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Environmental and Socio-Economic Impacts of the Circular Economy Transition in the EU Aluminium Sector

Identification of Circular Economy levers and assessment of their impact with life cycle-based and macroeconomic models

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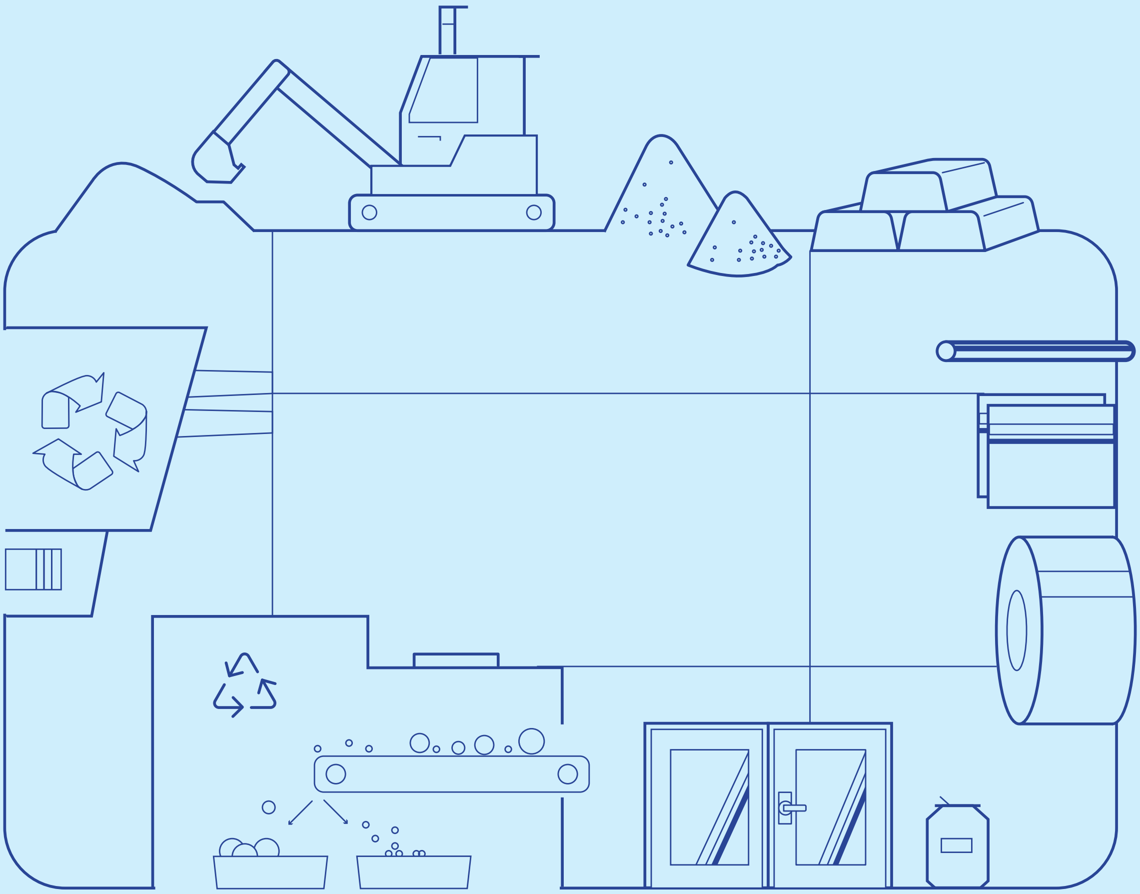

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Contents

Abstract

The implementation of Circular Economy (CE) levers in the EU aluminium sector has the potential to reduce greenhouse gas emissions by 12-14 Mt CO_2-eq. annually by 2050, in addition to what would be achieved by decarbonising the energy system only. CE levers also lead to a decrease in the demand for bauxite as well as reductions in energy demand, leading to a EUR 3.6 billion annual increase in the EU trade balance with import reductions from China, Russia, USA and the UK. However, this may come with potential trade-offs, such as reduced employment and Gross Value Added, which needs to be further investigated to obtain a more accurate assessment of the implications of CE levers on the service and research and development sector. The study's findings are policy-relevant, highlighting the need for a holistic approach and policy mix over the lifecycle of materials and products to materialise the CE potential, while informing EU policymakers on feasible strategies to support the aluminium sector's sustainability transition.

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Executive summary

Policy context

The EU aluminium sector faces significant challenges in relation to its sustainable transition and dependency on third countries. Bauxite and aluminium have been included in the list of Critical Raw Materials (CRMs) given their high supply risk, high economic importance in the European's manufacturing industry, and sourcing from countries with weak governance. The EU adopted in 2024 the CRMs Act that ensures to the EU a secure and sustainable supply of CRMs that are needed in the energy transition. The EU, under the EU Green Deal, has the ambitious goal of becoming the first climate-neutral continent by 2050. Aluminium is a key material in the EU's decarbonisation efforts, while also being identified as one of the energy-intensive sectors that are 'hard-to-abate'. Most recently, the EU released the Clean Industrial Deal and the EU Competitiveness Compass, outlining concrete actions to turn decarbonisation into a driver of growth for energy-intensive European industries, including the aluminium one. An essential element within this Deal is circularity, aiming to reduce waste and extend the life of materials by promoting recycling and reuse, and to maximise the use of EU's limited resources while reducing overdependencies on third countries for raw materials. Therefore, the circular economy plays a key role, and it is fundamental to fulfilling the long-term decarbonisation and sustainability goals related to the EU aluminium sector.

This study builds upon previous studies on the effects of CE, notably Material Economics (2018) and Zibell et al. (2022). The novelty of this study is on one side the focus on the socio-economic and trade effects of CE, and on the other side the combination of different methods and tools applied for achieving the goals of the assessment. To this aim, an interdisciplinary team composed of JRC-affiliated scientists and scientists affiliated to other research institutes contributed to the work.

While the conclusions and main findings of this study are useful for policymakers in the field of CE, the tools, methods, and data applied are valuable for scientists and consultants that aim to quantify the environmental and socio-economic effects of CE.

Key conclusions

The implementation of CE in the EU aluminium sector can lead to significant environmental benefits compared to the sole decarbonisation of energy mixes, including additional reductions in greenhouse gas (GHG) emissions, energy and resources consumption, and waste generation. This also determines a decreased EU dependency from extra-EU imports of fossil fuels and bauxite, leading to a positive increase in the EU trade balance with its global trade partners. The study also highlights possible trade-offs in terms of reduced employment and Gross Values Added, although further research is needed to better understand the consequences of implementing CE in the service sector, which was only limitedly assessed in this study.

A holistic approach, careful policy design, and coordination among stakeholders are required to unlock the potential of CE. In this sense, the study emphasizes the importance of a policy mix approach, combining different policy instruments to address the challenges to unlock CE potentials, including mandatory and voluntary instruments, such as administrative, economic, and informative ones. These instruments are essential to activate the CE levers investigated in this study, i.e. optimise production, extend lifetime of finished products, recover materials, and enhance recycling quality.

Main findings

The study's key scientific findings include:

- The implementation of CE levers can achieve reductions on Climate Change of 12-14 Mt CO_2-eq. annually by 2050, additional to the sole decarbonisation of energy mixes.
- CE can lead to a decrease in the EU demand for bauxite (ca. 3.6 Mt annually) and energy demand. The decrease in energy demand for the EU aluminium sector is quantified at about 10% for coal, 6.5% for natural gas, 5.5% for crude oil, and 22% for other fossil fuel relative to the baseline. Most of these reductions affect imported products (ca. 87%). The reduction of electricity demand is quite substantial at 22% in the aluminium industry.
- The decrease in resource and energy demand for the EU aluminium sector leads to an increase of the EU trade balance of ca. EUR 3.6 billion annually, and it is mainly related to a reduction in imports from China, Russia, USA and UK.
- The study also notes that, under the assumptions and limitations involved, CE implementation leads to decreases in Gross Value Added (and, hence, in Gross Domestic Product) and employment in the main industry sectors affected. This highlights the need for further research about the CE implications on the service sector.

Related and future JRC work

Relevant JRC studies that have provided background information and data in this study are Carrara et al. (2023), Georgitzikis et al. (2021), Passarini et al. (2018), RMIS (2024), and Zore (2024). The novelty of this study lies on the quantitative assessment of environmental and socio-economic impacts as well as the suggestion of specific policy instruments to unlock Circular Economy potentials. Future work should focus on better understanding: i) scrap quality, ii) primary aluminium demand in EU, iii) have a material flow analysis specifically for EU27, and iv) understand and accurately quantify socio-economic implications of CE on the EU service sector.

1 Introduction to the aluminium sector in the EU

1.1 EU policy landscape

The EU policy landscape for aluminium is evolving to tackle both competitiveness and sustainability challenges. Under the EU Green Deal, the EU has the ambitious goal of becoming the first climate-neutral continent by 2050, with an intermediate target of reducing greenhouse gases (GHGs) emissions to 55% compared to 1990 levels by 2030. The aluminium sector is responsible for about 2% of the global GHG emissions, and belongs to the “hard-to-abate” sectors, due to either technology or cost constraints (European Aluminium, 2023). The Clean Industrial Deal[1], released in 2025, sets out a roadmap to accelerate the green transition of energy-intensive (including “hard-to-abate”) industries, thereby including aluminium. Main pillars are affordable energy, boosting demand for clean (possibly made-in-EU) products, financing the clean transition, securing circularity and access to materials, global scale trade measures to protect EU industry from unfairness, and create a skilled workforce. Building on this, the European Commission (EC) has launched various initiatives to strengthen collaboration within the sector, including the Steel and Metals Action Plan, which compiles concrete measures to enhance the sector's competitiveness and sustainability. The upcoming Circular Economy Act will tackle circularity and access to materials.

Bauxite and aluminium have recently been included in the list of Critical Raw Materials (CRMs) given their high supply risk, high economic importance in the European’s manufacturing industry, and sourcing from countries with weak governance (Georgitzikis et al., 2021). The Critical Raw Materials (CRM) Act, adopted in 2024, will ensure EU access to a secure and sustainable supply of CRMs, enabling Europe to meet its 2030 climate and digital objectives, promoting responsible sourcing and reducing supply chain risks. To this aim, the EC's raw materials diplomacy establishes strategic raw material partnerships with non-EU countries[2]. Meanwhile, the EU's Circular Economy Package and the Ecodesign for Sustainable Product Regulation (ESPR) are frameworks for assessing ecodesign and circularity requirements to improve sustainability across the aluminium value chain. Notably, the recently adopted Packaging and Packaging Waste Regulation enforces requirements on packaging use and recycling to foster circularity, affecting a significant share of the aluminium product market. Further, the forthcoming End-of-Life Vehicles Regulation will also likely include recycled content targets for aluminium in vehicles, while also establishing requirements for the design of vehicles to facilitate their dismantling and recycling.

The aluminium industry has been included in the EU Emission Trading System (ETS) since its inception in 2005 with some exceptions. For example, small and medium-sized enterprises (SMEs) and certain aluminium production processes, such as anode baking and electrolysis, were initially exempt from the ETS. However, as part of the EU's Effort Sharing Regulation and the ETS revision for 2021-2030, the aluminium industry will be subject to more stringent GHG reduction targets and will have to surrender allowances for its emissions. To prevent carbon leakage, Carbon Border Adjustment Mechanism (CBAM) will take effect in 2026, particularly in the metal sector. Rising protectionism and threats of global aluminium tariffs increase the risk of diverting overcapacities to the EU. To counter unfair trade practices, the EC applies Trade Defence Instruments, including

[1] https://ec.europa.eu/commission/presscorner/detail/en/ip_25_550

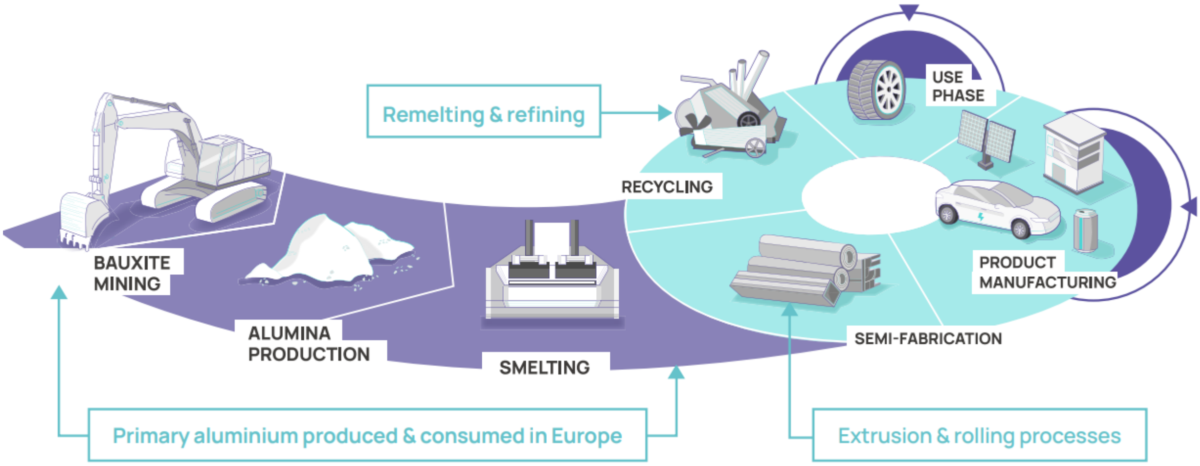
[2] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/raw-materials-diplomacy_en

anti-dumping and anti-subsidy duties, and responds to aluminium tariffs with swift, proportionate countermeasures.

1.2 Aluminium value chain

A simplified graphical representation of the aluminium supply chain is presented in Figure 1. Aluminium is produced from bauxite. The only active mine in EU is in Greece, which supplies only 9% of the total EU[3] demand for bauxite according to 2018 data. The EU highly relies on imports of bauxite (approx. 91% in 2018), with Guinea, Brazil, and Sierra Leone as the main providers of this ore (2018 data based on Georgitzikis et al., 2021).

Figure 1. Representation of the aluminium supply chain



Source: Taken from European Aluminium (2024)

Bauxite is refined via the Bayer process into alumina, of which the EU is a net exporter (Georgitzikis et al., 2021). The alumina is further processed via the smelting process (Hall-Héroult process) to obtain primary molten aluminium. This process is the most influential contributor of GHG emissions along the supply chain of aluminium production with 13.1 tonne CO_2-eq. per tonne of casted aluminium or ~77% of the total carbon footprint (International Aluminium Institute, 2019). Most of these emissions (~80%) are due to the electricity consumption (10.5 tonne CO_2-eq per tonne; International Aluminium Institute, 2019) as it requires about 15 MWh per tonne of primary molten aluminium produced (European Aluminium, 2018). The decarbonisation of existing grids is therefore key to lower the indirect emissions of the process in focus and of the entire value chain (Zore, 2024).

Further, the smelting process employs carbon anodes that can be produced via two technologies, the pre-bake (with a coverage of 95%) and the Söderberg one (with a coverage of 5%) (European Aluminium, 2018). The carbon anodes are consumed in the electrolytic process and emit CO_2 in the reduction reaction that occurs (~2 tonne CO_2-eq per tonne of aluminium; Moya et al., 2015). To overcome this problem, the use of inert anodes is identified as a possible solution to decarbonise

[3] 'EU' refers to the 27 Member States.

the smelting process; however, the low technology readiness level (4-5) and the estimated high capital investments required bring a large degree of uncertainty with respect to the implementation of this solution (Misison Possible Partnership, 2023; Zore, 2024). The EU is reliant (approx. 40% in 2018, according to Georgitzikis et al., 2021) on non-EU imports of unwrought aluminium that have significantly higher GHG emissions; indeed, the global average emissions amount to 17 tonne CO_2-eq per tonne aluminium produced compared to the EU average of 6.7 tonne CO_2-eq per tonne aluminium produced (from cradle to gate; European Aluminium, 2020).

The ingots are processed into semi-finished products and aluminium is usually alloyed with other elements to achieve specific characteristics. Specifically, two main families exist, i.e. wrought aluminium alloys and cast aluminium alloys. Wrought aluminium alloys admit 5% of alloys and impurities at most, while cast aluminium alloys allow up to 20% (Jarrín Jácome et al., 2021). Wrought aluminium alloys are intended for the production of wrought semi-finished products (i.e., rolling, extruding, forging and drawing), while cast aluminium alloys are intended for the production of castings (European Aluminium, 2002).

Semi-finished products are further manufactured into finished products containing aluminium. Aluminium is mostly used in the transport sector (40%), followed by the construction sector (24%), packaging sector (19%), engineering sector (11%), and consumer durables sector (6%) (European Aluminium, 2023). Wrought aluminium alloys are mainly employed in the construction, engineering, consumer durables, and packaging sectors, while cast aluminium alloys have mainly found their application in the transport sector. Yet, with vehicle fleets changing to electric ones, the demand for wrought aluminium alloys in the transport sector is expected to increase (Billy & Muller, 2023; Buchner et al., 2017; European Aluminium, 2020). It is expected that the aluminium use will grow, with an estimated increase of 40% in demand in Europe by 2050 (European Aluminium, 2020). The growth will be driven by replacing materials with aluminium, but also by, for example, lightweight requirements and increased demand for electric vehicles in the transport sector. Other factors affecting future aluminium demand are the employment of efficient aluminium solutions in building renovations, and policy changes such as in the packaging sector due to the adoption of the EU Single Use Plastics Directive, and the changing material requirements in the renewable, machinery, ICT, and aerospace and defence sectors (Carrara et al., 2023; European Aluminium, 2020).

Except for most products for the packaging sector, aluminium has a long lifespan and remains locked in the use phase for periods longer than 1 year adding to the societal stock of materials (e.g., in the construction sector it has a lifetime of 25-50 years, while in transport of 15 years; European Aluminium, 2020). When reaching the end-of-life, post-consumer scrap represents a pool of resources that can be reintroduced in the economy. Two technologies are employed for aluminium recycling depending on the aluminium alloy family that is produced, namely remelting and refining, the latter also providing inputs to the steel industry (where aluminium is used as a deoxidizing agent). Remelting produces aluminium wrought ingots from both post-consumer and pre-consumer scrap, which is generated at different production processes (i.e., fabrication and manufacturing). Refining produces aluminium cast ingots that find their main application in the transport sector for engine blocks in cars with combustion engines (European Aluminium, 2020; Georgitzikis et al., 2021). In Europe, the demand for recycled aluminium casting alloys is lower than the availability of unsorted scrap, i.e. scrap that is either highly alloyed or too mixed to produce wrought aluminium alloys and can only be employed for cast aluminium alloys production (Georgitzikis et al., 2021), with research forecasting a global aluminium scrap surplus of 5.4 Mt per year in 2030 (van den Eynde et al., 2022). Once mixed with cast aluminium alloys, it is no longer possible without further sorting (e.g. employing laser induced breakdown spectroscopy) to produce wrought aluminium alloys from these secondary sources due to high contamination levels. Further, the EU is a net exporter of aluminium scrap (approx. 1 Mt in 2021) to Asia, on top of which exports of vehicles need to be accounted for (estimated to be about one third of all vehicles; Liesbet & van Acker, 2022), leading to a significant flow of aluminium leaving the EU. The scrap that is exported is likely to be recycled due to its high value; nevertheless, this represents a loss for the European economy and contributes to the dependency on third countries for a material in scarcity in the EU (European Aluminium, 2020).

1.3 Aluminium sector challenges

The focus of the current analysis is not on specific technologies to be employed to decarbonise the sector, which are discussed in, among others, European Aluminium (2023), Mission Possible Partnership (2023), and Zore (2024), but rather on the actions that can be implemented to make the value chain more circular. Nevertheless, feeding the sector with secondary aluminium ultimately reduces the emissions of it, as recycled aluminium can reduce emissions by 92% compared to virgin one (based on estimates in Mission Possible Partnership, 2023). Furthermore, retaining aluminium in the European supply chain allows decreasing the dependency of the EU on third countries and increases the security of its supply. However, it is key to increase the quality of the scrap.

