation of the stock and flows per capita, sector by sector, and reduces the information gap between the in-use stock and the associated level of service. For example, if we anticipate an increase in transportation service, how does this translate to practical determinants such as level of car ownership, stock of cars, and stock of material per capita. Here, we develop a novel modelling framework implemented in an open-access tool called PRASTOF that generates bottom-up prospective scenarios of aluminium alloys stock and flows for each end-use industrial sector.

2 METHODS

2.1 PRASTOF GENERAL FRAMEWORK

The PRASTOF (PRospective Aluminium STOcks and Flows) open-source Python software calculates future aluminium stocks and flows with a bottom-up, sector-by-sector perspective. The overall strategy behind PRASTOF is to model sectors based on the services rendered to estimate per-capita stocks and their eventual specific saturation level. This approach allows a more detailed representation of each stock-level assumption, so that it becomes possible to critically assess its realism and consistency in terms of delivered functionality. A sector-by-sector approach also gives a more accurate choice of equations to better respect the system behavior and data availability. Scenarios generated by PRASTOF follow the SSP narratives (O'Neill et al., 2017; Riahi et al., 2017). Six main sectors are studied: building and construction (BC), transport (Trans), electrical engineering (EE), machinery and equipment (ME), consumer durables (CD), and packaging and cans (PC).

The framework is structured in four main steps (Figure 1). Firstly, the projection of the stock per capita is calculated for the different sectors and subsectors. Secondly, the total stocks are calculated by multiplying the projected population and stock per capita. Thirdly, inflows and outflows associated with these stock projections are calculated using the ODYM dMFA software (Pauliuk & Heeren, 2020) based on their average lifetime and initial stock composition. Finally, stocks, inflows and outflows are decomposed into 16 different alloys and 10 alloying elements. Similar steps are followed for sectors modelled according to an inflow-driven approach. Inflow per capita is projected, and then scaled to the total population. Stocks accumulation and outflows are calculated with ODYM (Pauliuk & Heeren, 2020) based on the lifetime of the stock and stocks and flows are decomposed into alloys and alloying elements.

The boundaries of the dMFA generated by PRASTOF cover the stock accumulation, the inflows (aluminium flows that supply the stock accumulation and renewal) and outflows (the discarded stocks when they reach the end of their lifetime). Inflows could come from primary or secondary production while outflows could either be landfilled or recycled. However, these distinctions are beyond the scope of this study.

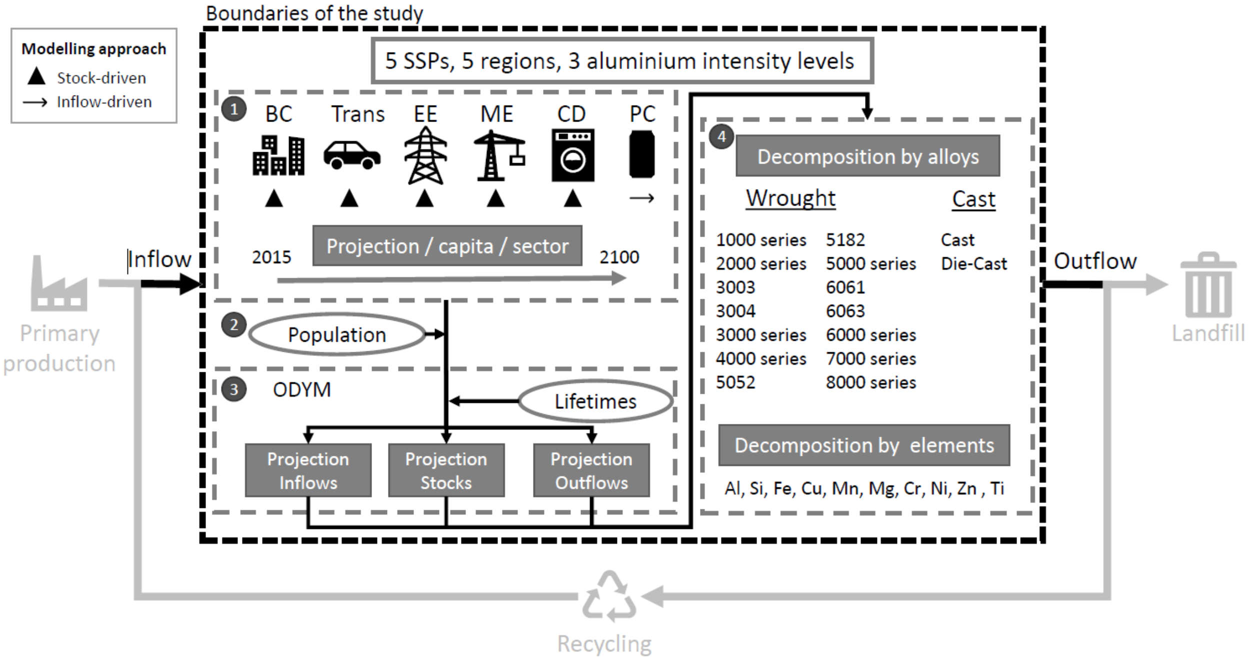

Figure 1: General framework and boundaries of PRASTOF to calculate future aluminium stocks and flows in different industrial sectors where BC is building and construction, Trans is transport, EE is electrical engineering, ME is machinery and equipment, CD is consumer durables and PC is packaging and cans. The Triangle pictogram under a sector indicates that the sector is calculated according to a stock-driven approach, while the arrow refers to an inflow driven approach.

PRASTOF scenarios cover the 5 different SSPs and their associated narratives across 5 regions consistent with the SSP framework: Asia, Latin America (LAM), Middle East and Africa (MAF), countries from the Organisation for Economic Co-operation and Development organisation (OECD), and countries from the Reforming Economies of Eastern Europe and the Former Soviet Union (REF). A global aggregation per capita is also performed with a weighting proportionate to each region's population.

The timeframe covers the period from 2015 to 2100. Projections beyond 2050 are highly speculative but will still provide useful insight into trends for sectors with a long lifetime such as buildings. Scenarios are also built according to 3 levels of aluminium use intensity to capture the sensitivity of aluminium content in products.

PRASTOF code is available on GitHub (https://github.com/jpedneault/PRASTOF, commit *Revision_1)* with all input data gathered in an Excel sheet (SI1). Users can download the PRASTOF class and can reproduce the results presented here by running a short Jupyter notebook. Users may also change input data and parameters in the excel sheet to produce their own aluminium projection scenarios.

2.2 MODELLING APPROACH PER SECTOR

We developed a flowchart to guide the selection of the appropriate modelling approach per sector or subsector (**Error! Reference source not found.**). Letters in parenthesis in the next paragraphs refer to a position in the flowchart in **Error! Reference source not found.**.

Human well-being includes the use of physical services such as food, shelter and transport, but these are supplied by in-use stocks in the form of products, buildings, factories or infrastructure (Pauliuk & Müller, 2014). Thus, the first question to ask for a sector is (a): *Do the stocks provide the service of the sector?* If yes, a stock-driven approach is selected, otherwise, we select an inflow-driven approach. For example, in the transport sector, it is the stock of material composing the vehicles that provide the transport service for consumers. In the packaging sector, an inflow-driven approach is used because the packaging is simply consumed when the food or the good is unpacked. For more details on the Stock–Flow–Service Nexus, see Haberl et al. (2017).

For the stock-driven branch, we then need to identify the service rendered by the stock (b) and evaluate the homogeneity of stock composition within the sector (c). If the sector is not sufficiently homogeneous in terms of stock composition or service rendered by the stock, it should be disaggregated into subsectors. However, if no data were found in the SSP database (Riahi et al., 2017), official statistics, or the scientific literature, no disaggregation of the sector is done despite the heterogeneity of the stock ((d): *Do data for subsector exist?)*. For example, the consumer-durables sector was not disaggregated because it was not possible to find specific projections of the services rendered. If data exist, the sector is disaggregated into subsectors. For example, the transport sector, which offers the service of displacing persons or commodities, is split into *automotive* and *freight* transport based on data available in the SSP database (Riahi et al., 2017). In this study, the automotive sector only covers the 4-wheeled private cars. Another subsector representing *other* transport is made to avoid major omissions of stock within the sector. This other subsector covers the wide range of vehicles excluded by the two other subsectors.

The next question is: *Are there published projections of the future demand levels for the services (functionality) rendered by this (sub-)sector?* (e). If yes, projections of the service are reconciled to different scenarios (f). Projections of stock are then made based on the aluminium intensity of the service projection (g). To continue the example on the transport *automotive* subsector, projections of person-km transported (pkm) exist which are used to evaluate the future vehicle stocks needed to supply that demand of service. Then, vehicle stocks are decomposed into stocks of aluminium based on the aluminium intensity of vehicles.

If no projection of the service exists, a projection is made based on a stock-per-capita perspective (h), which leads to the question: *Are there published projections of the future levels of stock per capita for the specific sector (i).* If yes, those projections are adapted to the SSP framework consistently with the narratives (O'Neill et al., 2017) (j). If no, stock projections must be made by the quantification of the potential maximum levels (k) according to the question: *Is there a functional limit to the maximum stock per capita within the time horizon of the study?* If it is possible to evaluate a potential maximum based on functional constraints beyond which additional stock brings no marginal gain in functionality, projections are made according to a Gompertz function with the maximum amplitude and the identified driver (l). For example, in the consumer durables sector, there is a certain limit in terms of the number of appliances, devices and furniture per capita beyond which they cease to add convenience; estimating this limit defines a reasonable maximum stock. Otherwise, barring a clear functionally maximum stock, the maximum of stock or flow per capita is estimated from existing literature; projections are then performed according to this maximum value and an identified driver (m). For example, in machinery and equipment, the maximum level of stock per capita for a medium level of aluminium intensity is selected based on the actual level currently observed in the USA. The GDP per capita is then used as driver.

For the inflow driven approach, a disaggregation is made if there is a lack of homogeneity within the sector and the necessary data are available (n). Then, projections are made according to the identified driver and the maximum level estimated from the literature (o). For example, the packaging sector is disaggregated into *cans* and *other,* and both projections are based on GDP per capita.

Grey ovals inside **Error! Reference source not found.** show the final position of different sectors and subsectors, indicating the calculation approaches used for each in PRASTOF.

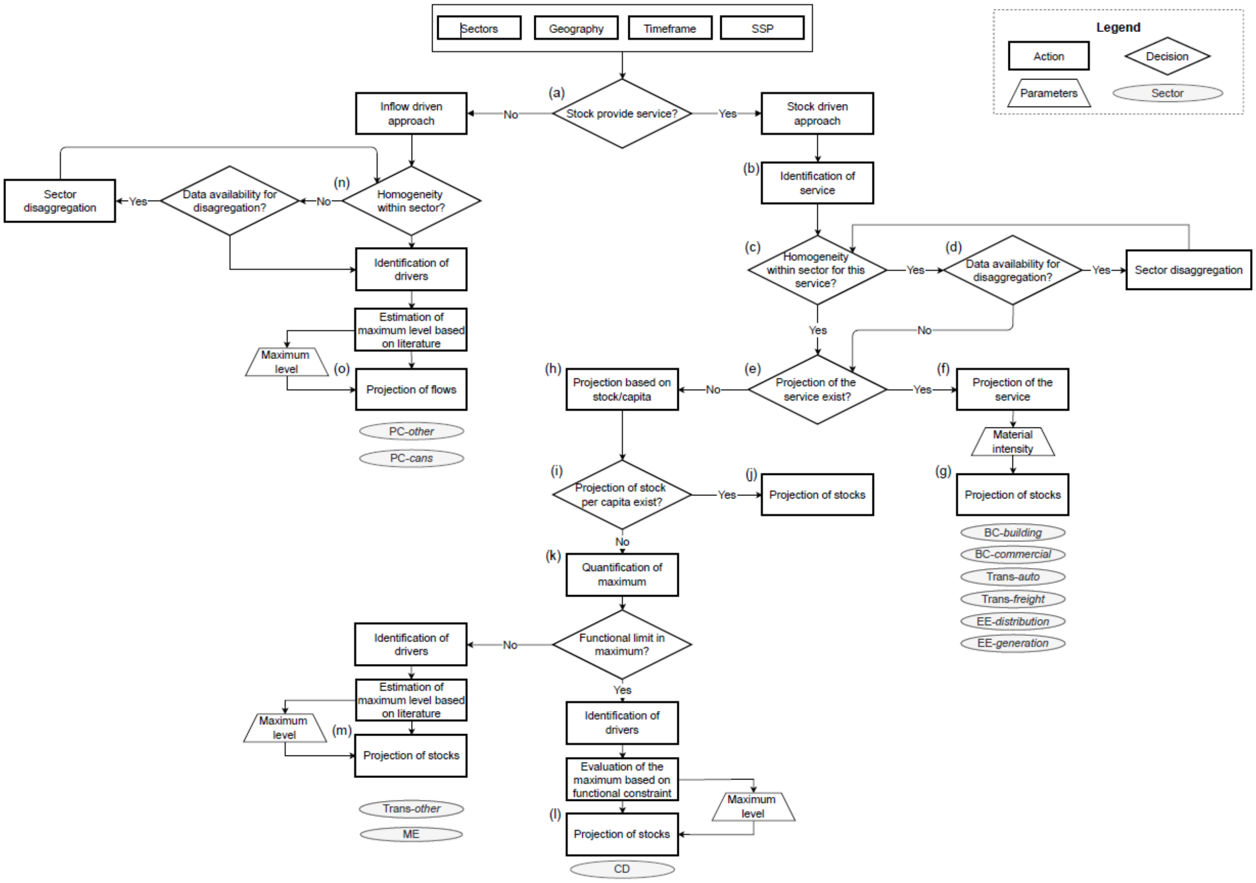

Figure 2: Flowchart describing the appropriate modelling approach per sector or subsector. The grey oval indicates the final position of different sectors in the flow chart; where BC is building and construction, Trans is Transport, EE is electrical engineering, ME is Machinery and equipment, CD is consumer durable, and PC is packaging and cans.

A description of the modeling approach, data used, and assumptions taken for different sectors and subsectors is presented in **Error! Reference source not found.**. Further details on the methods and equations are presented in SI2.

*Table 1: Calculation details for different sectors and subsectors. More exhaustive descriptions of methods and equations are available in SI2. The main driver refers to the parameter that changes according to the SSP scenarios. Aluminium intensity refers to the values of the parameter that change according to the three levels of aluminium intensity for the sensitivity analysis. For cases marked with **, the aluminium intensity depends on different parameters available in SI.*