Despite being highly recycled, the sector presents several challenges. Particularly, ensuring closed loop recycling, especially for wrought aluminium alloys, requires better collection and more refined sorting technologies, such as advanced Eddy Current Separators, or inductive sensor-based sorters (European Aluminium, 2020). Currently, different alloys are mixed restricting their recycling into cast aluminium alloys only. However, as discussed in Section 1.2, cast aluminium alloys primarily find an application into combustion engines that are expected to see their market share decrease in favour of electric vehicles (European Aluminium, 2020). Therefore, supporting better collection and sorting can lead to high-quality recycling ensuring closed-loops and thus keeping scrap and alloy type separates.

Another important aspect to address to increase recycling is designing products to support easier material identification, disassembly, and recycling. Indeed, some fractions are difficult to sort as they are attached to other materials thus hindering their recycling into closed loops. Furthermore, missorted aluminium (herein intended as aluminium collected with mixed waste) can undergo either incineration or landfill. This can be overcome by introducing, prior to final disposal, facilities to recover aluminium-containing products, ultimately increasing the amount of aluminium being recycled (European Aluminium, 2020).

Finally, where possible, production processes should be further optimised to decrease the amount of pre-consumer scrap produced. Nevertheless, this scrap is easy to sort and has a high economic value; hence, it is already fully recycled (European Aluminium, 2020).

1.4 Report structure

The report is structured into eight additional sections. Section 2 lines out how the concept of the circular economy (CE) can support more efficient management of material flows in the aluminium sector, followed by a description of future scenarios to be analysed. Thereafter, the bottom up perspective of the assessment is divided into Section 3, sketching the material flow analysis, and Section 4, describing the life cycle assessment and costing. The top-down perspective is enabled through an environmentally extended input output analysis laid out in Section 5, and dynamic modelling to capture socio-economic rebound effects in Section 6. A discussion in Section 7 synthesises the results from the different parts and infers their implications for policy makers. Finally, Section 8 concludes the study with a summary and further research avenues.

2 Circularity economy scenarios for the future

The research design of this study is composed of several components. First, the circular economy (CE) strategies are introduced to streamline different types of circularity for the analysis. In a second step, three scenarios are explored, one that simulates the absence of CE strategies, one in which the current CE policy targets for the aluminium sector are attained, and one that aims to maximise their material savings and minimise the negative environmental impact. These three scenarios are then assessed with the methodologies proposed in the following chapter.

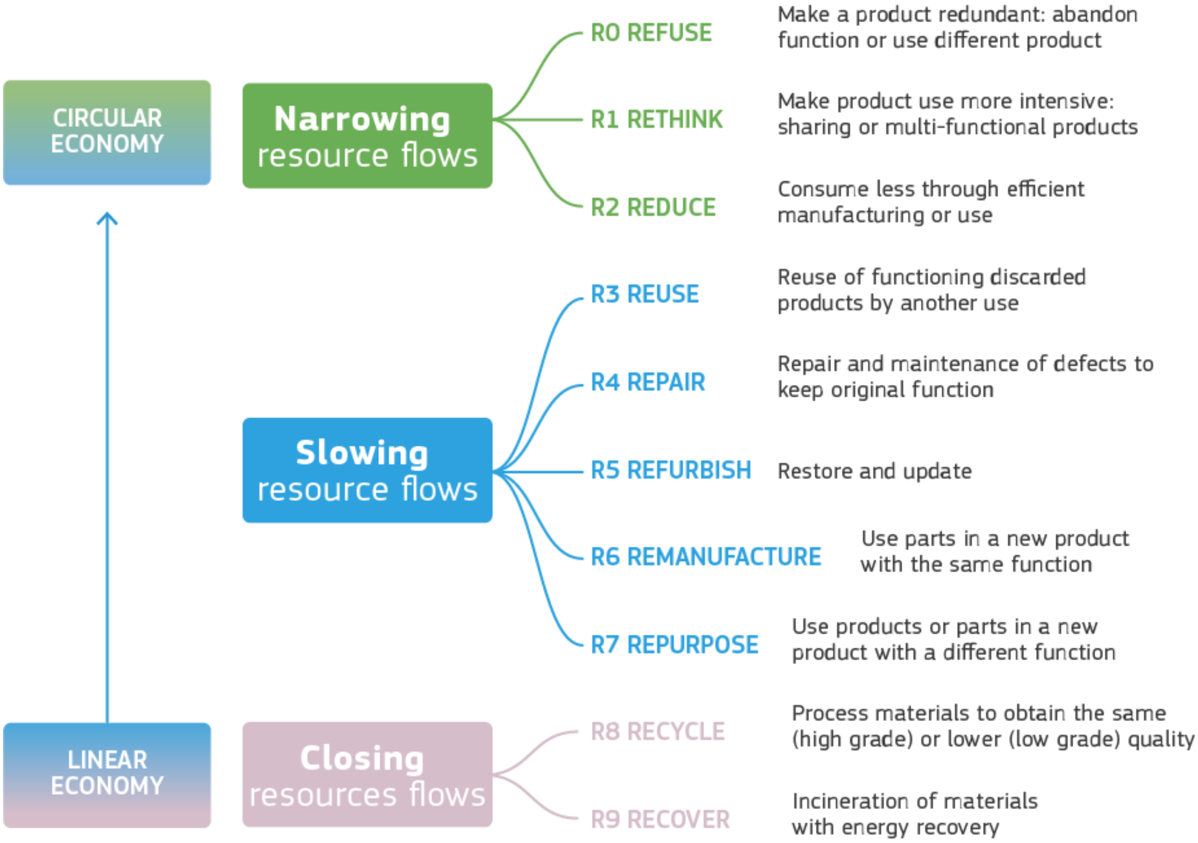
2.1 Circular economy strategies

The concept of CE has proliferated over the last decade, especially after the introduction of the first CE Action Plan for Europe published by the European Commission in 2015. Although there is no single definition for CE, it is generally understood as a systemic approach to the sustainable management of natural resources aiming at ensuring that the value of materials is maximised and maintained for as long as possible as a way to reduce environmental impacts, waste, and improving socio-economic conditions (Kirchherr et al., 2023). Or as presented by ISO 59004 Circular economy standard (2024), CE is an *'economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development.'*

This is to show that the concept of CE is multi-dimensional (Ghisellini et al., 2016) and relates to other concepts, including but not limited to, the so-called R-framework that distinguishes different strategies to achieve the goals of circularity, the concept of resource productivity or resource efficiency, and sustainable materials management. Though there are several types of classification of CE (Calisto Friant et al., 2020), the more techno-centric narrative used in this report has the objective of reducing natural resource extraction and decreasing environmental impacts, while limiting potential undesirable impacts on socio-economic indicators. In line with this argumentation, the implementation of CE strategies not only facilitates the sustainability transition, but should also contribute to increased competitiveness, job creation and re-industrialisation (OECD, 2024).

CE strategies take place at different levels, including different governance levels (regional, national, supra-national), different firm/sector levels and different geographical areas (Ghisellini et al., 2016). The most common approach to identifying and defining CE strategies is the 'R Framework' (Reike et al., 2018). The number of 'R's featured in the R Framework has evolved over time, from the Japanese Government's '3R Initiative' (reduce, reuse, recycle) in 2004, to the European Union's waste hierarchy in its 2008 Waste Framework Directive featuring four Rs (reduce, reuse, recycle, recover), to ten Rs which constitute the 2017 “Circularity Ladder” (Potting et al., 2017), illustrated in Figure 2.

Figure 2. Overview of CE strategies, separated into narrowing, slowing and closing resource flows



Source: Based on Potting et al. (2017)

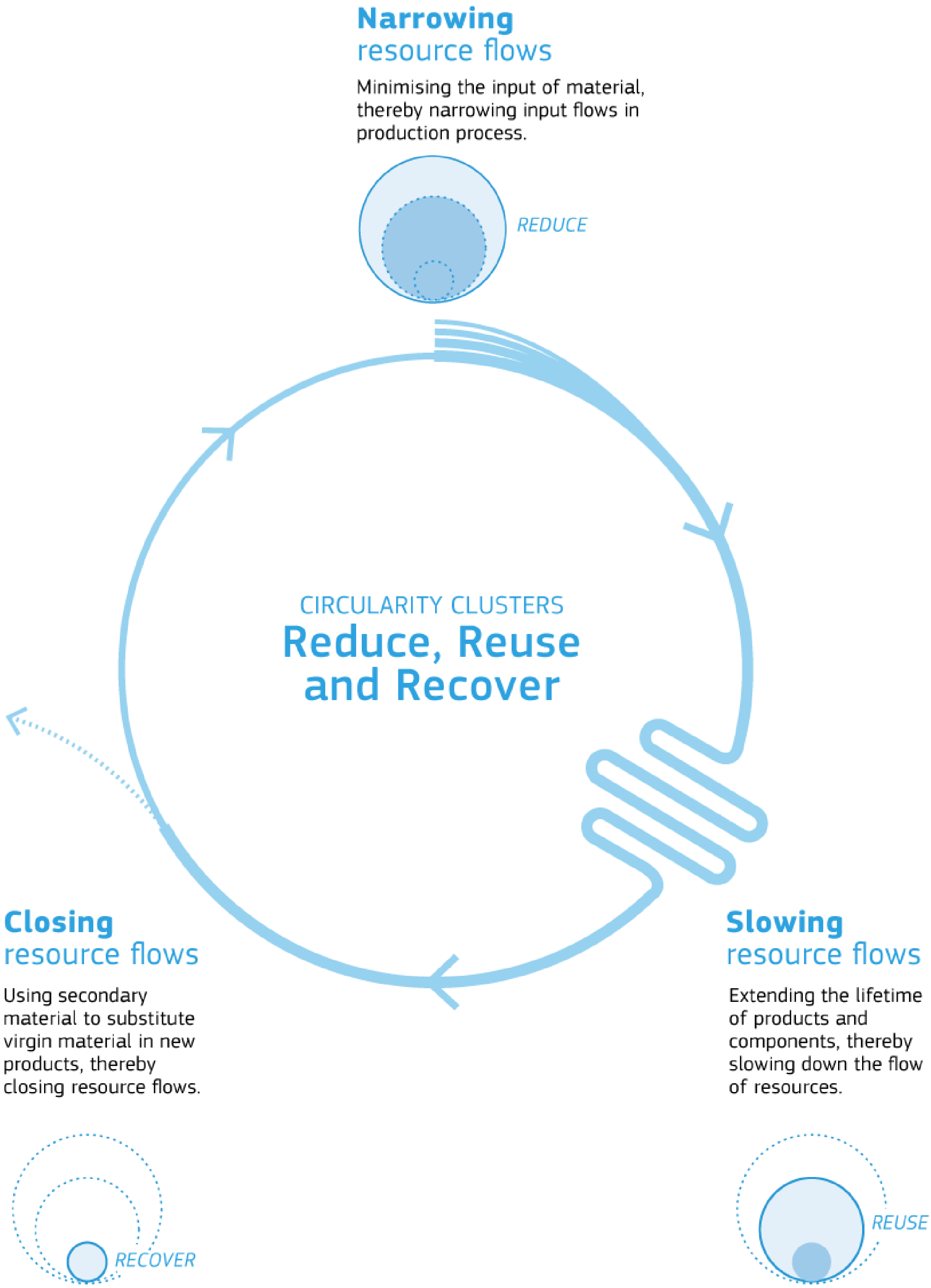
The R-Framework is useful in presenting a whole array of CE strategies aiming at a certain material flow outcome, specified as (i) reduction of material input, (ii) extension of material useful life, and (iii) recirculation of materials at the end of life of products. The specific CE strategies exemplify the different ways to achieve similar material flow outcomes, by diverse operations. For instance, the R-strategies ‘Reuse’, ‘Repair’, and ‘Refurbish’, all constitute distinct ways of extending the lifetime of products; yet, their outcome with regards to material use is the same. Therefore, the R-framework can be simplified into a resource outcome-oriented R-framework that puts forward the broad categories of “Reduce”, “Reuse”, and “Recover” as the primary clusters. Similarly, research on CE strategies concurs on the usefulness and applicability of this approach, especially when taking a business or policy perspective (OECD, 2024). For instance, Bocken et al. (2016) have introduced the ‘narrowing, ‘slowing’, and ‘closing’ resource loops approach, corresponding to the aforementioned ‘Reduce’, ‘Reuse’ and ‘Recover’ clusters of R-strategies. A more detailed description of the three clusters is presented below:

- Reduce: Narrowing resource loops and flows increases resource efficiency, either by decreasing the total amount of resources used per unit of output or by making more economic use of existing production capacity, and using natural resources, materials, and products more efficiently. This could be achieved either through the development and diffusion of new production technologies, the increased utilisation of existing assets, or shifts in consumption behaviour away from material intensive goods and services.

- Reuse: Slowing resource loops reduces the need for additional consumption and demand for primary raw materials by extending the lifetime of existing goods. This can be achieved by e.g. building long-lasting products that are easy to repair and the ownership of which can change during their lifecycle.
- Recover: Closing resource loops prevents waste from being generated by reprocessing materials that have reached their end of use stage and re-introducing them into new products as secondary raw materials, thus substituting demand for primary raw materials in production.

Furthermore, each of the R-strategies can be applied in isolation or in connection with another, according to anticipated outcomes. There is a certain dependency of the CE clusters in relation to their application, with the 'Reduce' cluster affecting also the outcomes of the remaining CE clusters, as illustrated in Figure 3. Since, on the one hand, in a 'narrow' resource loop – at the beginning of a product's lifecycle – the volume of material is defined, only that amount can become available for the application of the remaining CE clusters (i.e. slowing or closing loops). On the other hand, closing resource loops and reclaiming secondary raw materials can also have an effect on reducing the demand of primary raw materials.

Figure 3. Conceptualisation of circularity clusters into Reduce, Reuse and Recover



Source: Adapted from Konietzko et al. (2020); OECD (2024)

In conclusion, taking stock of the available knowledge on the definition of CE and respective R-strategies commonly applied, in this study we consider the following CE clusters:

- *Reduce resource input* (corresponding to R0-R2 and the 'narrowing' resource loop strategies), referred to as 'Reduce' in this study.
- *Slow resource throughput* (corresponding to R3-R7 and the 'slowing' resource loop strategies), referred to as 'Reuse' in this study.
- *Enhance resource recirculation of resources* (corresponding to R8 and the 'closing' resource loop strategies), referred to as 'Recover' in this study.

From the CE cluster framework applied in this study, the energy recovery from resources is explicitly excluded, since the focus is on material resource circularity. Once materials go through an energy recovery process, they cannot be reused in any physical operation, neither as secondary material inputs nor as spare parts/components and, therefore, are exiting the material economy.

2.2 Scenarios definition

To quantify the environmental and socio-economic impacts related to different CE strategies, a status quo reflecting today's situation, and three different future scenarios are defined as follows:

- *Status Quo scenario (STQ21)*, reflecting current conditions as of 2021.
- *Baseline scenario (BSL50)*, intended as the continuation of a historic trajectory for the material flows, but assuming energy transition occurs in line with relevant projections (GECO; Keramidas et al., 2023).
- *Compliance with selected Targets on Circular Economy scenario (CTC50)*, where selected CE policies (CEAP1-2) are implemented on the BSL50, and their quantitative targets are achieved (see list of selected policies in Table 1).
- *Ambitious Circular Economy scenario (ACE50)*, reflecting the implementation of ambitious CE levers on the BSL50, to maximise circularity.

2.2.1 Status Quo 2021 scenario (STQ21)

This scenario reflects the sector in its current conditions, which is here represented by year 2021 because of the data available on relevant flows of the supply chain. The status quo is used as a reference of comparison with the future 2050 scenarios (BSL50, CTC50, and ACE50) to visualize the changes in production flows and associated impacts, also due to the anticipated changes energy transition towards a cleaner grid.

2.2.2 Baseline scenario (BSL50)

This scenario reflects the evolution of the sector during the time horizon investigated (2021-2050) based on historical trends. It implies that the EU CE policies contained in the Circular Economy Action Plans (CEAP 1&2) after 2015 are not included and therefore the trends between 2005 and 2021 are extrapolated (i.e. we assume CEAP 1&2 policies have not determined an impact on the available waste/materials statistics up to 2021). However, this scenario accounts for all the remaining framework conditions prior to CEAP1-2 such as the previous EU Waste Framework Directive (as of 2008 or earlier) and associated targets, as well as decarbonisation efforts occurring in the energy production sector. In line with the EC Better Regulation toolbox, this scenario thus represents a benchmark against which the benefits generated by the EU policies on CE can be estimated. The background conditions considered include a future energy mix assumed to evolve towards a cleaner energy than the current one, in line with the energy mix projected by the Global Energy and Climate Outlook 2023 by JRC and DG CLIMA.

2.2.3 Compliance with selected Targets on Circular Economy scenario (CTC50)

This scenario reflects the evolution of the sector during the time horizon investigated (2021-2050) assuming that the policy targets listed in Table 1 are achieved. These targets reflect only selected quantitative material/waste policy targets contained in the CEAP 1-2. The difference between the BSL50 and CTC50 can be interpreted as the reduced environmental impact resulting from achieving the CEAP1-2 targets, as listed in Table 1. Notice that the list provided in Table 1 is not exhaustive and upcoming policies, such as the Ecodesign for Sustainable Product Regulation (ESPR) or the forthcoming End-of-Life Vehicles Regulation, could not be included during this study.

Table 1. CE policy targets considered in the scenario 'CTC50'

Policy	Target	Year	Value	Sector affected
Waste Framework Directive	Preparing for re-use and recycling of municipal waste	2035	65% by weight	All sectors generating municipal waste
End-of-Life vehicles	Reuse and recycling	2015	85% by average weight per vehicle	Transport
Packaging and Packaging Waste Directive[4]	Recycling	2030	60% by weight	Packaging
Batteries Regulation	Collection rate for waste portable batteries	2030	73%	Electrical
	Collection rate for waste light mean of transport batteries	2031	61%	Electrical
Waste electric and electrical equipment Directive*	Recovery, category 1 or 4	2018	85%	All sectors generating WEEE
	Prepared for re-use and recycling, category 1 or 4	2018	80%	All sectors generating WEEE
	Recovery, category 2	2018	80%	All sectors generating WEEE
	Prepared for re-use and recycling, category 2	2018	70%	All sectors generating WEEE

[4] A review of existing policies was performed in 2023. At that time, the Packaging and Packaging Waste Regulation was not adopted; hence, the Packaging and Packaging Waste Directive was considered instead.

	Recovery, category 5 or 6	2018	75%	All sectors generating WEEE
	Prepared for re-use and recycling, category 5 or 6	2018	55%	All sectors generating WEEE
	Recycled, category 3	2018	80%	All sectors generating WEEE

*Notice that for WEEE it was not possible to distinguish between the different categories. Therefore, in the assessment, the highest target has been assumed for the entire stream of aluminium (i.e. 85%).
Source: JRC elaboration

2.2.4 Ambitious Circular Economy scenario (ACE50)

This scenario reflects a normative scenario, in which an ambitious level of circularity is achieved in the aluminium sector based on the selection of a portfolio of R-strategies. Amid the different ways of increasing material circularity, the results support the identification of the most sustainable trajectory. This circularity scenario addresses both the issue of strategic autonomy (by ensuring the circulation of materials inside the EU), as well as the contribution of CE towards net-zero GHG emissions by 2050. It needs to be underlined that the scenario is not modelled in a way to achieve net-zero emissions by 2050 but simply includes R-strategies that are likely reducing GHG emissions in parallel to certainly decreasing mass flows. Moreover, the R-strategies are not employed at their technical maximum, but rather at an estimate defined by assumed future market conditions. The CE clusters outlined in Section 2.1 are functional to capture a wide spectrum of possible CE R-strategies, which can bring about favourable sustainability impacts. Their implementation from a business and policy perspective requires introducing the notion of "circularity lever" (Bressanelli et al., 2021). This concept refers to specific interventions, and it has already been adopted by, for example, a recent study aiming to assess the economic and environmental impact of different circularity levers in a specific economic sector in the EU (SYSTEMIQ, 2022). In this study, we define the notion of a circularity lever as follows:

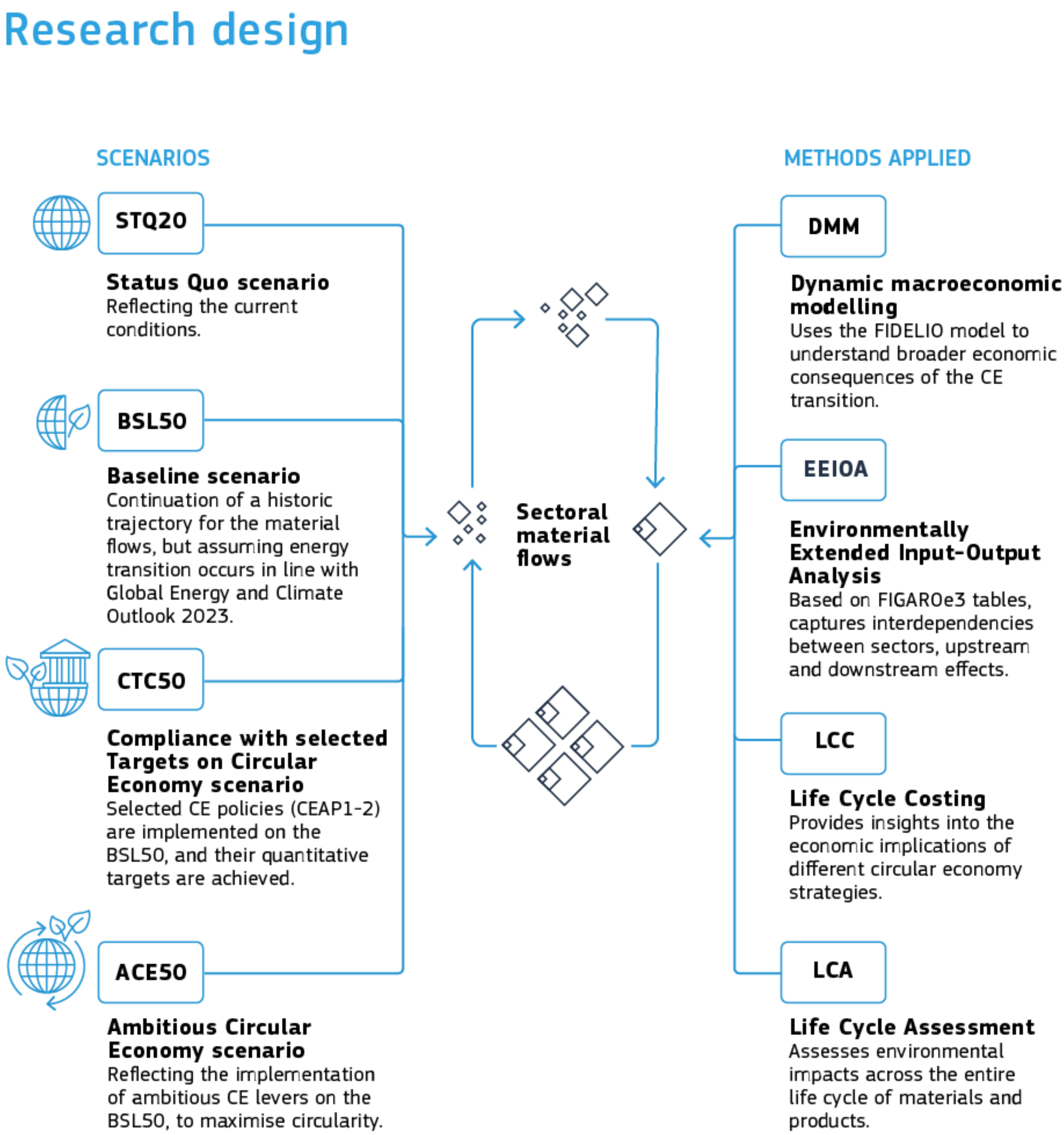
A circularity lever is a specific intervention based on one or more circular economy R-strategies, applied in the context of a specific material and sector, to increase resource efficiency, material durability and recirculation.

In line therewith, a selection of suitable circularity levers in the EU aluminium sector is identified from literature and discussed with the industry, and the corresponding economic and environmental impacts on the material system assessed. The levers are clustered according to the respective CE clusters previously defined (i.e. Reduce, Reuse and Recover). The CE levers assessed only include measures related to material flows and do not consider measures aiming at reducing emissions *per se*. For example, changes in the smelting technology targeting the reduction of direct emissions (e.g. via the use of inert anodes, or new smelters) are not included among the CE levers assessed as this would answer a different research question, i.e. how to decarbonise the sector. Further, the abovementioned improvements are not considered in the baseline as these technologies currently have low TRLs, as mentioned in Section 1.2.

2.3 Toolkit used for the assessment

To quantitatively assess the impacts of the CE scenarios, we apply a toolkit composed of Material Flow Analysis (MFA), (bottom-up) Life Cycle Assessment and Costing (LCA and LCC), Environmentally Extended Input-Output Analysis (EEIOA), and dynamic macroeconomic modelling to assess environmental and socioeconomic impacts of the scenarios investigated. A graphical representation of the research design is displayed in Figure 4.

Figure 4. Graphical representation of the research design applied in the study



Source: JRC elaboration

While the individual methodologies are described in detail in Section 3.1 (MFA), Section 4.1-4.2 (LCA and LCC, respectively), Section 5.1 (EEIOA) and Section 6.1 (dynamic economic modelling), we herein summarise the main strengths and weaknesses of each tool, and thus their complementarities in view of our broader research questions (see also Table 2).

- Material flow analysis provides a detailed understanding of material flows. It includes the status quo and its projection up to 2050.

- LCA allows for the assessment of environmental impacts across the entire life cycle of materials and products. LCA is a linear accounting method and, as such, it does not account for macroeconomic effects, such as spillover effects across countries and economic sectors, effects due to changes in prices, investments, and trades. Sensitivity analyses are done on the side to test the most critical assumptions related to methodology and other aspects.

- LCC provides insights into the changes in costs incurred by different circular economy strategies, given existing (gross) market prices. LCC is a linear accounting method and, as such, it does not account for macroeconomic effects such as spillover effects, changes in prices, investments, and trades.

- EEIOA, based on FIGARO tables (Cazcarro et al., 2025), captures the interdependencies between sectors, allowing for analysis of upstream and downstream effects, including spillover effects across sectors. FIGARO tables provide a detailed representation of economic transactions between industries, which allows for the assessment of the flow of materials and emissions throughout the EU and Global economy. Relative to LCA and LCC, the added value of this analysis is a better understanding of the spillover effects and selected macroeconomic indicators, such as Gross Value Added (GVA) changes, Gross Domestic Product (GDP), employment, and resource dependency. However, EEIOA does not consider investments, price change effects, and change in trade patterns. Therefore, GDP and employment are better captured via dynamic macroeconomic modelling.

- Dynamic macroeconomic modelling provides a framework for understanding the broader economic consequences of the CE transition. The analysis is performed employing the FIDELIO model (Rocchi et al., 2025), a dynamic, multi-regional Input-Output model with new-Keynesian features, suitable for analysing medium-term transitions. It is designed to capture spillover and rebound effects, and quantify impacts on jobs, growth, energy savings, resource use, and trade balance. Additionally to the EEIOA, it accounts for investments, price change effects, and change in trade patterns offering a better angle on the full macroeconomic effects.

Table 2. Illustration of the scope, strength and limitations of the methods applied, and their complementarities. DMM: dynamic macroeconomic modelling. EEIOA: Environmentally Extended Input-Output Analysis; LCA: Life Cycle Assessment; LCC: Life Cycle Costing

Assessment Method	Scope	Granularity	Strengths	Limitations
Material Flow Analysis (MFA)	European aluminium supply chain, inclusive of imports and exports to satisfy production and demand needs.	The system boundary represents detailed flows of aluminium from production to waste management. Imports and exports are included.	Detailed flows for the aluminium material system under assessment.	It is not always calculated as a dynamic material flow analysis
Life Cycle Assessment and Costing (LCA & LCC)	Limited to industry production and consumption in Europe, incl. waste	The system boundary represents detailed flows of aluminium from production to	Detailed flows and supply chain representation for the aluminium material system under assessment.	Relative to EEIOA and DMM: Truncation error (it does not consider spillovers, investments, price

	management. Trade flows are simplified via net trade. The rest of the economy is truncated.	waste management within EU. EU exported waste and its management is also considered.		change effects, and change in trade patterns).
Environmentally Extended Input-Output Analysis (EEIOA)	Global economy with disaggregated EU aluminium industry. The economy is not truncated.	The EU and Global economy are represented by 165 sectors (FIGARO IO tables); the EU aluminium sector is further disaggregated (sector C24E and C24F).	Interdependencies between EU and global economic sectors, spillover effects.	Relative to LCA: Aggregation error Relative to DMM: It does not consider investments, price change effects, and change in trade patterns.
Dynamic macroeconomic modelling	Global economy with aggregated industries. The economy is not truncated.	The EU and Global economy are represented by 64 sectors.	Investments, price change effects, and change in trade patterns.	Relative to LCA and EEIOA: Aggregation error.

Source: JRC elaboration

3 Material Flow Analysis

To assess the performance of the European economy in its transition to a more circular one, and to provide guidance on the creation of effective CE policy instruments, a range of different methodologies are combined. The aim is to identify the most promising CE lever(s) that, ultimately, can be transposed into policy options. The first methodology employed is material flow analysis (MFA), which then feeds into the bottom-up life cycle assessment (LCA) and life cycle costing (LCC) in a subsequent step. Before assessing the impact of material flows in the different scenarios, it is essential to understand how they are affected by the CE clusters – Reduce, Reuse and Recover – in the ACE50 scenario. Therefore, the CE clusters are further subdivided into CE levers based on the R-strategies, the effects of which are described in the following subchapters. Thereafter, the resulting MFAs provide the basis for the LCA and LCC, as well as the subsequent top-down assessment approaches such as Environmentally Extended Input-Output Analysis and dynamic macroeconomic modelling.

3.1 Methodology

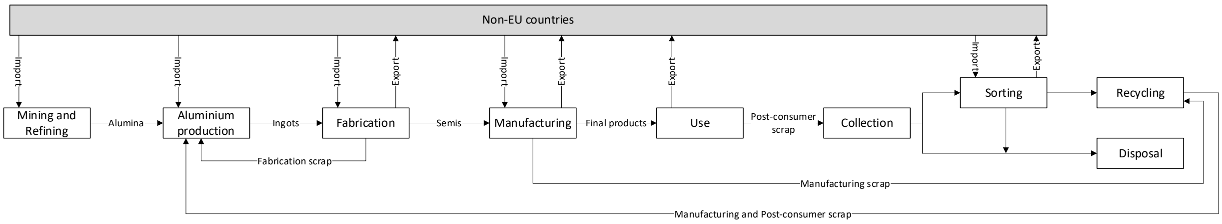
MFA allows for quantifying flows and stocks of a specific material (or substance) in a system and is needed as basis for the other methodologies employed in the assessment. Specifically, the MFA of aluminium is grounded on the data published by International Aluminium Institute (2021) based on the methodology described in Bertram et al. (2017). The geographical scope of the MFA is 'Europe' that encompasses EU27, Albania, Belarus, Bosnia-Herzegovina, Iceland, Macedonia, Moldavia, Montenegro, Norway, Serbia, Switzerland, Turkey, Ukraine, and United Kingdom. Despite the enlarged geographical scope, the MFA of International Aluminium Institute (2021) is used due to the detailed information it provides at semi-finished and finished product level, but also for the updated and complete data it provides, and for the embedded forecasts it has up to 2050 encompassing the lifetime of products and stock formation. It is acknowledged that other studies targeting specifically the EU and databases that can be tailored with EU figures exist. The study by Passarini et al. (2018) outlines and quantifies the MFA for the aluminium sector in EU28. Yet, the data presented refers to 2013 and, for the purpose of the study, more recent data were needed to detail the Status Quo. Further, COMEXT (Eurostat, 2025a), PRODCOM (Eurostat, 2025b), and COMTRADE (United Nations, 2025) are databases that can be used to single out EU27 to have more representative data. However, it was decided to employ the data of International Aluminium Institute (2021) for the high level of detail it provides and that was needed for the analyses. Nevertheless, future efforts should be placed in scaling the MFA to EU27 only.

The boundaries of the MFA go from bauxite extraction to final disposal and recycling of aluminium scrap (i.e. following a cradle to grave approach), including imports and exports at different stages of the European supply chain (Figure 5). After the use phase, post-consumer scrap aluminium is either collected or transported to sorting facilities prior to recycling. Aluminium that has been wrongly segregated and losses are treated via final disposal, herein assumed to be a split between incineration and landfilling (based on the env_wasmun statistics of Eurostat, 2024).

In the MFA, the only distinction made on alloys is between the two principal classifications, namely wrought and cast alloys, as a detailed assessment of all aluminium alloys would be too complex and requires an analysis at product level that is beyond the scope of this study. At the fabrication stage, production of rolling, extrusion, foil, casting and other (assumed as an average of the four) are considered as semis. Further, the following sectors have been included following other studies (e.g. Langhorst et al., 2024; Liu et al., 2013): building, transport (automobiles and light trucks, aerospace, and other), packaging (cans, foil), machinery and equipment, electrical (cable, and other), consumer durables, and other.

The MFAs of STQ21 and BSL50 are entirely based on the data and projections provided by International Aluminium Institute (2021) for 2021 and 2050. Data related on trade is presented as 'net trade' from 2022 onwards. Therefore, it was assumed that the ratio of imports and exports at the different stages of the supply chain was the same as for 2021, i.e. the trade pattern for 2050 reflects the one of 2021.

Figure 5. Visualisation of the general aluminium supply chain stages included in the material flow analysis



Source: JRC elaboration based on Bertram et al. (2017)

3.1.1 Compliance with selected Targets on Circular Economy scenario (CTC50)

For the CTC50 scenario, the underlying MFA data is grounded on the 2050 projections provided by International Aluminium Institute (2021). To reflect the achievement of the targets on recycling rates based on the policies listed in Table 1, the corresponding collection rates were recalculated and adjusted, relative to the baseline, while the sorting efficiencies were kept constant.

3.1.2 Ambitious Circular Economy scenario (ACE50)

The material flow analysis in the ACE50 scenario is affected by the implementation of the CE levers. More specifically, the MFA of the BSL50 scenario is adapted to the changes related to the circularity levers considered, which are summarised in Table 3. It reports the relative reduction of material flows to the BSL50 value and the first order effect on the affected flows. For an in-depth description of each lever, their combination, and the modelling parameters for the environmental and economic assessments, consult Annex 1. As to get a better understanding of the first order effects, the changes are highlighted in Figure 6, depicting the material system for the ACE50 scenario. The levers have an effect throughout the entire supply chain, but general trends can be observed. Levers related to the reduction of resource inputs (i.e., Reduce) are implemented upstream, while levers focused on slowing material cycles (i.e., Reuse) are located towards the middle where finished products are manufactured. Finally, levers connected to enhancing the recirculation of resources (i.e., Recover) are implemented downstream in the supply chain, corresponding to end-of-life stages.

Table 3. Overview and categorization of circularity levers in the EU aluminium applied in the *Ambitious Circular Economy* scenario

CE strategy	CE lever		Description	Quantification	First order effect	Sectors	Source
Reduce	1	Pre-consumer scrap reduction	The aim of this lever is the reduction of fabrication and manufacturing scrap by improving the yields of the two processes. A practical example is the aluminium scrap resulting from the cutting of aluminium sheets. Ultimately, the lever entails producing the same amount of final products with less input material.	5% reduction in scrap generation at fabrication and manufacturing	Reduced scap at fabrication and manufacturing	All sectors	Adapted from Milford et al. (2011)
Reuse	2	Design for reusability	The aim of the lever is to extend the lifetime of finished products or components thereof via remanufacturing, reforming, relocating or cascading. Cumulatively, extending the lifetime of finished products results in reducing overall demand for products and materials. Ultimately, the finished products – despite extended lifespans – would become waste; however, their extended use has displaced the need for additional finished products entering the market for a defined period.	Extension of lifetime by : 10% in Transport, passenger car; 36% in Transport, aerospace; 10% in Transport, other transport; 5% in Construction; 5% in Electrical, cable; 10% in Electrical, other; 10% in Mechanical equipment; 50% in Consumer durables; 10% in Other.	Reduced production of finished products and related disposal	All sectors, except for Packaging	Adapted from Cooper & Allwood (2012)
	3	Remanufacturing of automotive components	The aim of the lever is to extend the lifetime of passenger cars components to reduce the demand for aluminium in the targeted application. Passenger cars components are remanufactured, which is intended as the	Extension of lifetime by 10%	Reduced production of finished products and related disposal	Transport, passenger car	Yang et al. (2015)

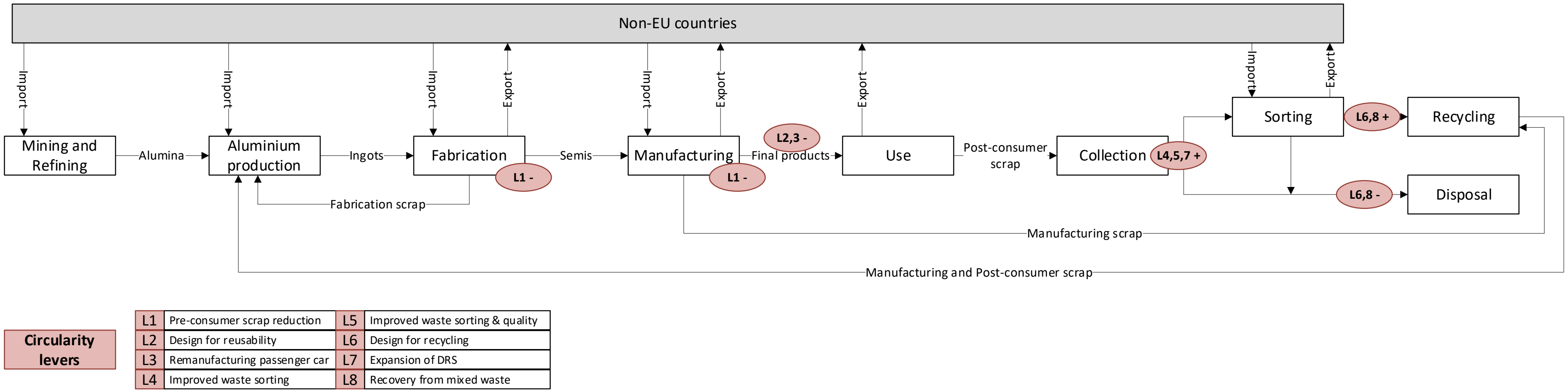
			restoring of end-of-life products to 'like-new' conditions through several operations, namely disassembly, inspection, cleaning, reconditioning or replacement, and reassembly.				
Recover	4	Improved waste sorting	The lever aims at improving collection and sorting to increase closed-loop recycling. Indeed, having "cleaner" aluminium collected and sorted according to its application, can increase the share of wrought alloys remelted as opposed to their refining.	5.2% increase in sorted aluminium waste	Increase in collection rates and increase in remelting as opposed to refining	All sectors	Adapted from Cui & Roven (2010); Løvik et al. (2014); Pedneault et al. (2023)
	5	Improved waste sorting and scrap quality	The lever aims at improving collection and sorting to increase closed-loop recycling. Indeed, having "cleaner" aluminium collected and sorted according to its application, can increase the share of wrought alloys remelted as opposed to their refining. Further, it aims at closing the loop for wrought aluminium alloys recycling.	5.2% increase in sorted aluminium waste and 100% diversion of wrought aluminium scrap to remelting	Increase in amount of recycled aluminium and increase in secondary material quality	All sectors	Adapted from Cui & Roven (2010); Løvik et al. (2014); Pedneault et al. (2023), and educated guess
	6	Design for packaging recoverability and recycling	The lever focuses on the changes in design of packaging to facilitate material recovery at the end-of-life to promote higher recycling volumes of packaging over incineration or landfilling.	10% reduction in incinerated and landfilled packaging aluminium waste	Decrease in incineration and landfilling in favour of recycling	Packaging, cans and foil	Warrings & Fellner (2018)
	7	Expansion of deposit return system	The lever aims at expanding the deposit return system (DRS) to all packaging cans within the EU. By collecting the packaging cans separately, a close-loop recycling can be ensured, therefore increasing the amount of cans undergoing remelting as opposed to refining.	100% coverage of DRS on packaging cans	Increase in collection rates and increase in remelting as opposed to refining	Packaging, cans	
	8	Recovery from mixed waste	Advanced material recovery facilities can allow recovering aluminium waste that is wrongly segregated from household as mixed waste. The lever aims at expanding the coverage of such technologies to pre-treat all packaging related waste through an advanced sorting	100% coverage of advanced sorting facilities and increased efficiency to 93% separation	Increase in recovery of aluminium from mixed waste in favour of recycling	Packaging, cans and foil	Labberton (2020); Warrings & Fellner (2021)

			facility prior to undergoing incineration or landfilling.				