Sector	Subsector	Calculation details	Main driver	Aluminium intensity [low-medium-high]	Link to SI
Building and construction (BC)	Residential	The floor area per capita [m2/cap] is projected according to different SSP and different regions based on (Haberl et al., 2021; Pauliuk et al., 2019). It is then multiplied by an aluminium intensity parameter [kg/m²] (Recalde et al., 2008) to obtain the stock / cap.	m²/cap	[0.6 – 2 - 5.3] kg Al / m²	SI2-1.1.1
	Commercial	The floor area per capita is calculated according to a logistic function based on GDP projection from the SSP database (Riahi et al., 2017), the maximum floor area per employee , the share of service sector employee in total employee and the share of active population (Hong et al., 2016). The stock / cap is than calculated by the product of the area and the aluminium intensity of floor area [kg/m²] (Recalde et al., 2008).	GDP/cap	[0.6 – 2 - 5.3] kg Al / m²	SI2-1.1.2
Transport (Trans)	Automotive	The stock of aluminium is the product of the stock of vehicle by the aluminium intensity by vehicle [kg/vehicle] (Hertwich et al., 2020; Pauliuk et al., 2019). The stock of vehicle is calculated based on transportation need projections from SSP in pkm/cap (Riahi et al., 2017), the average occupancy rate per vehicle (OR) projections (Pauliuk et al., 2019) and the annually average traveled distance per vehicle projections (ATD) (Pauliuk et al., 2019). The stock of vehicle is also decomposed into different type and size of vehicle (Pauliuk et al., 2019).	pkm/cap*	[40 – 50 – 60]** kg Al / vehicle	SI2-1.2.1
	Freight	The stock of aluminium is the product of the stock of freight vehicle by the aluminium intensity by freight vehicle [kg/freight vehicle]. The stock of freight vehicles per capita is calculated based on the annual freight transportation demand in tkm per capita (Riahi et al., 2017), the average market share of freight transport mode (Rodrigue, 2020), the average mass transported per freight vehicle and the average distance travelled annually per freight vehicle (Wernet et al., 2016).	tkm/cap	kg Al / freight vehicle**	SI2-1.2.2
	Other	The stock per capita is projected according to a Gompertz function based on GDP projection from the SSP (Riahi et al., 2017). The fitting constants of the function were determined by regression via the sum of least squares using USA GDP data between 1960 and 2010 (The World Bank, 2021) and historical aluminium stock (Chen, 2017). The maximum of the function, according to the medium level intensity, is estimate at the current stock/cap in USA. Low level and high level are estimated at 20% under and over the medium level.	GDP/cap	[22 – 27.5 – 33] maximum kg Al /cap	SI2-1.2.3
Electrical engineering (EE)	Distribution	The stock per capita is calculated based on the annual total consumption of electricity per capita projection from SSP database (Riahi et al., 2017) and the stock of distribution infrastructure needed per kW. The distribution infrastructure is split into four different types of distribution line: long-distance, high voltage, medium voltage and low voltage. Parameters used are the km of transmission line per kWh, the average lifetime of the distribution cable and its aluminium content (Wernet et al., 2016).	kW/cap	kg Al / kW / tech **	SI2-1.3.1
	Generation	The stock per capita is calculated based on the electrical capacity per capita projection from SSP database according to different electric generation technology (coal, hydro, wind, etc.) (Riahi et al., 2017). It is then multiplied by the aluminium intensity per kW of different electric generation technology (Bödeker et al., 2010; Wernet et al., 2016).	kWh/cap	kg Al / km **	Si2-1.3.2
Consumer durable (CD)		The stock per capita is projected according to a Gompertz function based on GDP projection from the SSP (Riahi et al., 2017). The fitting constants of the function were determined by regression via the sum of least squares using USA GDP data between 1960 and 2010 (The World Bank, 2021) and historical aluminium stock (Chen, 2017). The maximum of the function, according to the medium level intensity, is estimated at the current stock/cap in USA. The maximum associated to the high-level intensity is calculated from a physical constraint where each person has one unit of each furniture and electronic device. More than that would be equivalent to a superfluous luxury which we do not see as part of the SSP storylines. The low is estimated at 20% under the medium level.	GDP/cap	[25 – 30 – 50] maximum kg Al /cap	SI2-1.4
Machinery and equipment (ME)		The stock per capita is projected according to a Gompertz function based on GDP projection from the SSP (Riahi et al., 2017). The fitting constants of the function were determined by regression via the sum of least squares using USA GDP data between 1960 and 2010 (The World Bank, 2021) and historical aluminium stock (Chen, 2017). The maximum of the function, according to the medium level intensity, is estimated at the current stock/cap in USA. Low level and high level are estimated at 20% under and over the medium level.	GDP/cap	[40 – 50 – 60] maximum kg Al /cap	SI2-1.5
Packaging and cans (PC)	Cans	The annual inflow per capita is projected according to a Gompertz function based on GDP projection from the SSP (Riahi et al., 2017). The fitting constants of the function were determined by regression via the sum of least squares using final shipment data from different regions between 1960 and 2010(IAI, 2020b). The maximum of the function, according to the medium level intensity, is estimate at the current inflow/cap in USA. Low level and high level are estimated at 20% under and over the medium level.	GDP/cap	[2 – 2.5 – 3] maximum kg Al /cap	SI2-1.5.1
	Other	The annual inflow per capita are calculated similarly to the cans subsector (IAI, 2020b; Riahi et al., 2017; The World Bank, 2021). The different saturation levels were estimated based on North America level.	GDP/cap	[1 – 1.5 – 2] maximum kg Al /cap	SI2-1.5.2

2.3 POPULATION PROJECTION

After having completed the projections of the stocks and flows on a per-capita basis, these projections were then scaled up to total stocks and flows through multiplication with the projected population per region, following the population scenarios from the SSP database (Riahi et al., 2017). These population scenarios are condensed in SI1-SSP_pop.

2.4 DYNAMIC MASS FLOW ANALYSIS

To perform the dMFA related to the previously calculated stocks and flows, we used ODYM (Pauliuk & Heeren, 2020), an open-source framework for material systems modeling.

2.4.1 General modeling approach

The flow projections of sectors with a stock-driven approach were calculated in three steps using the evolution of the stock over time, the lifetime of the stock, and the characterisation of the initial stock cohort. A cohort refers to a lot of goods produced in a specific year (Vásquez, Løvik, Sandberg, & Müller, 2016). First, we determined the inflow from the difference between the stock level and the sum of stock cohorts available. Second, outflow by cohort and stock by cohort are determined with a survival function. Third, we determine the total outflow by summing all the outflows of past cohorts.

For the inflow-driven model, the outflows were calculated from the difference of stock by cohort. Stock projections were calculated from the inflow and the survival function. See Lauinger et al. (2021) for a general framework regarding stock dynamics.

2.4.2 Lifetime

The lifetime of different products within a sector was estimated from Bertram et al. (2017) and Pauliuk (2019) for the *trans-auto* subsector. We assume similar lifetimes in the SSP2, SSP3 and SSP4 scenarios.

For SSP1, we assumed an increase of 20% lifetime of all sectors except PC. According to O’Neil et al. (2017) narrative: «Consumption is oriented towards low material growth and lower resource and energy intensity […]», which can be interpreted as a will from the consumers to use their products and goods for a longer period of time. Conversely, we assume a reduction of 20% of all lifetimes for SSP5. Its associated narrative describes a world where: «economic growth is driven in part by consumerism and resource-intensive status consumption», meaning that consumers replace more frequently their goods. Finally, based on previous studies (Muller, Wang, & Duval, 2010; Pauliuk, Wang, & Müller, 2012), we assumed a normal distribution of lifetime with a standard deviation of 30% around the mean lifetime. Lifetime data are available in SI1-Lifetime.

2.4.3 Initial stock

The initial stock must be generated to calculate the associate inflows and outflows. For consistency with our previous assumptions, we also assumed a normal lifetime distribution of the cohorts within the initial stock with a standard deviation of 30% of the average lifetime (Muller et al., 2010; Pauliuk et al., 2012). This approach is effective when no additional information on past cohorts is available, but it may slightly bias the age distributions in sectors with a fast expansion. In a system with a fast-growing stock, the more recent cohorts should constitute a larger share of the total stock, in comparison with a normal distribution.

The calculation of the initial stock is made in four steps. First, the survival function (the function that gives the probability that a stock is still in use beyond a specified point in time) is calculated by subtracting the cumulative distribution function (based on the lifetime and standard deviation) from one. Second, the survival function is scaled to 1 by dividing the values of the vector by the sum of the vector. Third, we scaled this new vector by multiplying it by the magnitude of initial stock in the year 2015. Fourth, the order of the vector elements is reversed, with the oldest stock in the first place and the newest at the end in the past. A table is available in SI2-2 showing graphically the output of those four steps leading to the definition of the initial stock vector needed to calculate future stock dynamics.

2.5 DECOMPOSITION PER ALLOY

A decomposition of different stocks and flows according to 16 different alloys or alloy series (*1000 series, 2000 series, 3003, 3004, other 3000 series, 4000 series, 5052, 5182, other 5000 series, 6061, 6063, Other 6000 series, 7000 series, 8000 series* for wrought alloys and *Cast, Die-Cast* for cast alloys) is made in three distinct steps. Firstly, a decomposition between wrought and cast alloys is made for every sector using market share from final shipment product statistics in 2019 (IAI, 2020a). For the transport sector, we used specific vehicle decomposition per type of vehicle from Pauliuk et al. (2019). Secondly, we subdivided wrought alloys into different specific alloys and alloy series using the same market shares of alloys per sector as Hatayama et al. (2007). For the transport sector, we calculated the composition of the alloys of an average vehicle based on the decomposition by Modaresi et al. (2014). See SI1-Alloys for more details and data on alloy decomposition. No change in alloy composition of each product overtime is assumed due to missing information in the literature. Thirdly, we decomposed every alloy into a proportion of alloying elements (*Al, Si, Fe, Cu, Mn, Mg, Cr, Ni, Zn, Ti*) according to the maximum alloying tolerance of each alloy (ASTM, 2011; The Aluminum Association, 2015). For more generic series categories, we use the tolerance from an archetype alloy within the series (see SI1-Element for values).

3 RESULTS

Projections of stock per capita, total stock, inflows, and outflows for different SSP, regions, sectors, alloys, and alloying elements are published online in a data repository (Pedneault, Majeau-Bettez, Pauliuk, & Margni, 2022). The following sections describe and discuss those results.

3.1 STOCK AND FLOWS PROJECTIONS

The global average aluminium stocks per capita obtained by PRASTOF starts from 140 kg in 2015 and is projected to increase up to a range between 200 kg (SSP3) and 385 kg (SSP5) (**Error! Reference source not found.**), which is in line with the low development and high consumption of their respective narratives. SSP1 is the scenario with the second largest increase of stock per capita due to quick electrification and increase of GDP, followed by SSP2 and SSP4. A similar trend is observed for different regions, except that the starting point is different: starting at 110 kg for Asia, 170 kg in LAM, 95 kg in MAF, 270 kg in OECD and 160 kg in REF. While the increase of stock per capita slows over time, saturation is only observed for some SSPs and regions in the last five years of the century (SSP3: GLO, Asia, OCDE and SSP5: OCDE). Numerical results are presented in SI3-data_from_figure_3.

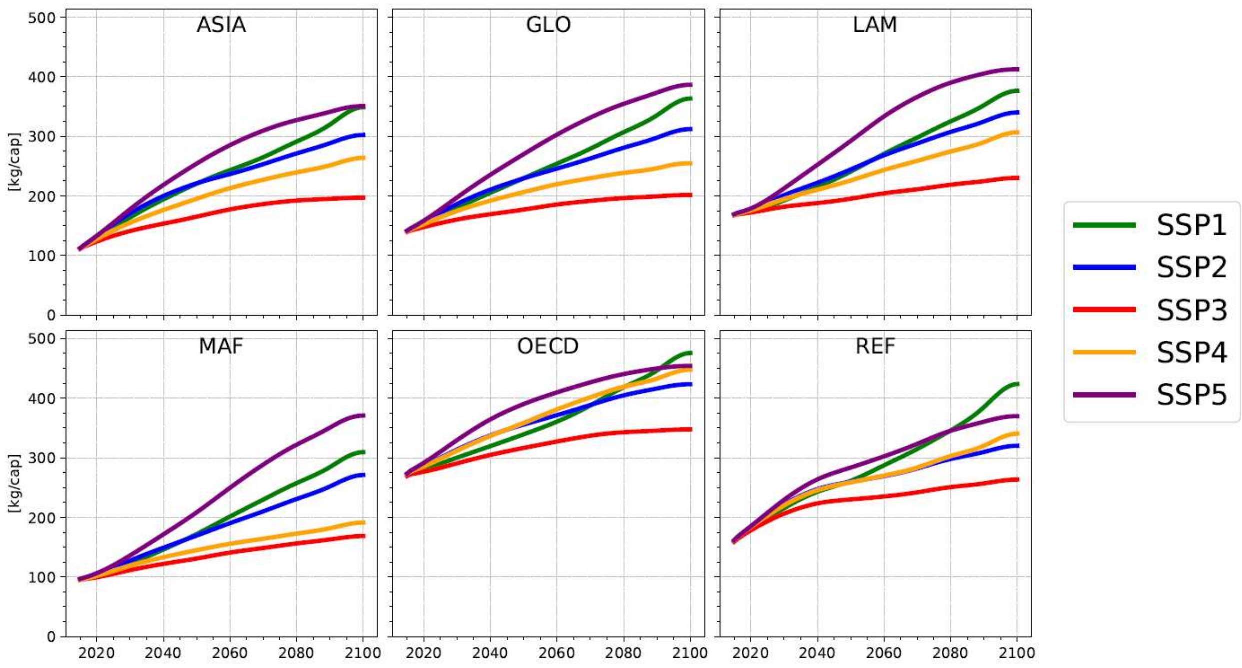

Figure 3: Evolution of stock per capita according to different SSP for 5 regions and the global average. The timeframe of the projection is between 2015 to 2100. The region acronym stands for: ASIA: Asia, GLO: Global average, LAM: Latin America, MAF: Middle East and Africa, OECD: Organisation for Economic Co-operation and Development, REF: Reforming Economies of Eastern Europe and the Former Soviet Union. The names of the scenarios are as follows: SSP1: Sustainability—Taking the green road, SSP2: Middle of the road, SSP3: Regional rivalry—A rocky road, SSP4: Inequality—A road divided and SSP5: Fossil-fueled development—Taking the highway.

The evolution of the total stock of aluminium, inflows, and outflows, according to a medium level of material intensity, is presented in **Error! Reference source not found.** (See SI3-data_from_figure_4 for values). An increase of stock from 1020 Mt in 2015 to a level between 2300 and 2900 Mt is projected in 2100 depending on the SSP. Only the SSP5 scenario shows a saturation of total stock. Small reductions in total stock starting from 2085 are also observed in SSP5. The magnitude of the increase is sensitive to the socio-economic evolution of societies because of the assumed population evolution trajectories and the projection of aluminium stocks per capita. The relative range between scenarios is smaller for absolute stock projections (Figure 4) than for per-capita projections (Figure 3) due to differences in population projections. The SSPs with lower population projections (SSP1 and SSP5) are the ones with the highest aluminium projections per capita. Conversely, the higher population projections have the lower aluminium per capita projections (SSP3), attenuating the total stock range between SSPs.

Different trends are observed in the evolution of aluminium stocks depending on the region (see SI3-Stock_SSP_regions). While the stock is mainly concentrated in OECD and Asia in 2015, MAF becomes increasingly important over time due to the growth of population and stock per capita. The REF and LAM regions, with their relatively small populations, are responsible for less than 10% of the global stock. The regional definition shows saturation and a subsequent decrease in aluminium stocks for the SSP1, SSP4, and SSP5 in Asia, along with SSP3 and SSP4 in OECD, due to saturation of stocks/capita and population decrease. Globally, the projected MAF stock accumulation overcomes the decreases in the other regions, thereby resulting in an overall constant increase in the total aluminium stocks, as shown in **Error! Reference source not found.**.

For the SSP2 scenario, the inflow of aluminium starts at approximately 75 Mt per year and increases to 130 in 2090, before slightly decreasing over the last decade of the century. SSP1, SSP3, and SSP4 follow similar trends, but with lower values. According to the SSP5 scenario, the inflow increases up to almost 150 Mt per year and peaks in 2070, which is earlier than the peaks reached in the other SSPs. Like the stock projections, these increases are mainly led by the fast development of MAF regions from 2030, in contrast with other regions, where the demands slow down from 2060. Further results describing regional projections and their values are presented in SI2 SI3-Inflow_SSP_regions.