Source: JRC elaboration

A graphical representation of where in the supply chain the CE levers are implemented is provided in Figure 6.

Figure 6. Material system in the Ambitious Circular Economy (ACE50) scenario in the aluminium sector with first order effects of changes induced by the levers



Note: Levers are labelled by numbers, with either positive (+) or negative (-) effects on material flows

Source: JRC elaboration based on Bertram et al. (2017)

3.2 Results

The material flow analysis of 2021 and 2050 is entirely based on the data provided by International Aluminium Institute (2021). The full data cannot be disclosed as per an agreement of confidentiality; therefore, aggregated data and trends are mainly discussed in this section. Notice that values reported refer to million metric tonnes (Mt) of aluminium.

The material flow analysis of the Status Quo scenario (STQ21) is displayed in Figure 7, while the one of the Baseline scenario (BSL50) is depicted in Figure 8. From the MFA of STQ21 and BSL50 it is evident that Europe is largely reliant on imports of ingots from third countries to satisfy its demand. The total input to the casting phase consists of approx. 30% imported semis in STQ21, which is expected to decrease to approx. 20% in BSL50 due to an increase in the recirculation of manufacturing and post-consumer scrap (approx. 40% of the input in BSL50 and approx. 33% in STQ21). The amount of semis demanded in Europe amounts to approx. 13 Mt in STQ21 and it is expected to grow by approx. 40% in BSL50, which is in line with estimations based on the information reported in European Aluminium (2020). At sector level, similar growth rates as in European Aluminium (2020) are expected in 2050 for the amount of semis used in the transport, packaging, and other sectors (55%, 25%, and 27%, respectively, according to European Aluminium (2020), and 53%, 25% and 32%, respectively, according to JRC elaborations of the projections of International Aluminium Institute (2021)). According to the data used in the current assessment, lower growth rates are expected for the building, and machinery and equipment sector (28% and 29%, respectively, according to European Aluminium (2020) against JRC elaborations of 13% and 18%, respectively), while higher growth rates are estimated for the electrical and consumer durables sectors (34% and 25%, respectively, according to European Aluminium (2020) against JRC elaborations of 44% and 122%, respectively).

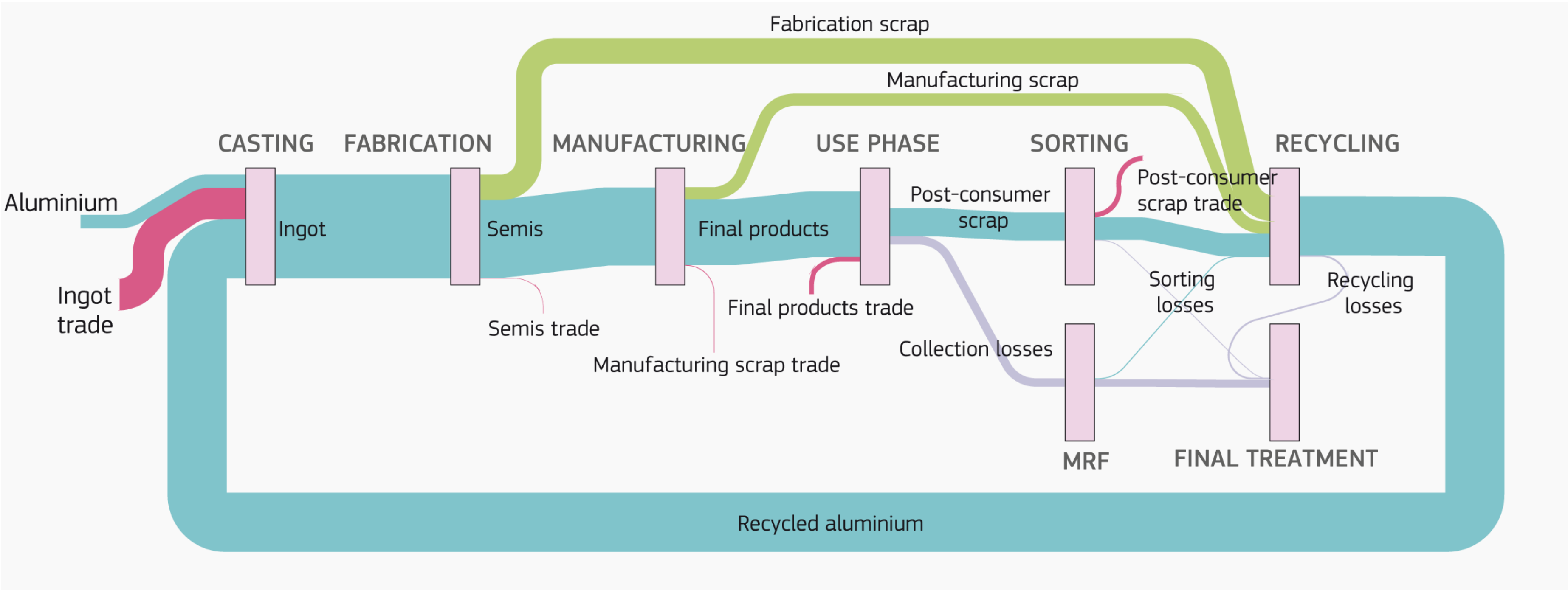
When focusing on the finished products demanded in Europe, they amount to approx. 12.5 Mt in STQ21, and they are expected to grow by approx. 31% in the BSL50. Its repartition into the different sectors considered in the assessment (namely, building, transport, packaging, machinery and equipment, electrical, consumer durables, and other) follows the same hierarchy presented in European Aluminium (2021), in which the authors highlight that the majority of aluminium-containing finished products are found in transport, followed by building, packaging, engineering products, and consumer durables (as discussed in Section 1.2). As it can be observed in Figure 7 and Figure 8, the output from the use phase highlights that a great amount of aluminium is locked in at this stage. Indeed, approx. 46% of the input is added to the stock in STQ21 and approx. 25% in BSL50, thus indicating that a great share of aluminium is not available for producing secondary materials. Further, it is also noteworthy the considerable amount of post-consumer scrap that is exported from Europe. This amounts to approx. 1 Mt in STQ21 and is expected to increase to 2 Mt in BSL50.

The material flow analysis of the CTC50 (Figure 9) and ACE50 (Figure 10) scenarios are calculated departing from the data of the BSL50 scenario and applying the corresponding targets and CE levers, respectively. Regarding the casting phase, a decrease in the input of virgin aluminium and an increase in the amount of recycled aluminium is observed both in the CTC50 and ACE50 scenario compared to BSL50. In the CTC50 scenario, the input of virgin aluminium is estimated to decrease by 10%, while the amount of recycled aluminium increases by approx. 4% consequently to the attainment of selected targets (Table 1). In the ACE50 scenario, the input of virgin aluminium is estimated to decrease by 27%, while the input of secondary materials increases by approx. 10% consequently to the implementation of Recover levers. The differences between CTC50 and ACE50 suggest that current policy targets could be more ambitious.

Nevertheless, upcoming regulations (e.g. ESPR or the End-of-Life Vehicles Regulation) may have a positive effect by lowering the demand of virgin aluminium (via, e.g., recycled content targets or requirements) and increasing the amount of recycling (via, e.g., requirements on design for disassembly of vehicles). Furthermore, the demand for semis in the CTC50 scenario remains unchanged compared to the BSL50 scenario, while it decreases by 10% in the ACE50 scenario because of the implementation of Reduce and Reuse levers.

As the CTC50 scenario only targets changes occurring at end-of-life phases, no changes are observed for the demand of finished products, while in the ACE50 scenario a decrease of 11% is estimated compared to the BSL50 scenario. With respect to the repartition of aluminium-containing products into the sectors considered in the assessment, the same trend as for the BSL50 scenario is observed for the CTC50 and ACE50 scenario, namely the sector employing the greatest amount of aluminium-based finished products is transport, followed by building, packaging, engineering products, and consumer durables. Focusing on the amount of collected waste after the use phase, an increase of 6% is calculated for the CTC50 scenario and of 10% in the ACE50 scenario compared to the BSL50 one. Finally, the amount of recycled aluminium (with respect to the total aluminium entering the recycling phase) increases by 1% in the CTC50 scenario compared to the BSL50 scenario, and by 6% in the ACE50.

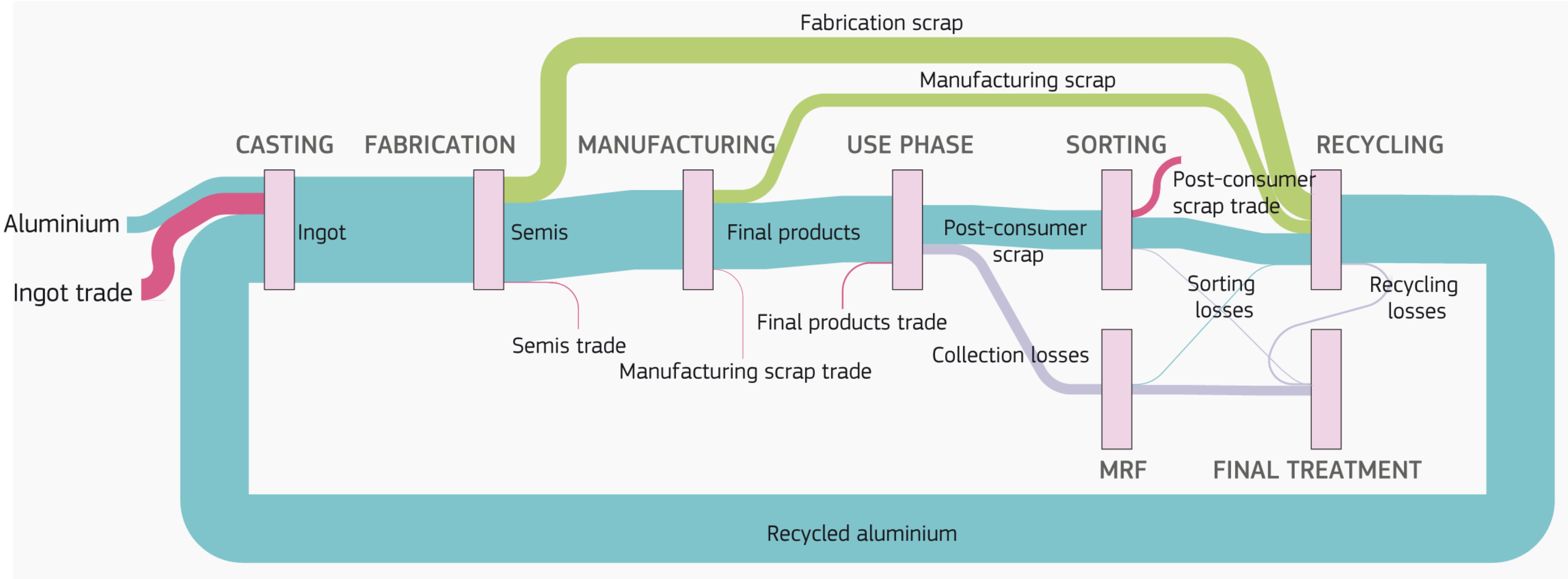
Figure 7. Mass flow analysis relative to the Status Quo scenario (STQ21)



Note: Trade is to be intended as the net trade; ‘MRF’ stands for material recovery facility

Source: JRC elaboration based International Aluminium Institute (2021)

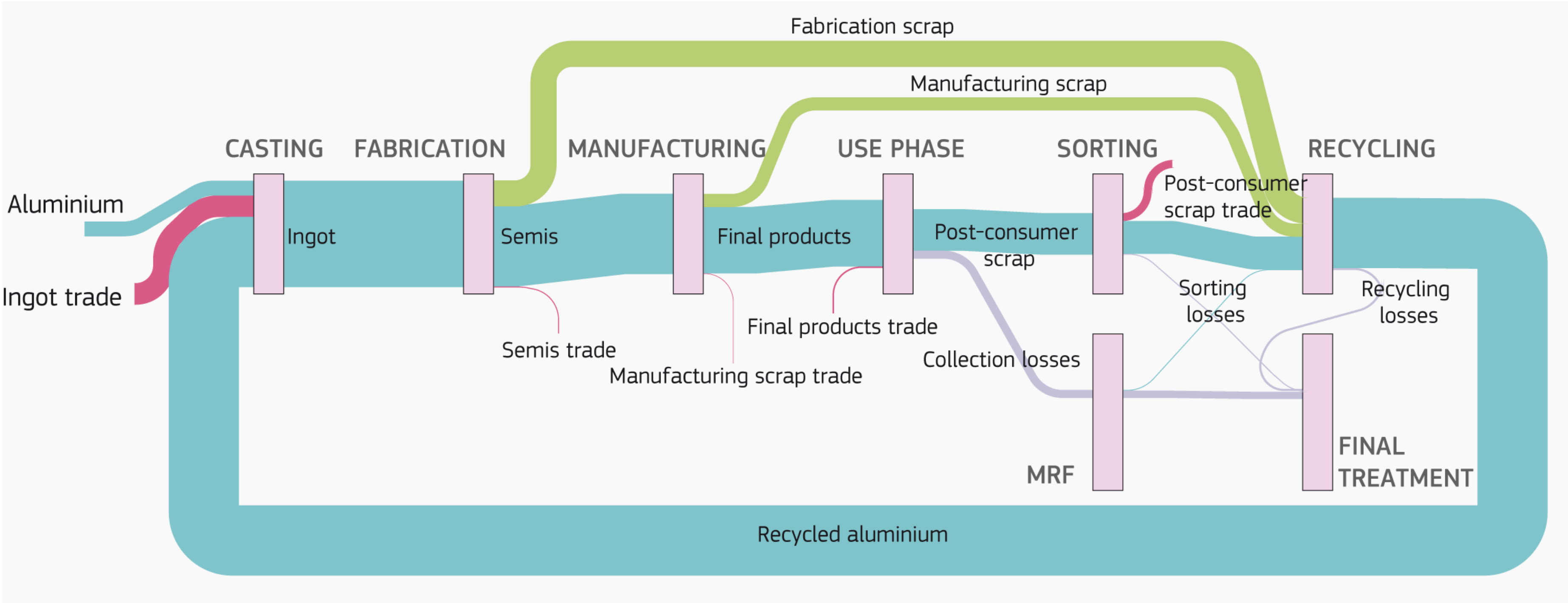
Figure 8. Mass flow analysis relative to the Baseline scenario (BSL50)



Note: Trade is to be intended as the net trade; 'MRF' stands for material recovery facility

Source: JRC elaboration based International Aluminium Institute (2021)

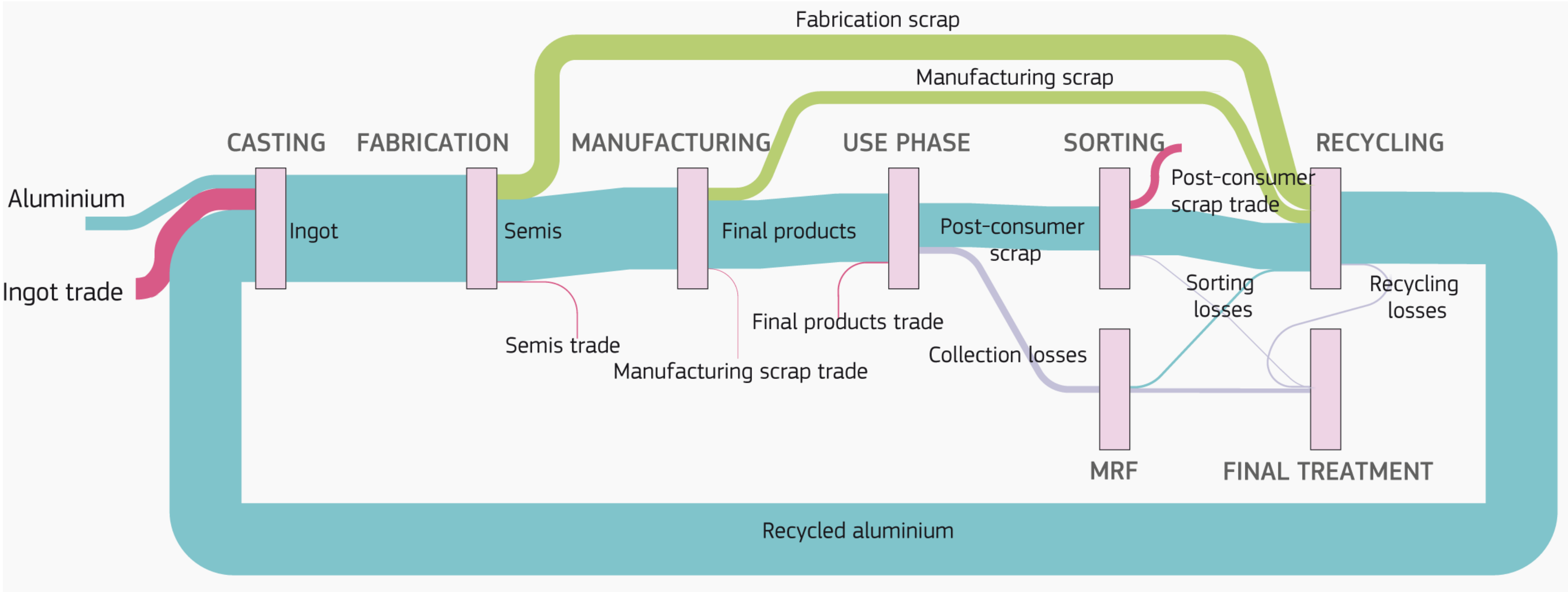
Figure 9. Mass flow analysis relative to the Compliance with selected Targets on Circular Economy scenario (CTC50)



Note: Trade is to be intended as the net trade; 'MRF' stands for material recovery facility

Source: JRC elaboration based International Aluminium Institute (2021)

Figure 10. Mass flow analysis relative to the Ambitious Circular Economy scenario (ACE50)



Note: Trade is to be intended as the net trade; 'MRF' stands for material recovery facility

Source: JRC elaboration based International Aluminium Institute (2021)

4 Life cycle assessment and costing

This section details the life cycle assessment (LCA) and life cycle costing (LCC) methodologies used to quantify the environmental and economic impacts with a bottom-up approach. Section 4.1 details the general features of the LCA methodology, Section 4.2 describes the LCC methodology, Section 4.3 summarises the findings on the other environmental impact categories, while Section 4.4 illustrates alternative socio-economic futures employed for the sensitivity analysis. Finally, in Section 4.5 the results obtained for the environmental and economic assessments are presented. In addition to the environmental and economic impacts, the secondary material used to substitute primary material is also quantified as an additional impact category. It is used to calculate the circular material use rate (CMUR), which is obtained by dividing the use of secondary material use (i.e. recycled material in line with the Waste Framework Directive) by the overall material use (Eurostat, 2018) including imports and exports. In contrast to the MFA, the use of secondary materials from different material cycles (e.g. by-products of other industries) is considered in neither the secondary material use nor the CMUR, due to its definition.