The outflows, according to the SSP2 scenario, start from 43 Mt per year and increase to 122 Mt. Similar trends are observed for other SSPs. See SI3-Outflow_SSP_regions for SSP and regional projections. No reduction in outflows is observed. Interestingly, the difference between outflows and inflows decreases over time, thus implying a possible increase in recycled content to fulfil demand (inflows). The ratio between outflow and inflow is approximately 55% in 2020 and increases up to 100% in 2100, showing global saturation at the end of the century.

The contribution analysis of stock per sector and subsector, according to the SSP2 scenario, shows that stock is mainly in the building and construction sector (BC), followed by Transport (Trans)-*automotive*, Trans-*other* and Electrical engineering (EE)-*generation*. The projections show a saturation of in-use stock for the BC sector, while other sectors continue increasing over the decades. The stock growth in the EE sector is attributed to the increase in electricity demand, which in turn leads to increased electricity generation and expansion in distribution equipment. The consumer durables (CD) and machinery and equipment (ME) sectors increase due to the increase in GDP per capita, which consequently leads to higher consumption of goods and expansion of production capacity, thereby increasing the stock per capita. The Trans sector also increases over time due to the increase in vehicles per capita and the increase in GDP per capita, leading to an increase in the Trans-*other* subsector. The stock from Trans-*freight* starts at 1 Mt and increases up to 4 Mt. However, these values are very modest in comparison with the overall stock.

In terms of inflows, the sectors that contribute the most are BC, transport, and PC-*cans*. The sector with the biggest increase in market share over time is the EE-g*eneration* due to the growth in the market share of solar energy, a type of technology that requires more aluminium per kW, and the increase in overall electricity demand. Conversely, the BC inflows remain approximately the same due to stock saturation, but the relative contribution to the overall inflow decreases from 40% to 18% over the modelled period. The packaging and cans (PC) sector shows an increase in inflow until the end of the century, slightly increasing their share of total aluminium demand.

Trends observed for the contribution by sector of outflows are similar to those observed in inflows, except that they are temporally shifted due to the lifetime of the in-use stock.

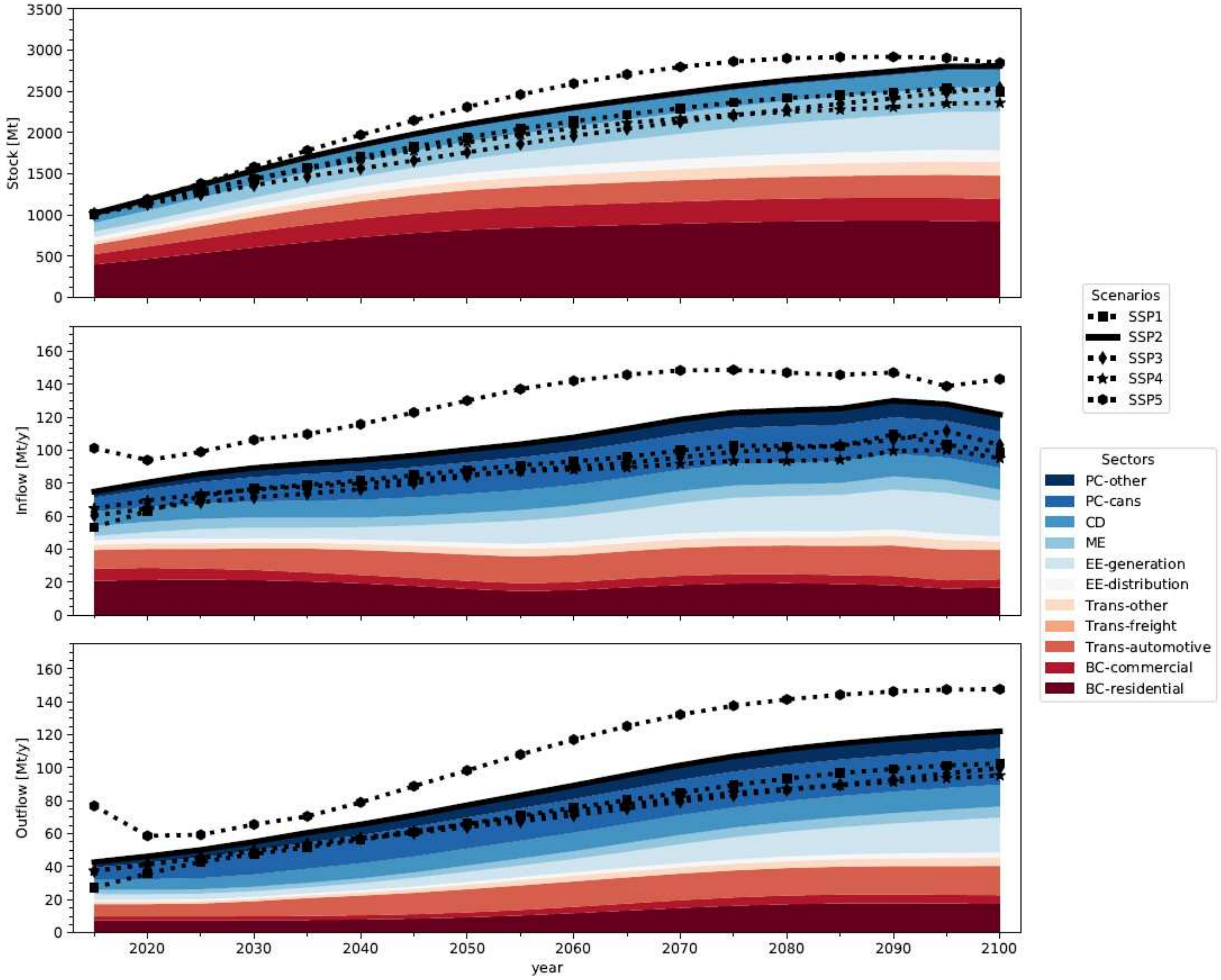

Figure 4: Projection of total stock inflow and outflow per SSP and contribution analysis of SSP2 stock per sector and subsectors where BC is building and construction, Trans is Transport, EE is electrical engineering, ME is Machinery and equipment, CD is consumer durable, and PC is packaging and cans. The timeframe of the projection is between 2015 to 2100.

In addition to the overall evolution of aluminium stocks and flows, the SSPs also play a role in influencing the relative contribution over time of the different sectors. More specifically, the relative contribution of the EE sector has a high variability because the electrification of the energy sectors can vary a lot across the different SSPs. SSP1 would lead to a larger proportion of stocks and flows of the EE sector due to fast and widespread electrification (+5% in 2050 and +18% in 2100 of stock in comparison to SSP2).

Conversely, SSP3 has a smaller proportion of EE (-5% in 2100 of stock in comparison to SSP2). The relative contribution of stocks and flows of other sectors remain mostly constant across all SSPs.

3.2 ALLOYS AND ALLOYING ELEMENTS

Error! Reference source not found. decomposes the global projections of alloys stocks, inflows, and outflows in terms of the different alloys, focussing on the SSP2 and using the medium aluminium intensity level. Numerical values are presented in SI3-data_from_figure_5.

The alloy 6063 is the dominant contributor in all stocks and flows, but its share decreases over time. This wrought alloy is mainly used in the BC sector, but also in ME and EE-*generation* sectors. The shares of the 1000 series and 8000 series alloys, the purest alloys in terms of aluminium content, doubles over the study period, mainly due to the increase in EE stocks and flows. The 3004 alloy, used for aluminium can, contributes less than 1% to the total stock but accounts for about 15% of the total inflow and outflow. This discrepancy between stock and flow contribution is explained by the very short lifespan of aluminium cans. Inflows and outflows of cast alloys and other alloys also increase over time without a major change in market share.