4.1 Methodology

This section details the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies used to quantify the environmental and economic impacts with a bottom-up approach.

4.1.1 Scope, functional unit and system boundary

The LCA has been carried out in accordance with the guidelines of the ISO 14040/14044 standards (ISO, 2006a, 2006b). The scope of the LCA is the European aluminium supply chain and its global inter-country linkages, with the overarching goal of quantifying the global environmental impacts associated with a set of targets and CE levers applied in Europe under two different scenarios (CTC50 and ACE50). The STQ21 and BSL50 scenarios represent a benchmark of comparison to quantify the impact reductions incurred by the targets and CE levers in selected environmental and socio-economic indicators. Notice that bottom-up LCA is by nature limited in its ability to capture global effects due to the (well-known) truncation effect. This is why the EEIOA is performed to quantify environmental impacts, as it adds value by capturing inter-country interlinkages and spillovers (see Section 5).

As for the LCA, when analysing the CE levers individually, we define a functional unit tailored to each case, which means that we include/exclude parts of the system boundary accordingly. The related system boundary, following ISO 14040/44, is expanded to the extent necessary to capture the consequences of the CE lever assessed. We do not alter final consumer demand in Europe or in the Rest of the World (RoW) (*ceteris paribus*). This corresponds to a consumption footprint perspective at global level. For example, increasing recycling in Europe incurs reduction of virgin production in Europe with beneficial environmental consequences at global level (more recycled content in European products), *ceteris paribus*; alternatively, improving European production influences the environmental performance of the material consumed in both Europe and at global level, *ceteris paribus*.

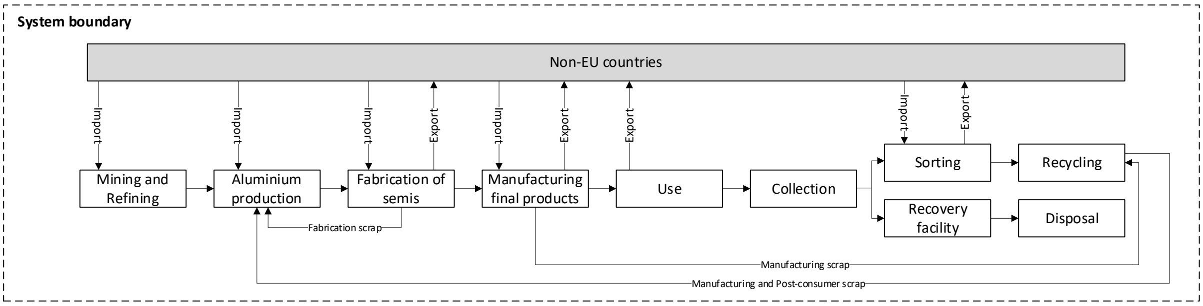
It should be noticed that, while each CE lever studied individually has a tailored functional unit, when the entire set of CE levers are studied altogether the new functional unit is the combination of all the individual functional units (as all changes are applied at once, simultaneously). Since there may be dependencies, we ensure that synergies/diverges amid CE levers are duly considered to avoid mass balance errors or similar inconsistencies. Notably, when Reduce levers are implemented, less waste is available for the Recover levers; similarly, when Reuse levers are applied. The order of implementation of the CE levers in the modelling thus affects the outcome.

The system boundary is global, i.e. we strive to include the sectors of Europe and the global economy that are affected by the CE levers applied within the European aluminium economy (Figure 11). The system boundary includes all processes from bauxite mining to final disposal via incineration or landfilling, as well as import-export flows except for the use phase, which is out of the scope of the study[5]. To address multi-functionalities that may arise in the system at end-of-life, system expansion is performed following common practices (ISO, 2006a, 2006b; Laurent, Bakas, et al., 2014; Laurent, Clavreul, et al., 2014). Therefore, for example, recyclates and energy that arise from managing the waste are credited to the waste management system by assuming the displacement of the virgin (for materials) or conventional sources (for energy mixes) counterparts. Background life cycle impact assessment data are obtained from the ecoinvent v3.9.1 database taking the 'allocation at the point of substitution' (APOS) system model (Wernet et al., 2016). As the study assesses the difference in impacts due to the implementation of specific changes, the ecoinvent 'consequential' system model would have been more indicated for the purpose of the study as it is designed for studies following a consequential thinking. However, it was decided to use the APOS datasets to be able to define marginal suppliers and substitutions bearing in mind also that such datasets do not include impacts related to indirect land use changes.

Given the analysis is assessing a future material system, it can be considered a prospective LCA (Arvidsson et al., 2023). Even though prospective LCAs have traditionally been connected to emerging technologies, Arvidsson et al. (2023) argue to unify future-oriented LCA under the definition of prospective LCA as an *"LCA that models the product system at a future point in time relative to the time at which the study is conducted"*. In contrast to traditional LCAs, critical aspects to be defined are the exact point in time in the future, the technological maturity and upscaling of systems modelled, scenario development (described in Section 2), the involvement of stakeholders (see Section 4.4) and the use of background data, further specified in the following sections. A limitation is that the life cycle impact assessment used has not been adapted to future impacts in terms of characterisation factors, as research on this is only available for a subset of impact categories with considerable uncertainties (Arvidsson et al., 2023). By taking into account the aforementioned issues, the prospective LCA can be considered as inspired by the more structured methodology proposed by Langkau et al. (2023), yet does not follow each step systematically.

[5] Excluding the use phase leads to an underestimation of the impacts (e.g. fuel consumed by a car). To be able to account for the impacts related to the use phase, specific finished products would need to be defined. However, this is beyond the scope of the analysis.

Figure 11. Simplified illustration of the system boundary of the system under assessment and main processes included



Note: Transport is also included in the assessment but not shown in this illustration for simplicity

Source: JRC elaboration

To model the electricity and heat production mixes, the official Global Energy and Climate Outlook (GECO) projections of the European Commission Joint Research Centre are used (further described in Section 4.1.3; Keramidas et al., 2023). The use of these projections has a similar function as, for example, the employment of the REMIND or IMAGE database of future energy scenarios (Sacchi et al., 2022; Stehfest et al., 2014), as is good practice in prospective LCA. It needs to be underlined, however, that in contrast to using these databases, which are altering the energy processes in ecoinvent databases, the GECO 2023 data is only applied to foreground processes and not, for example, to the extraction of raw materials due to limitations of the employed LCA tool. These rely on the unaltered ecoinvent v.3.9.1 processes, which lead to minor distortions of the results.

The environmental impacts are quantified following the Environmental Footprint Life Cycle Impact Assessment method (EF, v3.1) (Andreasi Bassi et al., 2023). The 16 environmental impact categories are considered, namely: Climate Change; Ozone Depletion; Human Toxicity, cancer; Human Toxicity, non-cancer; Particulate Matter; Ionising Radiation; Photochemical Ozone Formation; Acidification; Eutrophication, terrestrial; Eutrophication, freshwater; Eutrophication, marine; Ecotoxicity, freshwater; Land Use; Water Use; Resource Use, minerals and metals; and, Resource Use, energy carrier. The LCA software EASETECH v.3.6.0 was used (Astrup et al., 2012; Clavreul et al., 2014).

Finally, as it is common practice to use secondary aluminium together with primary aluminium in the production process, the Circular Footprint Formula (CFF), and, specifically, the material part of the formula was applied to correctly allocate burdens and credits to producers and recyclers between two life cycles ([Equation 1). Notice that the application of the CFF has been extended to the LCC, i.e. costs and revenues are also allocated to producers and recyclers between two life cycles. The function of the A factor is, indeed, to allocate the burdens and credits between two life cycles reflecting the market reality. The European Commission (2022) suggests to use in the case of aluminium an A factor equal to 0.2, hence representing low offer of recycled materials and high demand. Yet, in our assessment, we assume as base case an A factor equal to 0, both for allocating the impacts of the virgin production for obtaining the recycled mass, and for the burdens of recycling.

$$(1-R_1)*E_V+R_1*\left[A*E_{recycled}+(1-A)*E_V*\frac{Q_{Sin}}{Q_P}\right]+(1-A)*R_2*(E_{recyclingEoL}-E_V^{*}*\frac{Q_{Sout}}{Q_P}$$

[Equation 1]

Where A: allocation factor of burdens and credits between supplier and user of recycled materials

Q_{Sin}: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution

Q_{Sout}: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution

Q_P: quality of the primary material, i.e. quality of the virgin material

R_1: it is the proportion of material in the input to the production that has been recycled from a previous system

R_2: it is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R_2 shall therefore consider the inefficiencies in the collection and recycling (or reuse) processes. R_2 shall be measured at the output of the recycling plant

$E_{recycled}$: specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process

$E_{recyclingEoL}$: specific emissions and resources consumed (per functional unit) arising from the recycling process at end of life (EoL), including collection, sorting and transportation process

E_V: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material

E_V^{*}: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials

4.1.2 Modelling assumptions and life cycle inventory of material flows

4.1.2.1 Modelling the material supply chain

The processes considered in the life cycle assessment are mainly based on the inventories reported in European Aluminium (2018, 2021) and, whenever necessary, on the inventories of ecoinvent v3.9.1 database (Wernet et al., 2016). Imports have been modelled considering both the production in non-European countries and their transport to Europe, while for exports the production of semis and finished products in Europe is accounted for but their transport, use and end-of-life management are excluded. The recycling related to exported scrap is considered in the assessment as the scope of the study aims to capture all the effects of CE levers throughout the material economy (production, consumption, though excluding the use phase[6]), and related waste from consumption of the European aluminium supply chain. Scrap that is exported to non-European countries is waste generated by European consumption and, hence, needs to be accounted for as a change in its management would incur effects either in Europe or abroad.

[6] Excluding the use phase leads to an underestimation of the impacts (e.g. fuel consumed by a car). To be able to account for the impacts related to the use phase, specific finsihed products would need to be defined. However, this is outside of the scope of the current analysis.

In the following paragraphs, the inventories and assumptions made for the different stages of the aluminium supply chain considered in the assessment are presented.

Mining, refining and smelting

The processes related to mining, refining, and smelting are modelled based on the processes "aluminium production, primary, liquid, Söderberg"[7] and "aluminium production, primary, liquid, prebake"[8] assuming a coverage of the prebake technology of 95% and for the Söderberg one of 5% (European Aluminium, 2018). The energy mixes of the two ecoinvent processes are isolated and substituted with the foreground processes based on the GECO projections, both for 2021 and for 2050. Notice that changes in the smelting technologies (e.g. the use of inert anodes) are not considered as the technology readiness levels are still low and these are changes driven by the decarbonisation of the supply chain, which is not related to the primary goal of the study, i.e. investigating the potential of circular economy in the aluminium sector.

Ingot production

The production of ingots at the cast house is based on the inventory reported in European Aluminium (2018). At this stage, inputs of pre-consumer and post-consumer scrap may be mixed with primary aluminium, hence resulting in an output containing recycled content. Therefore, at this stage the CFF is implemented both on the input of primary aluminium, post-consumer scrap, and manufacturing scrap. Notice that fabrication scrap only carries the burdens of remelting the scrap, and is considered as 'free of burden' from mining, refining and smelting (i.e. primary production) following common practices (e.g. International Aluminium, 2023). If burdens related to primary production of fabrication scrap would be considered, one would need to implement an additional CFF on this input. However, what primary production processes would need to be accounted for and the value of the A factor to be applied are unclear. As this falls outside of the objectives of the current study, it was decided to take a cut-off approach.

The production of ingots in non-European countries for import to Europe is modelled based on the ecoinvent process "aluminium production, primary, ingot"[9] in which the energy mixes are isolated and substituted with the foreground processes based on the GECO projections for non-European countries, for both 2021 and 2050.

Fabrication of semis

In the study, five types of semis are considered, namely: extrusion, sheet, foil, cast, and other. The LCIs of extrusion, sheet, and foil are based on the inventories provided in European Aluminium (2018), while the one of cast is based on Liu et al. (2021). As other was not specified with any composition, the inventory was modelled as the average of extrusion, sheet, foil, and cast.

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[7] Wu, L., aluminium production, primary, liquid, Söderberg, IAI Area, EU27 & EFTA, Allocation at the point of substitution, ecoinvent database version 3.9.1.

[8] Wu, L., aluminium production, primary, liquid, prebake, IAI Area, EU27 & EFTA, Allocation at the point of substitution, ecoinvent database version 3.9.1.

[9] Wu, L., aluminium production, primary, ingot, RoW, Allocation at the point of substitution, ecoinvent database version 3.9.1.

The production of ingots in non-European countries for import to Europe is modelled based on the inventories of the European processes adapting the energy inputs to the ones calculated based on the GECO projections for non-European countries, both for 2021 and for 2050.

Manufacturing

An average manufacturing process was assumed for all sectors where aluminium is used. Specifically, the ecoinvent process "metal working, average for aluminium product manufacturing"[10] was used. In the process, the energy mixes are isolated and substituted with the foreground processes based on the GECO projections, for both 2021 and 2050.

The manufacturing of non-European aluminium products is based on the ecoinvent process "metal working, average for aluminium product manufacturing"[11]. In the process, the energy mixes are isolated and substituted with the energy processes based on the GECO projections for non-European countries, for both 2021 and 2050.

Use phase

As impacts related to the use phase would require a detailed modelling of all aluminium containing finished products and their usage, this specific life cycle stage is disregarded in the analysis. Excluding the use phase leads to an underestimation of the impacts, but it requires to define all (or key) aluminium-containing finished products (e.g. windows, passenger car) and the inputs of energy and/or auxiliary materials needed at the use phase now and especially in the future (2050). Such an analysis is beyond the scope of the study.

Collection

Collection via a collection truck was assumed only for packaging and mixed waste. The diesel consumption is based on the amounts reported in Albizzati, Foster, et al. (2024)[12]. For all the other sectors, it is assumed that waste is directly transported to a sorting facility prior recycling.

Transport

Transport is assumed throughout the supply chain, both for transport within Europe, for imports, and for the export of scrap. Transport distances are based on Nessi et al. (2021)[13] and Albizzati, Foster, et al. (2024)[14]. Exports of ingots, semis, and final products are not associated with any environmental impact related to transport.

Sorting

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[10] Steiner, R., metal working, average for aluminium product manufacturing, RER, Allocation at the point of substitution, ecoinvent database version 3.9.1.

[11] Steiner, R., metal working, average for aluminium product manufacturing, RoW, Allocation at the point of substitution, ecoinvent database version 3.9.1.

[12] The diesel combustion of separately collected is 2 L per tonne, while for aluminium collected with mixed waste is 4.8 L.

[13] For imports, it is assumed that goods are transported by truck for 200km, by railway for 100 km, and by barge for 20,000 km.

[14] Transport by truck of 150 km.

A sorting process prior recycling (both remelting and refining) is assumed and modelled based on the energy consumption reported in Rigamonti et al. (2009)[15]. The energy mixes are modelled based on the GECO projections for European countries, for both 2021 and 2050.

Remelting and refining

As recycling processes two technologies are considered, namely remelting and refining. The former is a dedicated process for only wrought aluminium, while the latter can take as input both wrought and cast aluminium. The LCI of remelting is based on European Aluminium (2018), while the inventory of refining is based on European Aluminium (2021). Notice that the split for wrought aluminium containing products is based on the elaboration of the figures provided in Boin & Bertram (2005). The same split is assumed for 2021 and 2050, i.e. no increases in the share of aluminium going to remelt is assumed (as also in Langhorst et al., 2024). This means that the baseline to 2050 assumes no improvements in sorting and recycling quality (this is instead studied in dedicated levers).

Exported scrap is assumed to undergo refining, which is modelled as the European recycling process considering as energy mix the ones based on the GECO projections for 2021 and 2050 for non-European countries.

Mechanical recovery facility

Packaging aluminium containing products that have been wrongly segregated at households, ending up in the so-called mixed (residual) waste stream, are assumed to be pretreated in a material recovery facility prior to final disposal of the mixed waste, as this is common practice in several Member States. The coverage of such a technology and its inventory is based on the information provided in Albizzati, Foster, et al. (2024). The technology allows for recovering additional aluminium prior to its final disposal.

Final disposal (incineration and landfilling)

Packaging aluminium that has been wrongly segregated at households and has not been recovered via MRF, losses from collection, and sorting processes are assumed to be disposed of via incineration and landfilling (based on the env_wasmun statistics of Eurostat, 2024, it corresponds to 46% landfilling and 54% incineration in 2021, and 43% landfilling and 57% incineration in 2050 based on a linear extrapolation). The incinerator is modelled as in Albizzati, Foster, et al. (2024), while landfilling is based on the ecoinvent process "treatment of waste aluminium, sanitary landfill"[16].

4.1.3 Background energy modelling

The projections presented in the GECO 2023 update (Keramidas et al., 2023) are used to calculate the composition of the average energy mix, distinguishing amongst electricity, industrial heat (specific to the sector analysed), district heating, and space heating, of EU and non-EU from 2020 to 2050. Out of the three scenarios considered in the GECO 2023 (Keramidas et al., 2023), the Nationally Determined Contribution (NDC) Long-Term Strategies (LTS) is assumed as default energy

[15] Electricity required is 69 kWh per tonne, and heat 845 MJ per tonne.

[16] Doka, G., treatment of waste aluminium, sanitary landfill, CH, Allocation at the point of substitution, ecoinvent database version 3.9.1.

mix. In this scenario, the targets of the NDC towards CO_2 reduction are considered in the medium and the longer term. Moreover, the scenario presupposes that the objectives in the NDCs are met in the target year (mostly 2030). Beyond 2030, whenever they exist, the LTS targets of the different countries or regions, as in the case of the EU, are pursued, which is the net-zero target for 2050 (Keramidas et al., 2023). In the GECO 2023 projection, transport is also decarbonised. However, for the sake of simplicity, the decarbonisation of the transport sector is not considered in this study.

Within the NDC-LTS scenario, the energy grid is decarbonised due to high shares of renewables in the mix, but also as a result of the implementation of Carbon Capture and Storage (CCS). As mentioned in Section 4.1.1, ecoinvent datasets are used to model the background processes, including the energy mixes. The life cycle inventories related to energy production from biomass, combined heat and power fuelled by natural gas, coal, lignite, natural gas, and oil, are modified to account for the energy penalty related to the usage of CCS (i.e., to produce 1kWh from coal, more coal is required by the process to power the CCS), which corresponds to 10% according to Bauer et al. (2008). The extraction emissions are not affected by the implementation of the CCS. The additional emissions related to the usage of CCS are slightly overestimated, because we apply the penalty to the entire dataset while they should only be related to the additional extraction of the fuel source used to produce energy. Further, we assume that the technology implemented for CCS is the monoethanolamide (MEA) scrubbing, having a 90% effectiveness in absorption of CO_2, NO_x and SO_2 (ETC, 2022).

Aluminium production is highly demanding in terms of electricity needs. Usually, aluminium production plants are located close to energy production plants to keep the costs low. Hence, the composition of the electricity average mix would need to be specific for aluminium. Yet, due to data gaps in future projections, it was decided to assume the electricity mix required by the aluminium industry equal to the EU one. On the other hand, the composition of the heat required by the sector in focus is specific to it. Yet, in the GECO model, there is not a specific sector for aluminium, but this is rather included in “Other industry” (Després et al., 2018). Finally, on top of accounting for the implementation of CCS in the energy sector (electricity, heat), the establishment of CCS in aluminium production itself (to reduce on-site CO_2 emissions) is also considered. Yet, based on the projections of the GECO the coverage of CCS in the aluminium sector is low (below 10%).

4.1.4 Sensitivity analyses

4.1.4.1 Background energy system

The sensitivity analysis is focused on the assumption made on the energy mixes. The GECO 2023 (Keramidas et al., 2023) provides three different scenarios, namely a Reference scenario, the NDC-LTS scenario, and the 1.5°C scenario. The assumption made in the default case (i.e. using the NDC-LTS scenario for the projections of European and non-European energy system) is challenged against considering the energy mixes calculated under the Reference scenario conditions. The Reference scenario models a world where only policies legislated as of June 2023 are considered and stated targets or policies, whether legislated or not, that have not been supported by concrete actions plans are assumed not to be fulfilled (Keramidas et al., 2023). Therefore, the energy mix is overall less ‘green’, and the implementation of CCS is even more limited than in the NDC-LTS one.