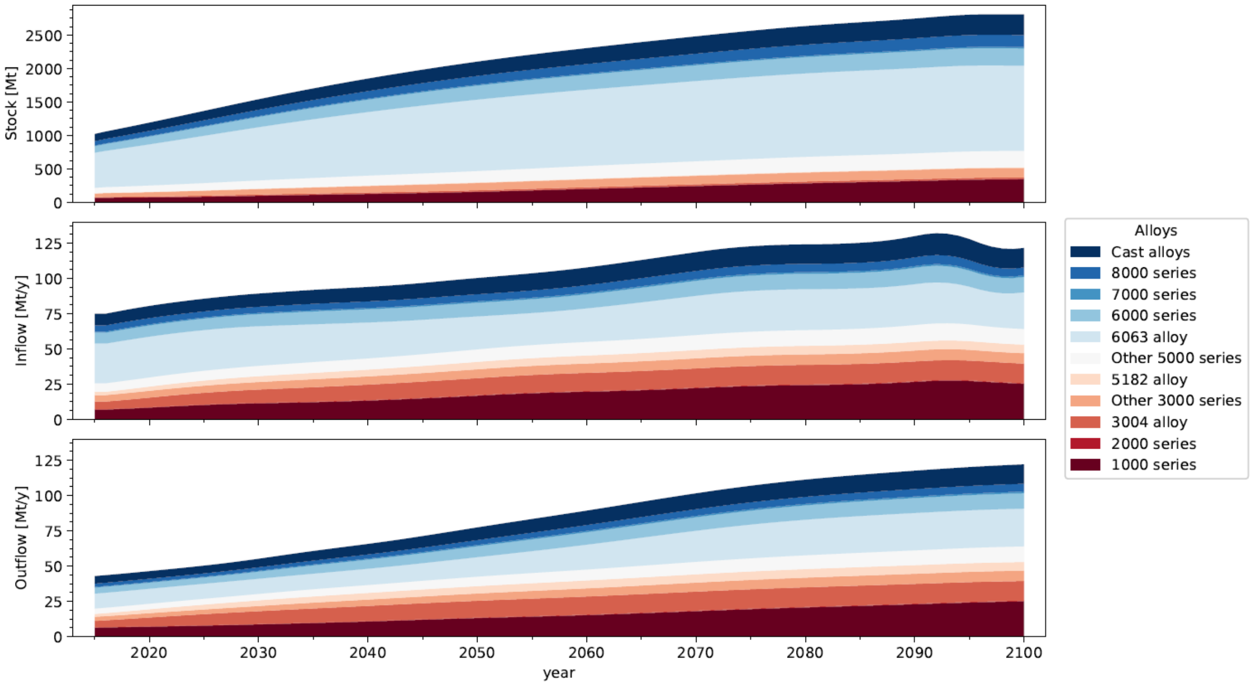

Figure 5: Contribution analysis per alloys of stock, inflow, and outflow projections for SSP2, and global geography. The timeframe of the projection is between 2015 to 2100

Alloy mixes change only slightly according to the SSP narrative. The biggest change observed concerns scenarios with high electrification rates, which lead to an increase in the market shares of the 1000 and 8000 series because of their use in the EE sector.

3.3 SENSITIVITY ANALYSIS

Two types of sensitivity analyses were conducted. The first one aims to capture the impact of the aluminium intensity of products. The second covers the lifespan, knowing that the lifespan of products is an essential parameter for the accounting and analysis of material stocks and flows (Murakami, Oguchi, Tasaki, Daigo, & Hashimoto, 2010). The analysis is made by increasing and decreasing the lifetime of aluminium in different sectors by an arbitrary value of 25%. So far, the results presented have been associated with a medium level of aluminium content and lifespan. **Error! Reference source not found.** represents the sensitivity analysis of the stock, inflows, and outflows of all three intensity levels for all

SSPs at the global scale and for different lifespans. In comparison with the medium level of aluminium content, the high level almost doubles the stocks, while the low level reduces them by 40%. The inflows and outflows converge towards an increase of 40% of flows, while the low level shows a reduction of 30%. Aluminium stocks and flows are less sensitive to changes in lifespan than aluminium content. Longer lifespans cause a decrease of around 15 to 20% of the inflows and outflows. Shorter lifespans are associated with an increase in the inflow and outflow between 15 to 25%.

The range of aluminium contents of products is greater than the one between SSP scenarios and between the different lifespans. This indicates the high sensitivity of the aluminium intensity parameter in our modelling.

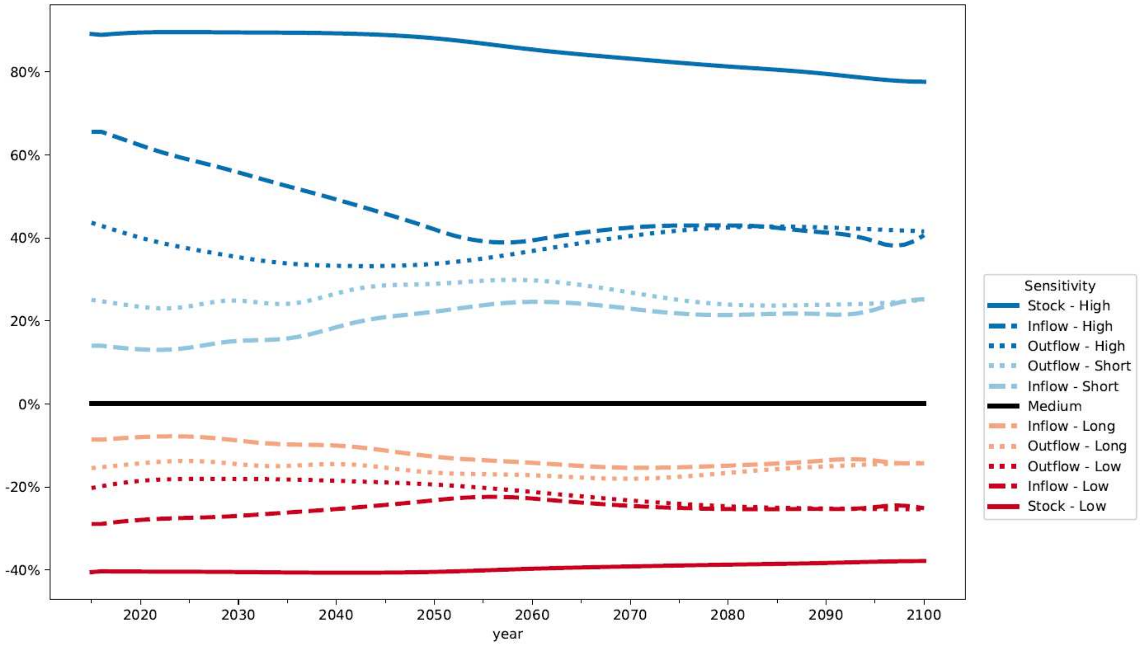

Figure 6: Sensitivity analysis of global stock, inflow, and outflows according to different aluminium levels and lifespans based on SSP2 results. The timeframe of the projection is between 2015 to 2100

Similar figures for different SSPs are available in SI3-data_from_figure_6. The results of the sensitivity analysis are similar for all SSPs.

4 DISCUSSION

4.1 VALIDATION AND LIMITATIONS

PRASTOF results are in line with the existing MFA literature (See SI3-Comparison_literature for graphical comparisons). The average projections for global stock per capita fall in a range between 200 kg and 400 kg per capita, which respectively correspond to the low and medium scenario saturation levels of Müller et al. (2012). These authors, however, assumed a saturation of the stocks at different timeframes (2050, 2075, 2100), while our stock accumulation is more gradual and could potentially cap to higher values. PRASTOF global stock per capita projections are in line with Alu-Cycle projections (IAI, 2020a), which are 122 kg/cap in 2015 (13% less than PRASTOF – SSP2) and 285/cap kg in 2050 (20% more than PRASTOF – SSP2).

In terms of total stock, Rauch (2009) estimated a global aluminium stocks of 504 Mt in 2000 using nighttime lights data, while Alu-Cycle (IAI, 2020a) estimated overall stocks of 915 Mt in 2015. Our model calculates a level of around 1000 Mt for 2015. In Alu-Cycle (IAI, 2020a), the overall stock is projected to 2775 Mt in 2050, while PRASTOF has a lower projection, between 1800 and 2300 Mt at the medium level of aluminium intensity, depending on the SSP. The difference could be partly explained by the disparity in the population projections in the different models.

Comparisons between studies projecting metal demands are difficult, as stated by Watari et al. (2021): «projected metal demands are subject to large uncertainties due to a variety of factors, including methodology choices, assumed socio-economic variables, and the year used to initiate projections». Nevertheless, the inflow projections by PRASTOF in 2015 are similar to those reported in a critical review by Watari et al. (2021). Projections from Alu-Cycle (IAI, 2020a) lie between the medium and high-level intensity scenarios from PRASTOF, and below those reported by Watari et al (2021).

Cullen and Allwood (2013) have evaluated a global final demand of 45 Mt in 2007, which is approximately 60% of the SSP2 values from PRASTOF in 2015. The difference can be explained by the fact that aluminium demand has risen drastically between 2007 and 2015. For instance, the production of primary aluminium has risen from 38.1 to 58.5 Mt between 2007 and 2015 (IAI, 2020c). The outflows projected by PRASTOF are also in line with Alu-Cycle values (IAI, 2020a).

In order to evaluate our modeling approach per sector and its associated assumptions, we compared aluminium stocks/cap per sector in 2015, 2050 and 2100 to the maximum levels estimated by Liu et al. (2012). For most sectors, 2100 levels are similar to their medium levels, and none of our projections exceeds their high level of saturation. The sector with the biggest difference is the transport, where our projections only reach their low-level estimation. However, we are comfortable with this difference because the transport sector has been calculated with a strong physical perspective based on transport demand projections rather than on the estimation of stock per capita. Comparison numbers and figures are available in SI3-Comparison_sector.

Concerning the alloy composition of the future inflows, PRASTOF projects an increase in cast alloys despite the electrification of transport. This is a different conclusion from the projections of Hatayama et al. (2012), who assume a saturation of cast alloy demand around 2040. This is explained by the increase in stock of vehicles per capita counterbalancing the decrease in cast alloy intensity per car.

Although PRASTOF results are globally in line with existing literature, some limitations exist. Despite a bottom-up approach driven by the physical decomposition of services into aluminium stocks, we had to resort to using statistical fits and extrapolations of current behaviour for some sectors with insufficient data. Projections of ME, transport-*other*, CD, and PC were made using GDP as a driver due to a lack of better modeling possibilities in line with the SSP framework. Long-term projections based on GDP, however, do not capture the dematerialisation of the economy or scarcity of some resources. A previous study has shown that GDP is a poor predictor of stock per capita, consumption, and scrap generation per capita (Pauliuk, Arvesen, Stadler, & Hertwich, 2017). However, it is necessary to assume a causal link between drivers and system variables even if such a link is a simplification of the real system (Lauinger et al., 2021). Some sectors have a strong rationale based on physically intuitive decompositions like the number of vehicles per capita for automotive transport, capacity to supply future energy demand, and future demand in terms of dwelling areas. Since one definition sees GDP as the economic value of all goods and services purchased for final use at their point of supply/production, one can still argue that there must be a strong causal link between future GDP and the demand for physical goods and services for most major end-use sectors (McMillan, Moore, Keoleian, & Bulkley, 2010).

To test the plausibility of sectoral demand scenarios without physical rationale, we calculated the ratios between 2050 and 2015 values, and also between 2100 and 2050 values, for a key parameter of each sector. **Error! Reference source not found.** shows the main drivers used for the calculation and the ratios in the percentage of the evolution of key parameters by region for each sector and subsector. Sectors with GDP as driver have a similar range of increases compared to those with more physical drivers. The exception is the PC-*Cans* consumer durables sector with a higher ratio in regions other than OECD due to initial flows in non-OECD regions being very low in 2015.

Sector	Subsector	Driver	Ratio calculated	Ratio: 2050/2015 | 2100/2015 [%]				
				Asia	*LAM*	*MAF*	*OECD*	*REF*
BC	**Residential**	m^2	m^2/cap	183 | 217	129 | 131	228 | 252	130 | 156	185 | 213
	Commercial	GDP	m^2/cap	196 | 209	155 | 171	192 | 334	103 | 99	138 | 137
Trans	**Automotive**	pkm	veh/cap	138 | 170	150 | 235	129 | 209	124 | 145	162 | 232
	Freight	tkm	tkm/cap	230 | 411	177 | 373	173 | 410	142 | 220	200 | 343
	Other	GDP	stock/cap	302 | 512	209 | 411	175 | 412	151|172	233 | 356
EE	**Generation**	kW	kW/cap	229 | 346	212 | 350	221 | 476	133 | 155	127 | 141
	Distribution	kWh	kWh/cap	229 | 346	212 | 350	221 | 476	133 | 155	127 | 141
ME		GDP	stock/cap	193 | 284	156 | 257	135 | 224	141 | 165	172 | 245
CD		GDP	stock/cap	153 | 195	133 | 183	122 | 169	124 | 136	142 | 176
PC	**Can**	GDP	inflow/cap	276 | 287	165 | 175	416 | 849	101 | 101	135 | 136
	Others	GDP	inflow/cap	239 | 344	178 | 284	159 | 312	130 | 140	189 | 248

Table 2: Ratios in the percentage of the evolution of key parameters by subsector and regions. The left number in each cell is the ratio between 2050 and 2015, while the right number is the one between 2100 and 2015. Sector abbreviation of BC is for building and construction, Trans for Transport, EE for electrical engineering, ME for Machinery and equipment, CD for consumer durable and PC for packaging and cans

The breakdown into 5 regions is one of the limitations of the study. The modelling assumes homogeneity within each sector in each region, which doesn't necessarily correspond to the reality. Notably, heterogeneous traffic types are observed across the countries of a same region. For example, we observe a high variability in motorcycle and three-wheeler and other vehicle types depending on the culture and habits of different countries. However, it was not possible to capture such detailed distinctions in PRASTOF because insufficient data on the subject exist, with the literature mainly focusing on car ownership evolution (Dargay, Gately, & Sommer, 2007; Fishman et al., 2021; Kresnanto, 2019; Ma et al., 2019; Ukonze, Nwachukwu, Mba, Okeke, & Jiburum, 2020).

Another limitation concerns the methodological choice to estimate the initial stock in 2015 using a normal distribution based on average lifetime. Our assumption might slightly bias the age distributions in sectors with a fast expansion by defining initial stocks as older than reality. The assumption mainly overestimates the values of outflows in the first years of the study in the sectors that are still far from reaching a steady state. This is particularly true for sectors with a long material lifetime. The evaluation of historical stock based on historical data could improve this part of the model, but such an operation would be data-intensive and would require data fitting to match the regional definition of PRASTOF.

The model assumed an average aluminium content in a product, while a wide variation exists within the products of the same sector. We tested the aluminium content according to three levels in a sensitivity analysis by expanding the average value to two extreme values. In further work, a statistical approach integrating uncertainty distributions of aluminium content would lead to more robust results.

Finally, the alloy decomposition has been based on the best data available in peer-reviewed literature, but some additional assumptions were needed. Specific data about alloy content in different products are needed and would improve the modeling of aluminium stocks and flows. We also assumed constant composition per alloy over time, which prevents PRASTOF from capturing the potential change of technology or design in some sectors. An open-access and collaborative database of aluminium content managed by the scientific community could be another path toward better data; such a database would be similar to the existing community-driven material intensity for buildings research platform (Heeren & Fishman, 2019).