4.1.4.2 Methodological aspects: choice of A factor and average vs marginal suppliers

The sensitivity analysis is conducted on key LCA methodological choices, namely the A factor applied in the CFF, and the datasets used to represent the suppliers of aluminium and of energy (electricity and industrial heat). As for the A factor, the default value applied (A=zero) is challenged applying a value of A=0.2, which is the value recommended for aluminium in European Commission (2022). As for the market suppliers of aluminium and energy, we tested the average datasets (reflecting a rather attributional approach) applied as default by applying marginal datasets (reflecting a rather consequential approach). While both average and marginal datasets for energy were derived from the GECO projections, further details on the specific composition of the datasets may be found in Annex 2.

4.2 Methodology LCC

The life cycle costing (LCC) is performed following state-of-the art approaches as detailed in Hunkeler et al. (2008) and Martinez-Sanchez et al. (2015). The LCC shares the same goal, scope, system boundaries and functional unit as the LCA. Furthermore, as in the LCA the CFF is applied, the formula is also employed in the LCC to duly allocate costs and savings at production and end-of-life stages.

In LCC, two types of costs are accounted for, namely internal and external costs (also referred to as externalities). Internal costs include production and management costs (i.e. costs incurred by the different actors in the supply chain), usually distinguishing between operating and capital costs (OPEX and CAPEX). They also cover transfers (i.e. taxes, subsidies, fees, and value added tax) which represents a re-distribution of capital amongst the different stakeholders in the system. In contrast, external costs are non-monetary transactions reflecting the shadow prices of the emissions. While there are several ways to monetise the damage costs of emissions, they are herein estimated in line with De Bruyn et al. (2018). They cover prices for emissions to air/soil/water, but not for other disamenities, such as noise, odour, accidents, or others.

Two types of LCC are distinguished based on the definition provided in Hoogmartens et al. (2014), namely the *environmental* LCC (eLCC) and the *full environmental* LCC (feLCC)[17]. The former includes all internal costs, while the latter accounts for the monetised environmental emissions from the 16 environmental impact categories assessed, which are currently not internalised in the internal costs. Notice that one needs to be careful with transfers in a feLCC. If the transfers already cover the entire external costs, then they should not be included to avoid double counting, given the environmental externalities are already accounted for. Finally, costs and externalities occurring in the future are neither corrected for inflation to ensure consistency with the LCA, and thus expressed as EUR2022, nor are discounted[18] (that assumes future costs to be lower due to technological development; Gollier et al., 2009).

[17] The feLCC has originally been referred to as societal LCC by Hunkeler et al. (2008). It implies a monetisation of the LCA results and adds these costs on top of the internal costs.

[18] To account for future costs, social or equity discount rates should be applied. Social discount rates should be applied to public projects when implementing specific/targeted regulations; further, social discount rates are usually lower than equity discount rates and focus on society rather than revenues. Equity discount rates are usually applied both to CAPEX and OPEX and to non-state-owned projects (Tazi, N., Safei, F., and Hnaien, F. (2022). Assessment of the levelized cost of energy using a stochastic model. *Energy* vol. 238, Part B, 121776. https://doi.org/10.1016/j.energy.2021.121776).

4.3 Additional indicators

On top of the 16 environmental indicators, the eLCC and feLCC, employment was quantified as an additional impact category. The impacts related to job creation are estimated following the methodology reported in Taelman et al. (2020), while cost of labour is included as an operational expenditure in both the eLCC and the feLCC. The underlying inventory data used to describe costs and employment for each process included in the system under assessment may be consulted in Annex 2.

Further, the results also encompass the quantification of the Circular Material Use Rate (CMUR), which is an indicator that strives at measuring an economy's circularity. The CMUR is the ratio of the amount of waste going to be recovered domestically corrected by the amount of imported waste to be recycled and the amount of exported waste destined for recovery, and of the domestic material consumption (inclusive of imports and exports).

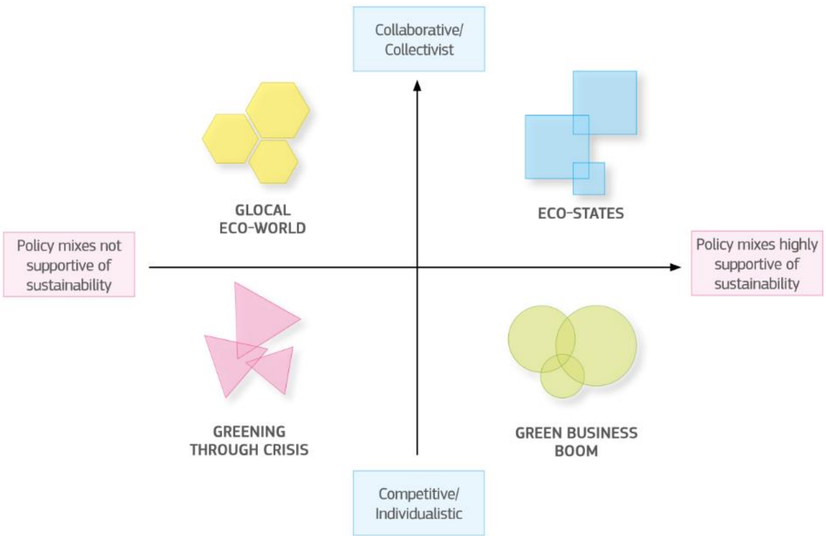
Finally, as presented in Section 1.2, two main alloy families exist, namely wrought aluminium and cast aluminium alloys. When reaching its end-of-life, aluminium can either undergo remelting or refining, with the former producing wrought aluminium ingots and the latter cast aluminium ingots. Once mixed with other alloys, wrought aluminium alloys cannot be recycled back into wrought aluminium alloys (i.e. in a 'closed-loop' fashion), but can only be recycled into cast aluminium alloy due to higher contamination levels. Herein, quality is intended as the potential of achieving closed loop recycling for wrought and cast aluminium. Wrought aluminium alloys are herein considered of high-quality (due to its low alloy and impurity levels), while cast aluminium alloys are considered of low-quality (due to its high alloy and impurity levels). In the bottom-up assessment and based on the MFA data, the share of wrought-to-wrought and wrought/cast-to-cast aluminium recycling is calculated as an additional indicator.

4.4 Epistemic uncertainty of alternative socio-economy futures

With the current design of the analysis, there is an underlying assumption that the socio-economic system on which the industrial system is based will not change significantly. Thus, it is expected that technological and socio-economic trends will continue as per the historical trajectory. Taking an anticipatory governance approach, it is essential to understand that the current reality might develop in radically different ways, subjecting the present analysis and its results to substantial epistemic uncertainty (Langkau et al., 2023). One way to address these is the use of alternative socio-economic scenarios which can be predictive, explorative or normative (Börjeson et al., 2006). A well-known set of scenarios used in integrated assessment models are for example the explorative shared socio-economic pathways scenarios (van Vuuren et al., 2017), for which global data regarding population, GDP growth, inequalities, material flows and related emissions corresponding to different socio-economic development paths are available (Narayan et al., 2023; Schandl et al., 2020; van Beek et al., 2020). Another set of explorative scenarios was proposed by Bauwens et al. (2020) with a 2x2 matrix, containing the axes along high-tech and low-tech innovations and the type of governance, being either centralised or decentralised. With a strong focus on technology rather than socio-economic aspects, it needs to be underlined that these four scenarios are more closely related to CE than the Shared socio-economic pathway scenarios. Both scenario sets are, however, explorative scenarios, while for the current analysis, the goal is to identify how the CE can best support the net-zero transition by 2050, requiring a normative scenario approach. Therefore, the Strategic Foresight scenarios and transition pathways for EU 2050, developed by the Policy Lab of the Joint Research Centre were deemed suitable for the current purpose. They allow for the imagination of different futures that all lead to a net-zero transition, though with different socio-economic implications. The scenario of not achieving net zero by 2050 is partially already covered by the previously described sensitivity analysis with the more fossil-based energy mix in Section 4.1.4.1.

The normative scenarios by the JRC are separated into a 2x2 matrix with the axes of policy mixes either supportive or not supportive of sustainability and with either a collaborative or competitive outlook on society (Matti et al., 2023). This results in four different background scenarios, into which the current analysis of circularity in the aluminium sector will be embedded to address the epistemic uncertainty of the results. It is important to understand that it is not the intention to claim that the future will develop in one way or the other, but rather to show different ways *how* the future could develop and to see how the ACE50 scenario would fare in these different futures. This is attempted by estimating the effectiveness of the CE levers in the different scenarios, while considering the characterising background conditions. While it is not the goal to create exact predictions of how CE policy will materialise in the four different worlds, understanding their main drivers and actors can support reflections around the implementation of the CE levers. This will enable policy makers to take more informed decision, by pushing the thinking towards implications of circularity levers that are beyond current realities (Muiderman et al., 2020). The following paragraphs will describe the main characteristics of the four scenarios, depicted in Figure 12.

Figure 12. Four scenarios leading towards a sustainable Europe 2050



Source: taken from Matti et al. (2023, p. 101)

4.4.1 Glocal Eco-World

In a Glocal Eco-World, there is an overall demand reduction because of a shrinking economy with strong local actors. Given the limited power of national actors, fiscal resource and related state investment in research and development as well as public infrastructure are limited. This makes large-scale efforts of e.g. investing in recycling capacity more challenging. Service-based business models have a high uptake due to collaborative mindset of people. There is a strong sense of duty to act sustainably and therefore an intrinsic motivation to engage in circular behaviour such as reuse or recycling. There is a focus on resilience, strategic autonomy and sufficiency. The economy is generally oriented towards local markets with short supply chain and trade with China is diminishing. Instead, the EU trades with likeminded partners.

4.4.2 Eco-states

In an Eco-states scenario, there are strong national governments with cohesive policy mixes towards more sustainability, leading to economic growth with limited resource use increase. Given the high fiscal power, there is high tax income and thus investment in green technology and innovation by the state. This entails a digital infrastructure, facilitating tools such as the digital product passport and communication through virtual platforms. As energy prices are set on EU level, industries are forced to save resources through stringent requirements on recycling, reuse and repair of goods. Given the utilitarian outlook of citizens with a focus on compliance, people conform to sustainable lifestyles promoted by governments and engage in individual and sharing CE practices. The global world order remains similar to the one of today with multilateralism continuing.

4.4.3 Greening through Crisis

In a world that is Greening through Crisis, CE is a survival strategy and serves to achieve strategic autonomy and to deal with resource scarcity. The overall economy is shrinking, requiring efficient resource use. Investment is limited to strategic independence, thus supporting the reshoring of manufacturing and increasing the importance of the local industry. There is ample public private partnership for innovation and technology made in the EU, given the low fiscal power of the EU itself and somewhat larger power of Member States. Policy coordination and standardisation across the EU is limited making the scaling of technologies and sharing business models more challenging. Overall, the citizens have limited trust in the EU and are focused on survival rather than the collective good. Trade policies have become more protectionist, increasingly imposing tariffs, and multilateralism has deteriorated.

4.4.4 Green Business Boom

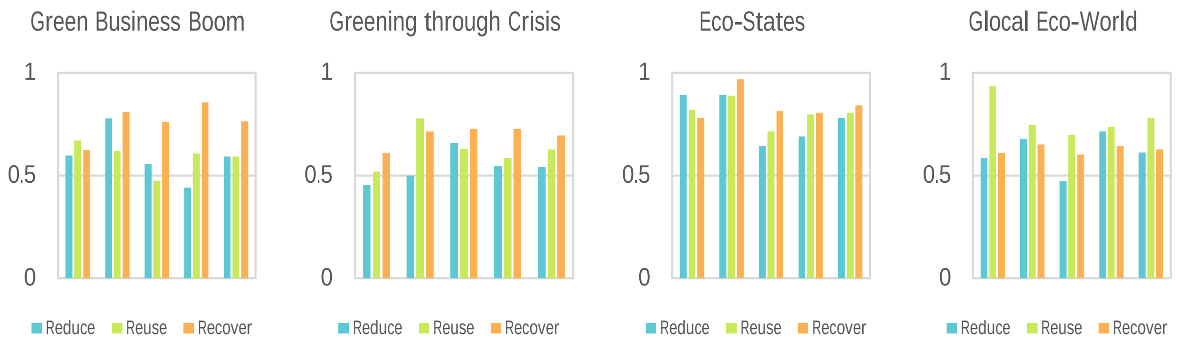
In the case of a Green Business Boom, international corporations are the main actors, taking their decisions in a framework of carefully designed incentives towards sustainability. Both investment and innovation are high and led by business. There is a green fiscal framework on EU level creating tax income and the economy overall is growing. As resource decoupling is limited, carbon capture plays an important role in the energy transition in addition to CE practices. The way CE R-strategies are proliferated is through standards and monitoring procedures. There is a focus on improved resource efficiency and waste recirculation, as they are considered resources. Citizens are acting according to individualist incentives, with sustainable behaviour mainly steered by price, rather than intrinsic motivation. In an attempt to become more resilient and efficient, the EU is in competition for raw materials and initiates strategic trade cooperation with selected countries.

4.4.5 Participatory evaluation of alternative socio-economic futures

Given the inherent epistemic uncertainty of the future, the LCA and LCC are supplemented by a sensitivity analysis based on the "European Strategic Foresight scenarios and transition pathways for EU 2050". To quantify the narratives underlying these scenarios for 2050, a participatory modelling approach with the inclusion of stakeholders is taken, merging the fields of foresight and prospective LCA (Bisinella et al., 2021; Langkau et al., 2023). This approach yielded i) quantitative estimates on the effectiveness of selected CE levers under different socio-economic scenarios, and ii) key background variables related to future scenarios.

The adaptation of the background system is in line with the description of the scenarios themselves, supported by expert consultation, while the effectiveness of the circularity levers in those scenarios was established through a participatory workshop as proposed by Langkau et al. (2023). This workshop was conducted to test the impact of the four different socio-economic futures on the effectiveness of the implementation of circularity levers in the aluminium sector. During the 3h interactive online workshop, ten experts had to rate the effectiveness of the circularity levers on a scale of 1 to 7, categorised into Reduce, Reuse and Recover, within the respective scenarios. Moreover, the participants added comments on sticky-notes onto a shared digital board, contextualising the scoring. The resulting effectiveness of the levers is then used in the sensitivity analysis, by correcting the default effectiveness value of the levers obtained from literature with the one established in the workshop. Indeed, we observed that the majority of previous studies implicitly assume a 100% effectiveness of CE levers, without considering external factors besides the energy transition (Material Economics, 2018, 2019; Nilsson et al., 2020; Zibell et al., 2022). After the workshop, a sense-making session with a subset (6) of the workshop participants helped to determine the values for the background variables pertaining to the scenarios, such as general demand increase in the economy.

Figure 13. Impact of circular economy clusters on material flows normalised to scale 0-1



Note: 0 = low effectiveness, 1 = high effectiveness

Source: JRC elaboration

Figure 13 shows that the lever related to Reduce has the highest effectiveness in a scenario with more protectionist trade policies and the deployment of CE to achieve strategic autonomy due to resource scarcity (Greening through Crisis) or a strong government (Eco-States), whereas Reuse levers are expected to function the best in scenarios with strong compliance (Eco-states). The recovery of aluminium is most effective where centrally supported by state legislation (Eco-States). In accordance with the sense-making session following the workshop, the obtained effectiveness factors are separated into the ranges low (45-59%), medium (60-74%) and high (75-89%). As for the second objective (testing background conditions), the participatory approach suggested to scale demand for aluminium to the size of the general economy in the respective scenario, with numerical values inspired by the quantification of integrated assessment models such as the shared socio-economic pathways (Narayan et al., 2023; Schandl et al., 2020). It was also decided to use rather extreme values to depict these scenarios, as to assure a notable effect in a caricaturising manner. The final numbers for both the lever effectiveness and background adaptations for the LCA and the dynamic modelling are presented in Annex 4.

4.5 Results

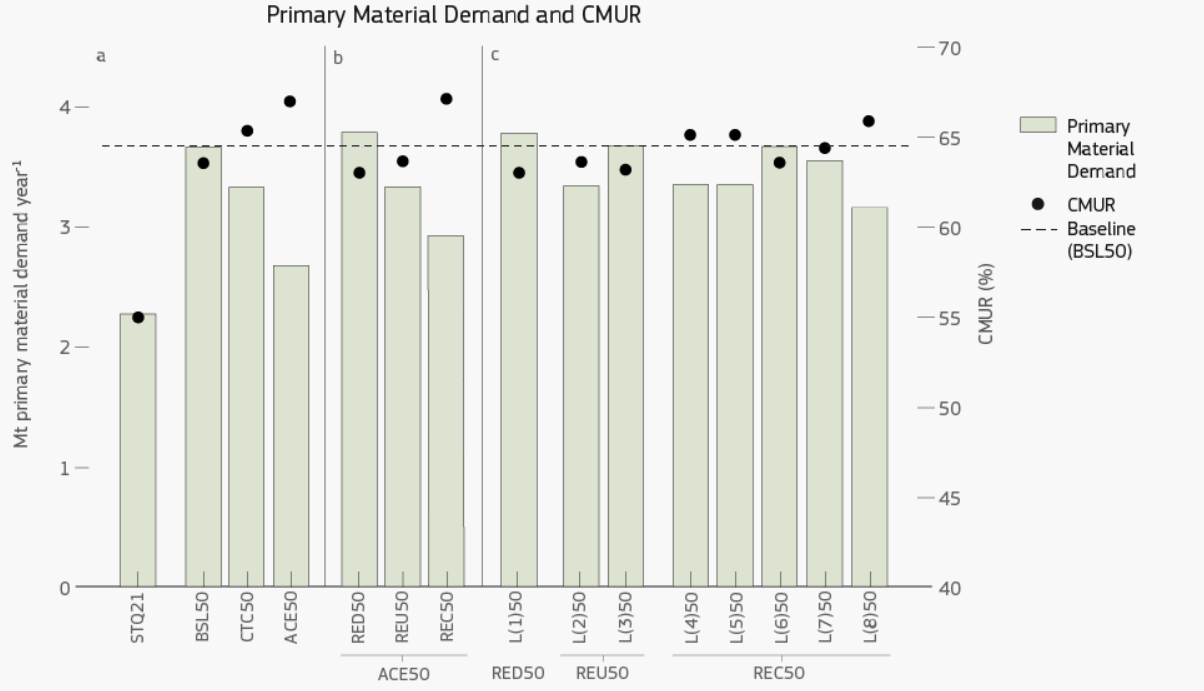
Whereas results are available for all 16 environmental categories of the EF v3.1 methodology and different costs categories, only a subset of them are herein presented. The rest are documented in Annex 3. For Primary Material Demand and the Circular Material Use Rate (CMUR), the mass of virgin aluminium is represented as a positive value. In the results for Climate Change and Environmental Life Cycle Costs, positive values represent a burden for the environment or a cost for the economy, while negative results reflect savings for the environment or economic revenues. As to account for the different impacts of the individual levers as well as their joint impact of either entire CE clusters or all levers at once, the results are presented in a disaggregated way. All the results presented are calculated considering the energy mixes based on the NDC-LTS scenario, for both the EU and non-European countries, and A factor equal to zero in the CFF. The results obtained for Climate Change relative to the sensitivity analyses performed on energy mixes and on the A factor and choice of suppliers are presented in Section 4.5.5 and Section 4.5.6, respectively. Finally, the results of the epistemic uncertainty are presented in Section 4.5.7.