4.2 IMPLICATIONS FOR THE ALUMINIUM INDUSTRY

While industries are claiming ambitious greenhouse gas emissions reduction targets for 2030 and 2050 (Alcoa, 2019; IAI, 2021; Rio Tinto, 2019; RUSAL, 2018), a better understanding of stocks and flows is essential to ensure a responsible and optimal recirculation of materials to reduce emissions related to primary production. However, a transformation towards an authentic circular industry cannot be achieved if the stocks continue to increase (Arnsperger & Bourg, 2016) as projected by all global scenarios of PRASTOF. From a regional perspective, stock saturations and even reductions in use are projected in 2100 in the OECD and ASIA regions, meaning that reaching a closed-loop economy could be achieved in those regions. In the MAF region, aluminium stocks are projected to double or triple in the coming decades, which in turn induces a global increase in stock. From a sectorial perspective, no major changes in market share between sectors and subsectors are observed in the stock evolution. For the inflows, the electrical engineering sector is the one with the biggest growth due to a large increase in electricity consumption. This trend is even bigger with the SSP1 and SSP5 scenarios, where electricity consumption increases even more per capita. The market share of the BC sector inflow tends to decrease over time while its stock reaches a saturation. Market shares of other sectors stay nearly constant. For the outflows, market share trends are similar to the ones for inflows but delayed.

According to our scenario, due to the continuous growth in the demand for aluminium, a closed-loop economy would not be possible before the end of the century. The achievement of climate neutrality in the industry by 2050 could not, therefore, rely on a closed-loop economy but would depend largely on low-carbon primary production. This highlights the great importance of quickly decarbonising the primary production to achieve climate neutrality (Pedneault et al., 2021). Research on the application of circular economy and improvement of material or product efficiency should also be pursued.

Reducing the inter-alloy contamination in recycling is key to minimizing the demand for primary aluminium used to dilute the concentration of alloying elements (Hatayama et al., 2012; Modaresi, Løvik, et al., 2014; Rombach et al., 2012). Our results for all the SSP scenarios do not show a major mismatch between the composition of inflows and outflows, which is partly explained by the fact that stocks only become saturated at the end of the century. This means that in a theoretically perfect scenario with appropriate dismantling and sorting, changes in alloys demand wouldn’t limit the implementation of a closed-loop aluminium industry. However, in practice, insufficient dismantling and sorting could lead to some inter-alloy contamination. Those life cycle stages are outside the boundaries of this present study; further research focussing on dismantling, sorting, and recycling should explore these potential limitations and the action needed to overcome them. Even if no changes in alloy ratios are projected, alloy contamination could still become an issue without appropriate sorting and purification techniques for recycled aluminium (Gaustad, Olivetti, & Kirchain, 2012).

Outflows higher than inflows are observed for a few alloys in certain SSP scenarios, but only after 2090 and never more than 11%. This quantity is likely overestimated since collection rates, which are outside the scope of this study, would reduce the quantity of outflows going for recirculation. A similar conclusion would be observed with a more detailed decomposition per alloys because stocks keep increasing. More specifically, for the automotive sector, cast alloys will still be in demand in electric vehicles, albeit in a lower proportion (18% instead of 28% of the vehicle mass) than in internal combustion vehicles. Because of the increase in vehicle stocks, the cast alloy demand continues increasing despite reductions in the proportion of cast alloy per average vehicle arising from the electrification of transport.

The results of our explorative scenarios are the starting point of new research questions that aim to understand how to supply future demand sustainably and in line with national, international, and industrial climate targets (Watari et al., 2020). A sustainable future would involve a decoupling that can be achieved with the promotion of policies in line with resource efficiency and sustainable consumption and production (Oberle et al., 2019).

4.3 SSPS AS A FRAMEWORK

By building on SSP narratives and results, our dMFA shows a method of integrating stock dynamics and the SSPs in a single framework. This framework allows for the definition of sets of material assumptions that are consistent with these narratives, which constitute scenarios around which a broader scientific community now gravitates. This consistency allows PRASTOF to generate scenarios with better comparability and possibilities for follow-up studies.

While material cycles are not well captured by actual integrated assessment models (IAM) (Pauliuk et al., 2017), the integration of the aluminium cycle within IAMs would add more consistency to the modelling due to the high consumption of electricity by the primary production of aluminium (around 8% of global electricity production (Kermeli, ter Weer, Crijns-Graus, & Worrell, 2015)) and the higher aluminium intensity of renewable electricity infrastructures. Aluminium is also often identified as a key light-weighting material for transport leading to reductions in environmental impacts (Modaresi, Pauliuk, Løvik, & Müller, 2014). Thus, as explained by Pauliuk et al. (2017), recycling, light-weighting, and other material-efficiency strategies should be part of technology-rich IAMs. Aluminium material cycles generated by PRASTOF could be integrated into IAMs, as the two models use the same drivers as input.

4.4 CONCLUSION

In this article, we have modelled aluminium stocks per capita, total stocks, inflows and outflows from 2015 to 2100, in line with the Shared Socioeconomic Pathways (SSP). The dynamic mass flow analysis was performed using an open-source tool named PRASTOF, developed with a sectorial bottom-up approach covering 5 world regions, 11 subsectors, 16 aluminium alloys, and 10 elements.

Results project an increase of global stock from 1020 Mt to an interval between 2280 and 2910 Mt in 2100, depending on the SSP. The final demand increases from 75 Mt/y in 2015 to an interval between 90 and 145 Mt/y in 2100. No saturation in global stock or end-use demand is observed in this business-as-usual scenario (SSP2) due to constant aluminium demand and stock increase in the Middle East and Africa regions, while other regions tend to reach stock saturation due to population decreases and saturation of stock per capita. The ratio between outflows and inflows tends to reduce over time due to a slowing of stock accumulation. Therefore, recycling could become increasingly important to supply the end-use demand. No drastic change in alloy demand is observed, but the market share of alloys used in building and construction will diminish gradually as the stock of this sector saturates. The demand for purer alloys will increase due to the increase in electrical engineering market share caused by the rise of the electricity demand per capita and the penetration of PV solar technology.

Integrating the SSP framework into dMFA allows for a consistent scenario modeling perspective, while the SSP database is used to select appropriate drivers of sectorial models. The bottom-up and sectorial methodology adopted by PRASTOF ensures an appropriate modelling approach that accounts for specificities in different sectors and data availability. The modular development of PRASTOF makes it easy to improve in the future if new projections or new data for a specific sector are generated.

Future research could link the PRASTOF framework and its results to the integrated assessment models guided by the SSPs. Other research in circular economy could start from the results and integrate high-resolution and technology-rich modelling to guide efforts to close the material loops of the aluminium industry. While the collection, sorting, and recycling were outside the scope of this study, a special focus on those life cycle stages is needed to lead a circular transformation of the industry.

CONFLICT OF 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.

ACKNOWLEDGMENTS

We gratefully thank Christine Hung for the meticulous proofreading of an early version of this manuscript. Finally, the authors would like to acknowledge the financial support of the industrial partners of the International Chair in Life Cycle Assessment (a research unit of the CIRAIG): Arcelor-Mittal, Hydro-Québec, LVMH, Michelin, Nestlé, Optel, Solvay, TotalEnergies and Umicore. The authors remain solely responsible for the content of this study.

DATA AVAILABILITY STATEMENT

The input data that supports the findings of this study are available in the supporting information of this article. The code used for calculation is available on GitHub (https://github.com/jpedneault/PRASTOF, commit *Revision_1)*. Complete results are published online in a data repository (https://doi.org/10.5281/zenodo.5497446)

SUMMARY OF SUPPORTING INFORMATION

Supporting Information SI1: This Supporting Information S1 all input data of PRASTOF model that are read by the program. The first tabs in blue are the data obtained from the SSP database (Riahi et al., 2017) needed for PRASTOF's calculation. Tabs in orange contain the pre-calculation to generate parameters for different sectors and their associated reference. Tabs in green contain the different parameters imported and used by the PRASTOF's python code.

Supporting Information SI2: This Supporting Information S2 provides additional explanation about the modelling approach used for of different sectors. The equation used for different sectors are also available with the explanation. A section providing extra information on how the initial stocks is calculated is also available in SI2.

Supporting Information SI3: This Supporting Information S3 provides data from our Figure 3, 4, 5 and 6. Tabs in orange provide additional figures (SI-Figure 1, 2, 3, 4, 5 and 6) and their associated data.

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