4.5.1 Material circularity: Primary Material Demand, Circular Material Use Rate, and availability and quality of secondary material

The CMUR is presented in Figure 14 together with the Primary Material Demand per year. As shown in Figure 14a, the CMUR increases from 55% in STQ21 to 64% in BSL50. The high CMUR in the STQ21 scenario indicates that recycling of the material itself is already high. Despite the higher demand for primary material, the CMUR of the BSL50 scenario increases by 9 percentage points because of more waste sent to recycling (either domestically or elsewhere). In the CTC50 scenario, the CMUR increases to 65%, while in the ACE50 scenario it reaches 67%. The higher CMUR calculated in the ACE50 scenario is the consequence of implementing simultaneously Recover (that results in a CMUR of 67%), Reduce (that results in a CMUR 63%) and Reuse (that results in a CMUR 64%) levers, which all contribute with lowering the demand for primary material (Figure 14b). The results further suggest that actions should tackle reduction in demands (Figure 14c). It is noteworthy that the focus of the numerator of the CMUR is to represent a country's (or region) ability to collect waste for recovery, regardless of its quality and destination country for its treatment. Hence, the CMUR does not reward countries (or regions) that implement actions that retain collected waste within their borders to treat and/or enhance the quality of it. This is well exemplified by the results of L(4)50 and L(5)50 in which both levers look at the effects of improving collection and sorting, but in L(5)50 higher quality in scrap separation is achieved to ensure closed-loop recycling (especially for wrought aluminium). Yet, regardless of the higher quality of recyclates obtained, both levers result in a CMUR of 65%.

As explained in Section 1.2, wrought aluminium alloys admit 5% of impurities at most, while cast aluminium alloys allow up to 20% (Jarrín Jácome et al., 2021); once wrought alloys are mixed together with cast alloys, it is not possible to recycle the former in a closed-loop due to the higher presence of impurities. Out of the total quantity of recyclates obtained, the share of wrought alloys recycled into a closed-loop (i.e., wrought-to-wrought) and the share of wrought and cast alloys recycled into cast alloys are shown in Figure 15. The results show that, under business-as-usual practices of sorting and recycling, there is an abundance of cast alloy recyclates both in the STQ21 (56%), the BSL50 (61%), and the CTC50 (61%) scenarios (Figure 15a). Differences in the share of wrought vs cast aluminium alloys can only be observed in the ACE50 scenario (49% cast aluminium alloys, and 51% wrought aluminium alloys) and, especially, when looking at the results for the individual levers (Figure 15c). Specifically, the share of cast aluminium alloys is the predominant one in all levers (ranging from 58% in L(7)50 to 62% in L(1)50) except for lever L(5)50, in which the potential of improving waste collection (i.e., both as an improvement in the collection rate and in separate collection[19]) is investigated. Indeed, L(5)50 shows that implementing separate collection would favour closed loop recycling for wrought aluminium alloys (reaching a share of cast aluminium alloys of 48% and of wrought aluminium alloys 52%) under the assumption that all wrought aluminium can be recycled back into wrought aluminium.

Figure 14. Demand for primary material across the scenarios investigated and Circular Material Use Rate

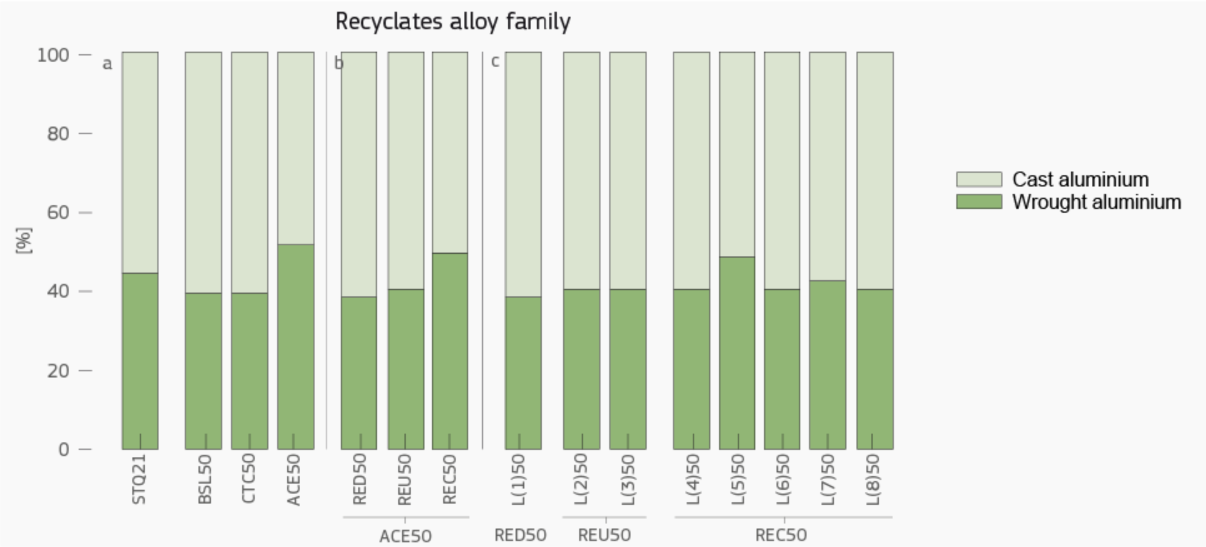


Note: The primary material demand is expressed as Mt (left-hand side), while the Circular Material Use Rate (CMUR) is expressed as % (right-hand side); a) full-fledged scenarios; b) cluster of levers scenarios; c) one-at-a-time levers scenarios

Source: JRC elaboration

[19] Separate collection is herein intended as separate collection by nature and type, e.g. keeping aluminium-containing products in the transport sector separated from the other applications and sorted according to the alloy type.

Figure 15. Share of wrought aluminium and cast aluminium alloys out of the total recyclates obtained



Note: a) full-fledged scenarios; b) cluster of levers scenarios; c) one-at-a-time levers scenarios

Source: JRC elaboration

4.5.2 Climate Change

The Climate Change impacts, quantified as Million tonnes of CO_2-equivalent emissions (Mt CO_2-eq.) for the entire system, are depicted in Figure 16. In the STQ21 scenario the impact is estimated at 160 Mt CO_2-eq., of which production of ingots[20] is 22 Mt CO_2-eq. (when including recycling savings, i.e., 22=71-49 Mt CO_2-eq., Figure 16), fabrication of semis is 7 Mt CO_2-eq., manufacturing of final products 9 Mt CO_2-eq., import[21] (inclusive of ingot, semi-finished products, finished products, and scrap) 117 Mt CO_2-eq., collection and transport 9 Mt CO_2-eq., sorting and recycling 5 Mt CO_2-eq., material substitution (i.e. aluminium recyclates obtained from the recycling processes) -49 Mt CO_2-eq., and export -10 Mt CO_2-eq. (including the burdens of recycling in non-European countries and the savings related to material substitution). The BSL50 scenario shows a reduction in total emissions

[20] When considering the impacts related to production of aluminium ingot castings, differences can be observed from the accounting reported in Zore (2024). Indeed, the author estimates a total impact of 100 Mt CO_2-eq., of which 13.4 Mt CO_2-eq. is related to producing virgin aluminium, 1.2 Mt CO_2-eq. is related to recycling, and 85.4 Mt CO_2-eq. is related to import. According to our calculations and considering A=0 in the CFF, the impact of producing virgin aluminium is 22 Mt CO_2-eq. (calculated as the difference between the impact of producing the virgin ingots, 71 Mt CO_2-eq., and the impacts of material substitution, -49 Mt CO_2-eq.). The higher impacts of virgin aluminium production are related to higher emissions of the electricity mix assumed in our assessment compared to, for example, the one assumed in the ecoinvent dataset for primary aluminium production (i.e., 0.29 kg CO_2-eq. kWh^{-1} and 0.17 kg CO_2-eq. kWh^{-1}, respectively). The impacts related to recycling in our assessment are 4.5 Mt CO_2-eq. while the ones related to imports are 85.5 Mt CO_2-eq. Considering the impacts of our assessment, the total impact of production corresponds to 112 Mt CO_2-eq (against the 100 Mt CO_2-eq. estimated by Zore, 2024).

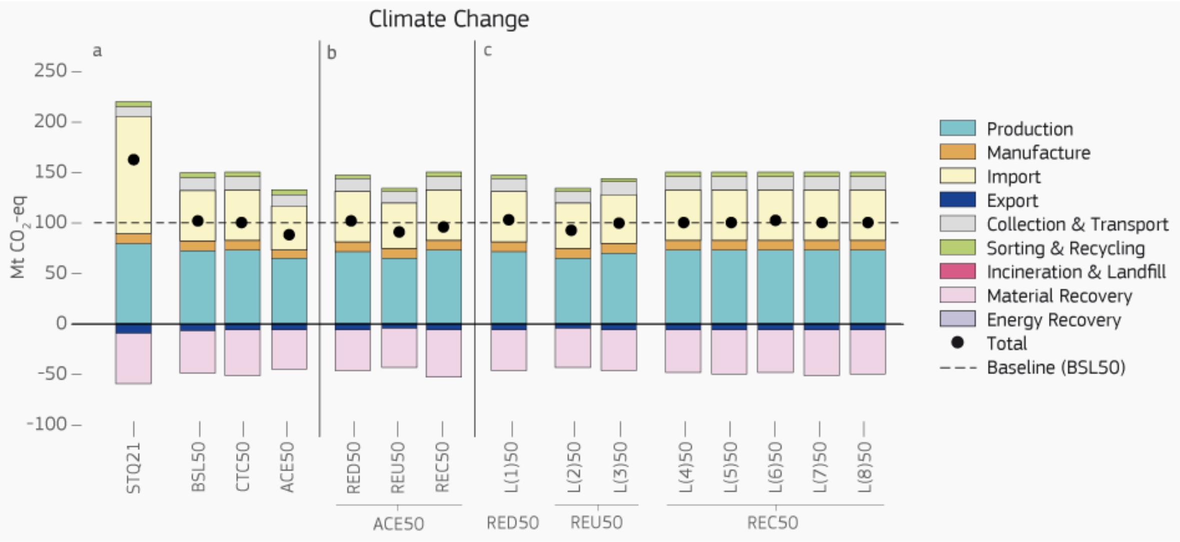
[21] An important remark needs to be made on the impact of imports and exports. Indeed, a different total impact is calculated when considering the totality of import and of export, and the net trade. Let us assume that there is an export of 300 kg with an impact of 400 kg CO_2-eq. kg^{-1} (relative to its production), and an import of 1,200 kg with an impact of 150 kg CO_2-eq. kg^{-1}. If we consider import and export separately, we will incur a total impact of 215 t CO_2-eq. (1200*150-300*400). On the other hand, if we consider first the difference in masses between import and export, i.e. the net trade, we will incur a net import of 900 kg (1200-300). Hence, the total impact relative to the net (mass) trade would be 135 t CO_2-eq. (900*0.15), which is considerably different from 215 t CO_2-eq.

to 101 Mt CO_2-eq.[22], which corresponds to a reduction of 37% compared to the STQ21 scenario. Despite the projected increase in demand in 2050, lower emissions are expected mainly due to the decarbonisation of the energy grid at both at EU and, especially, non-European level. The CTC50 scenario results in a total emission of 98 Mt CO_2-eq., which corresponds to a 3% reduction compared to the BSL50 scenario, suggesting that the targets considered in the study are not sufficient for a substantial additional reduction in GHG emissions. The greatest reduction compared to the BSL50 results for Climate Change mitigation is observed in the ACE50 scenario, which incurs a total impact of 87 Mt CO_2-eq. corresponding to a 14% reduction compared to the BSL50 result (Figure 16a). In the ACE50 scenario, all levers are applied simultaneously. Focusing on individual levers, the greatest reductions can be observed for L(2)50 (i.e. design for reusability, -11%) that results in a demand reduction, followed by L(7)50 (i.e. expansion of deposit return systems, -4%) (Figure 16b). The results show that energy decarbonisation alone is not sufficient to lead the sector to net-zero emissions. Circular economy strategies that go beyond current legislative targets can contribute to significant additional Climate Change mitigation, especially if implementing levers focused on reducing the demand for virgin aluminium. Nevertheless, this also reduces the amount of secondary material availability, which results in lower savings from virgin material substitution (Figure 16).

Focusing on the clusters of levers, Reduce levers only contribute with a 1% reduction in Climate Change impacts compared to the BSL50 ones, as the production process is already highly optimised, and a reduction in scrap at fabrication and manufacturing stages would not contribute significantly to overall reductions in GHG emissions (Figure 16b). The Reuse levers contribute with an 11% reduction in Climate Change impacts compared to the BSL50 ones, and the greatest reduction is relative to L(2)50 as this lever targets all the sectors in which aluminium-containing products have a lifetime longer than 1 year (Figure 16c). Finally, the combination of Recover levers incurs in a total 6% reduction in Climate Change impacts compared to the BSL50 ones (Figure 16b). The levers contributing the most are L(7)50 (i.e. expansion of deposit return systems, -4%) and L(5)50 (i.e. improved waste sorting and scrap quality, -3%).

[22] In the BSL50, where the energy transition is achieved, the total impact of production falls to 63 Mt CO_2-eq. Indeed, primary production contributes with 25 Mt CO_2-eq. (calculated as the difference between the impact of producing the virgin ingots, 67 Mt CO_2-eq., and the impacts of material substitution, -42 Mt CO_2-eq.), recycling with 4 Mt CO_2-eq., and imports with 34 Mt CO_2-eq.

Figure 16. Results obtained for Climate Change expressed as Mt CO_2-eq per entire system per year



Note: a) full-fledged scenarios (STQ21, BSL50, CTC50, ACE50); b) cluster of levers scenarios (RED50, REU50, REC50); c) one-at-a-time levers scenarios

Source: JRC elaboration

4.5.3 Remaining impact categories

When comparing ACE50 to BSL50, the impacts across all impact categories are significantly reduced. The same is observed for the CTC50 scenario, but with less reduction occurring. Further, by moving from STQ21 to BSL50 some trade-offs occur due to the expected changes in the EU energy mix, with an increased use of renewables, e.g. for Human Toxicity, cancer and non-cancer, Particulate Matter, Ecotoxicity, Land Use, Water Use, and Resource Use – Minerals and metals. The net results in these impact categories however are significantly reduced in the ACE50 scenario. The remaining impact categories follow the trend observed for Climate Change.

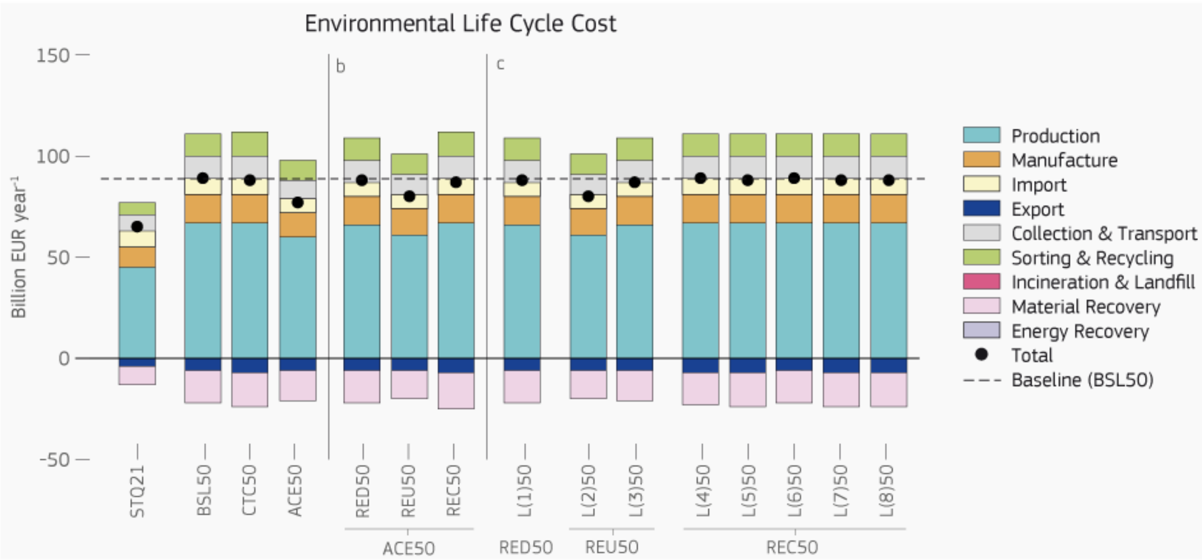
4.5.4 Life Cycle Costs

The Environmental Life Cycle Costs (eLCC) results expressed in billion EUR for the entire system per year are displayed in Figure 17. In the CTC50 scenario, a reduction of 1% in costs (EUR 88 billion) relative to the BSL50 scenario is estimated because of reduced demand for primary aluminium thanks to increased recycling. The greatest reduction in costs is observed for the ACE50 scenario (-13% relative to BSL50, EUR 77 billion) as a consequence of reduced demand for virgin aluminium production, reduced imports, and an increase in the recycled content (Figure 17a).

The Reduce lever (i.e., L(1)50) incurs a cost reduction of 1% relative to the BSL50 scenario, indicating that optimisation of scrap production at fabrication and manufacturing would not result in high cost savings at production level. The Reuse levers incur a cost reduction of 10% relative to the BSL50 scenario, where the main contribution is related to the implementation of L(2)50 that, as opposed to L(3)50, targets all sectors of aluminium-containing finished products with a lifetime longer than 1 year (Figure 17b,c). The implementation of Reuse levers indicates that reducing the demand of virgin aluminium leads to significant cost reductions at production level. Finally, Recover levers incur a cost reduction of 2% relative to the BSL50 scenario, mainly related to increased revenues from recycling (Figure 17b,c). The levers showing the greatest cost reduction potential out of the Recover levers are L(7)50 (i.e. expansion of deposit return systems, -1%) and L(8)50 and L(5)50 (i.e., recovery from mixed waste, 0.7%, and improved waste sorting and scrap quality, 0.7%, respectively). As for the difference in the net eLCC of the STQ21 and the BSL50, an increase of 38% is calculated in the Baseline scenario mainly due to an increase in costs for production of ingots and semis related to the expected increase in demand.

The results obtained for the Full Environmental Life Cycle Costs (feLCC, Figure 18) follow the trends observed for eLCC and Climate Change. Indeed, the CTC50 scenario contributes with a 2% (EUR 107 billion) reduction in feLCC compared to the BSL50 scenario (EUR 109 billion), while in the ACE50 scenario higher reductions are achieved (13% relative to BSL50, EUR 94 billion per entire system per year). Specifically, external costs contribute between EUR 17 and 31 billion to the total feLCC across the scenarios investigated (corresponding to a share of around 18-33% of the total feLCC). Amongst the clusters (Figure 18b), the Reuse lever reduce the total feLCC by 10% (from EUR 109 billion to EUR 98 billion), the Recover levers reduce it by 3% (from EUR 109 billion to EUR 106 billion), and the Reduce levers reduce it by 1% (from EUR 109 billion to EUR 108 billion) relative to BSL50. Reductions in costs are observed due to reduction in demand and related virgin production costs, reduction in imports, increases in recycled content, and monetised environmental savings from material recycling.

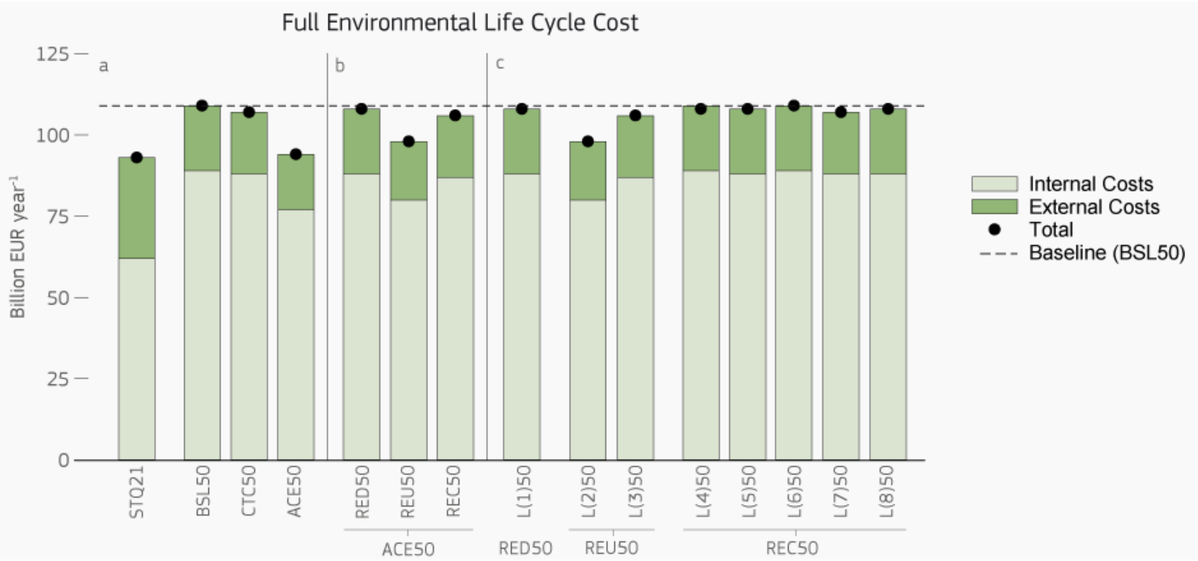
Figure 17. Results obtained for Environmental Life Cycle Cost expressed as billion EUR per entire system per year



Note: a) full-fledged scenarios (STQ21, BSL50, CTC50, ACE50); b) cluster of levers scenarios (RED50, REU50, REC50); c) one-at-a-time levers scenarios

Source: JRC elaboration

Figure 18. Results obtained for Full Environmental Life Cycle Cost expressed as billion EUR per entire system per year



Note: a) full-fledged scenarios (STQ21, BSL50, CTC50, ACE50); b) cluster of levers scenarios (RED50, REU50, REC50); c) one-at-a-time levers scenarios

Source: JRC elaboration

4.5.5 Sensitivity analysis I: testing energy mix assumptions

The Climate Change results expressed as Mt CO_2-eq. for the entire system per year are displayed in Figure 19 to analyse the impact of changing the energy mix. In this sensitivity analysis, the total results obtained using the energy mix based on the GECO NDC-LTS scenario are compared against those employing the GECO Reference scenario.

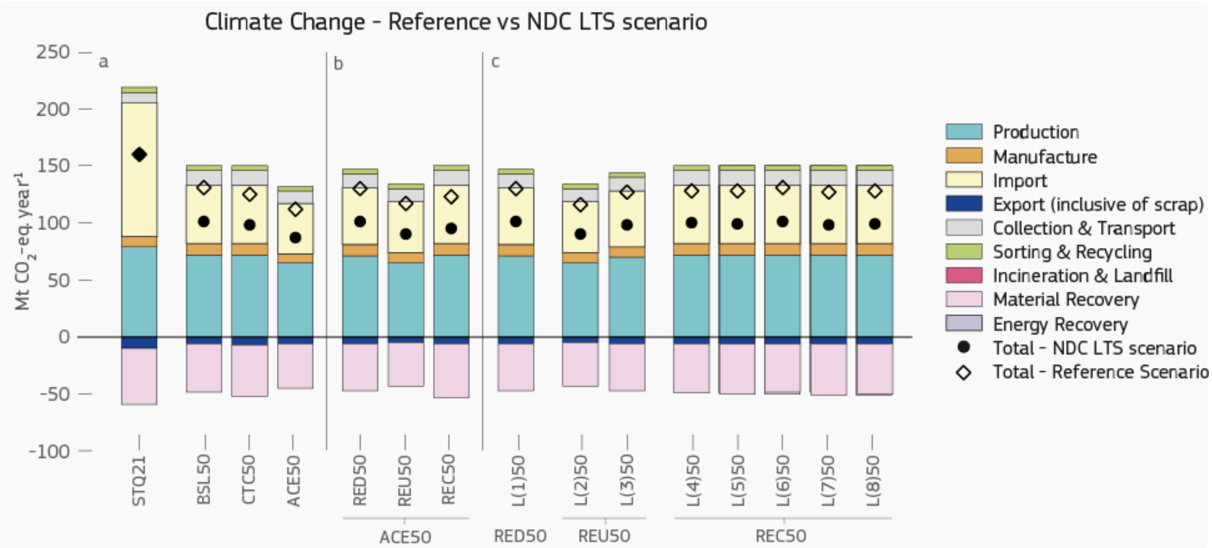
As expected, the total impacts when assuming the evolution of the energy mixes according to the GECO Reference scenario are higher than the NDC-LTS ones. Clearly, no difference is observed for the STQ21 scenario in the NDC-LTS (henceforth, the default case) and the Reference scenario (160 Mt CO_2-eq. for the entire system per year, Figure 19a), as there are no difference in the share of CCS technologies implemented and decarbonisation efforts at EU and non-European level.

The increase in emissions in the BSL50 scenario under the GECO Reference scenario energy mixes is mainly due to higher emissions in the production of ingots and semi-finished products, but also in the manufacturing of finished products, sorting and recycling, and impacts related to imports. Although the substitution of virgin aluminium is more emission-intensive, the savings related to it are not sufficient to counterbalance the rise in emissions related to the less green energy mix. This is especially relevant in the case of imports from non-European countries where the electricity mix has higher CO_2 emissions per kWh under the GECO Reference scenario compared to the NDC-LTS, applied as default in the analysis (i.e., 0.41 kg CO_2-eq kWh^{-1} and 0.09 kg CO_2-eq kWh^{-1}, respectively).

The impact reduction potential of each lever and of each cluster relative to the BSL50 scenario is similar in relative terms when comparing the results obtained using the GECO Reference scenario and the GECO NDC-LTS (applied as default in the analysis). Specifically, under the GECO Reference scenario, the CTC50 scenario results in a decrease of 4% compared to the BSL50 one (decreasing from 131 to 125 Mt CO_2-eq.; Figure 19a), while in the ACE50 it decreases by 14% (from 131 to

112 Mt CO_2-eq.; Figure 19a). Focusing on the clusters, the cluster Reduce incurs a decrease of 1% compared to the BSL50 one (from 131 to 130 Mt CO_2-eq.; Figure 19b), the Reuse one of 11% (from 131 to 117 Mt CO_2-eq.; Figure 19a), and the Recover one of 6% (from 131 to 123 Mt CO_2-eq.; Figure 19a). Nevertheless, in absolute terms the impact of the BSL50 scenario is 30% higher under the GECO Reference scenario relative to the NDC-LTS (applied as default in the analysis), the CTC50 28% higher, and the ACE50 29% higher. This indicates the crucial importance of decarbonising the energy system.

Figure 19. Comparison of the impacts obtained for Climate Change (expressed as Mt CO_2-eq. for the entire system per year) when applying the GECO NDC-LTS and Reference scenarios



Note: a) full-fledged scenarios (STQ21, BSL50, CTC50, ACE50); b) cluster of levers scenarios (RED50, REU50, REC50); c) one-at-a-time levers scenarios

Source: JRC elaboration

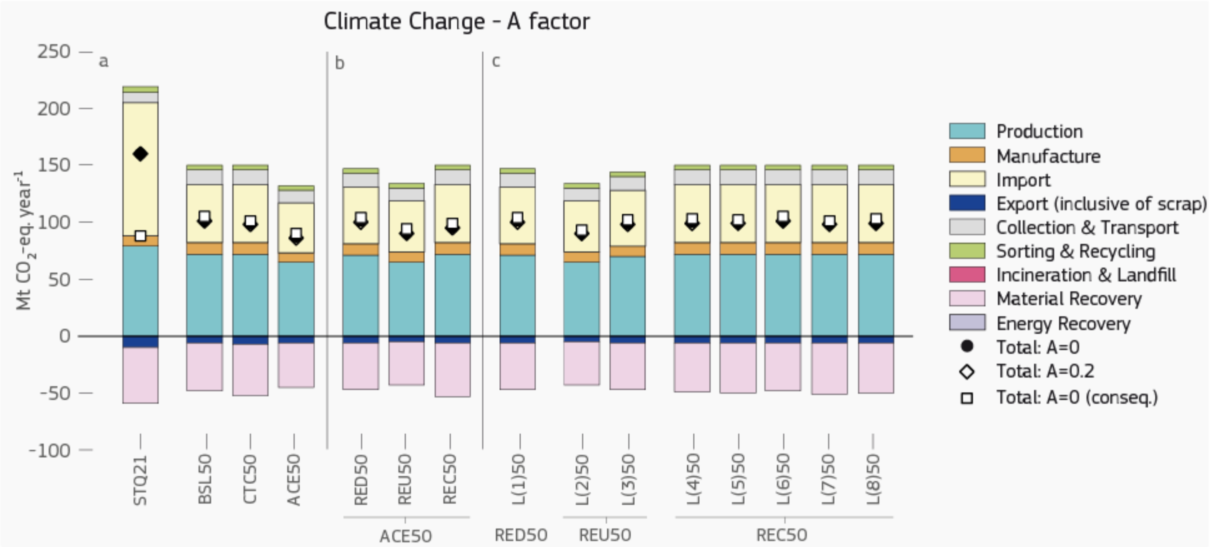
4.5.6 Sensitivity analysis II: testing A factor and market suppliers assumptions

The Climate Change results expressed as Mt CO_2-eq. for the entire system per year are displayed in Figure 20 to analyse the impact of changing i) the A factor, and ii) the market suppliers. As explained in Section 4.1.4.2, the function of the A factor in the CFF is to allocate burdens and savings of recycling between production and end-of-life stages of a product's life. The comparison herein made is between the net results obtained when applying A=0 and the ones obtained under A=0.2, which is the value recommended for aluminium in European Commission (2022). Further, the effect in the net result of applying marginal market suppliers (that affects the share of European vs non-European ingots) and marginal energy mixes, both for electricity and heat based on the GECO NDC-LTS scenario, are tested. The marginal market suppliers are calculated based on the shares provided by the ecoinvent dataset for 'market' processes of virgin ingot production; specifically, based on the consequential (market) ecoinvent dataset 52% of the supply comes from European production. Notice that in the default calculation, a share of 60-73% (depending on the scenario and lever) from European aluminium production is assumed based on JRC elaborations of the MFA data.

Total impacts under A=0 and A=0.2 are mostly consistent, with minor variations due to the different allocation of the impacts between production and end-of-life stages. The relative change between the BSL50 and the CTC50 and ACE50 is preserved, as well as the relative changes calculate at the level of cluster and individual levers (Figure 20).

Total impacts under A=0, and A=0 and market suppliers highlight a 4% difference with higher absolute emissions in the latter case. Indeed, as previously mentioned, the share of ingots supplied by non-European countries is higher under this configuration, and non-European countries have energy mixes with higher CO_2-eq. intensities per kWh than the European ones. Further, the savings estimated for material substitution under A=0 and market suppliers are higher (due to larger substitution of imports); yet, these are not sufficiently high to compensate for the higher impacts related to imported goods. Nevertheless, when observing the relative changes between the BSL50 and the CTC50, ACE50, clusters and one-at-a-time levers, the same percentage difference as in the default case (i.e. A=0) are calculated. Notwithstanding such changes in magnitude of some of the results, the overall conclusions and outcome remain the same.

Figure 20. Comparison of the impacts obtained for Climate Change (expressed as Mt CO_2-eq. for the entire system per year) when applying A=0 (default), A=0.2, and A=0 considering marginal market suppliers



Note: a) full-fledged scenarios (STQ21, BSL50, CTC50, ACE50); b) cluster of levers scenarios (RED50, REU50, REC50); c) one-at-a-time levers scenarios

Source: JRC elaboration

4.5.7 Epistemic uncertainty in LCA and LCC

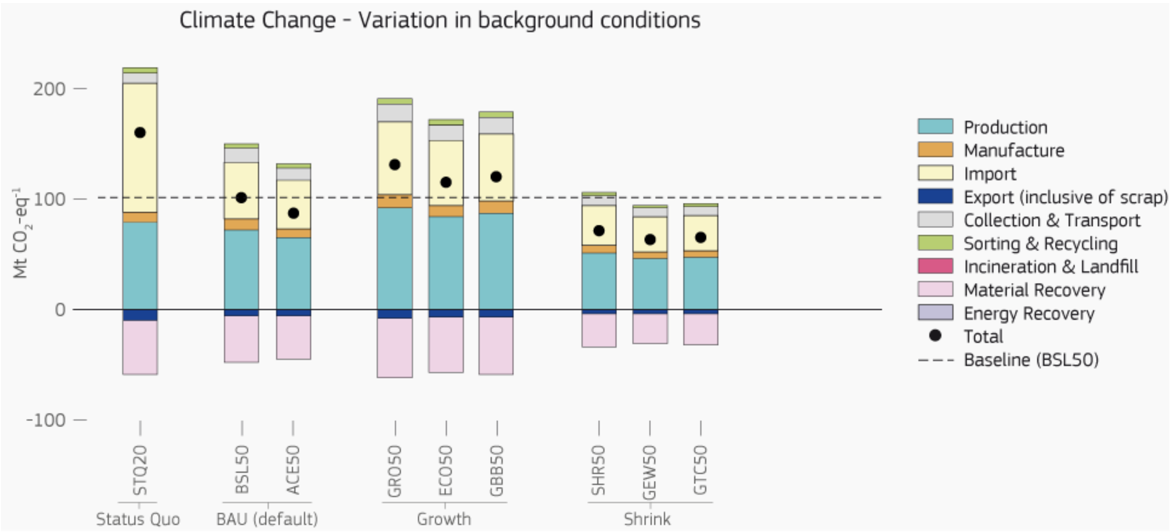
The Climate Change impacts, expressed as Mt CO_2-eq. for the entire system per year, under varying background conditions are displayed in Figure 21. Two new baselines are calculated, i.e. a growth-oriented (GRO50 in Figure 21) and a shrink-oriented one (SHR50 in Figure 21). The levers L(1)50-to-L(8)50 are implemented under these alternative baselines and different effectiveness in the implementation of the levers. Indeed, in the Business-as-Usual (BAU (default) in Figure 21) the effectiveness of the levers is assumed at 100%, meaning that the full potential of the lever is considered. However, in the other four scenarios (Eco-States, Glocal Eco-World, Green Business Boom, and Greening through Crisis) different effectiveness potentials were assumed based on the results of the sense-making session (Section 4.4.5). For the four scenarios, the impact of implementing the levers at once (i.e., the ACE50 scenario) was calculated according to the relative baseline and effectiveness potential of the levers.

The results show that under a growing economy (i.e., growing larger than what assumed in the BSL50 scenario), the impact on Climate Change is expectably higher than in BSL50 (101 Mt CO_2-eq. in BSL50 and 131 Mt CO_2-eq. in GRO50, Figure 21). Upon the implementation of the ACE50 scenario under the Eco-States and Green Business Boom scenarios, such impacts are mitigated. Further, the mitigation of Climate Change impacts compared to the GRO50 is more pronounced under the Ecostate scenario (ECO50 in Figure 21), which reflects the perspective of the experts that consider the levers to be more effective under strong national governments rather than a business-driven society.

Under a shrinking economy (SHR50 in Figure 21), the impact on Climate Change is expectably lower than in the BSL50 scenario (101 Mt CO_2-eq. in BSL50 and 71 Mt CO_2-eq. in SHR50). Upon the implementation of the ACE50 scenario under the Glocal Eco-World and the Greening through Crisis scenarios, such impacts are mitigated. Further, the mitigation of Climate Change impacts compared to the SHR50 is more pronounced under the Glocal Eco-World (GEW50 in Figure 21), which reflects the perspective of the experts that consider the levers to be more effective under a society with strong local actors rather than a resource-scarce one.

Considering the possible variations in the background conditions until 2050 and the different effectiveness potential of the levers, it can be argued that the implementation of the ACE50 scenario can incur GHG emission savings ranging between 18% and 61% relative to the STQ21 scenario that is herein taken as benchmark for comparison.

Figure 21. Comparison of the impact of the scenarios assessed on the Climate Change category when applying different background conditions than Business-as-Usual (BAU) expressed as Mt CO_2-eq. for the entire system per year



Note: The following acronyms are used: ACE50 'Ambitious Circular Economy scenario 2050', BSL50 'Baseline 2050', ECO50 'Eco-States 2050', GBB50 'Green Business Boom 2050', GEW50 'Glocal Eco-World 2050', GRO50 'Growth-oriented baseline 2050', GTC50 'Greening through Crisis 2050', SHR50 'Shrink-oriented baseline 2050', STQ21 'Status Quo 2021'

Source: JRC elaboration

5 Input-Output Analysis

This section describes the model and assumptions used to assess the impacts of Circular Economy levers at the macro-level. This top-down assessment is enabled using Environmentally Extended Multi-Regional Input Output (EEMRIO) data. EEMRIO data is well equipped to support the analysis of the interaction and interdependencies between sectors within and outside regions as well as the relationship between intermediate consumption and final consumption of goods and services globally. EEMRIO completeness of sectoral and regional representation, complements the bottom-up assessment described in the previous chapters typically characterised by high granularity of processes and their respective material flows and associated impacts (Murray & Lenzen, 2013).

The following subsections describes the methodology employed to analyse the scenarios using EEMRIO data and the model for Multi-Regional Input-Output Analysis (MRIOA). Emphasis is also given to the integration of the bottom-up LCI to increase the process detail of the industry of interest, the creation of the respective extension tables as well as the use of the GECO 2022 data for the prospective EEMRIO data to the year 2050. Thereafter, the results of the analysis are presented in Section 5.2. A more detailed description of the model used here can be found in Wagner et al. (2025).

5.1 Methodology

"MRIOA provides a useful toolbox for assessing social, environmental, and economy-wide impacts of goods and services" of the transition towards a more circular economy (Wiebe et al., 2019), avoiding a cut-off on (economic) flows (Lenzen, 2008). In this work, we refer to the MRIOA model as the use of the demand-driven quantity model of Leontief using MRIO data (i.e. FIGAROe3). The fundamental assumption of the demand-driven Leontief model is that changes in consumption of goods and services result in linear changes of demand of production (Leontief, 1941).

While several IO models exist, the FIGAROe3 model was chosen for this work because of its comprehensive inter-country Supply and Use, and Input-Output database for 2015, featuring labour and environmental extensions that are in line with official statistics. The database encompasses data for 213 products and 176 industries across 45 geographical areas (country disaggregation is equal to FIGARO), as well as one aggregated Rest of the World region. The selection criteria as well as a comparison to other IO models are presented in Annex 5, while a more detailed description of FIGARO3 model's structure, i.e. the monetary Supply and Use Tables, is presented in Annex 6.

The MRIO model uses environmentally extended industry-by-industry tables, from which the Leontief inverse is calculated. This model assumes consistent input structure for products and industries. To each unit of output, a respective (environmental or social) impact coefficient is associated, enabling the assessment of sustainability impacts and resource use. The scope includes both indirect and direct impacts/resource use, resulting in the total (or global) impacts of the EU27 final demand. The indirect use covers upstream production-related impacts, while the direct use entails impact directly generated by final demand (mostly by households, e.g. emissions at the chimney or at the exhaust). The detailed formulas for these calculations are available in Annex 7.

Through this model and data, we can incorporate explicit exogenous supply (i.e., affecting production) and demand (i.e., affecting consumption) changes, and asses direct and indirect effects of what-if scenarios. Exogenous changes can be applied either in the Supply and Use Tables (e.g., Aguilar-Hernandez et al., 2018; Wiebe et al., 2018, 2019) or directly in the Input-Output tables (e.g., Donati et al., 2020). It is preferred to model exogenous changes in the Supply and Use Tables as distinction between multiple production outputs of a sector are retained. An IO table is then generated from these counterfactual Supply and Use Tables using Model B or Model D transformation methods to allow for IOA later on (Eurostat, 2008).

Modelling CE interventions in an EEMRIO must be understood as a comparison between the status quo (results of the baseline model) and results from modelled what-if scenarios (Aguilar-Hernandez et al., 2018). The net effect of circularity interventions can then be quantified by calculating the difference between baseline results and the results from the scenarios developed in this study (i.e., BSL50 and the ACE50).

5.1.1 Overcoming the limitations of EEMRIO for Circular Economy modelling

In this subsection, we present the most important limitations of the EEMRIO and how they are overcome in the context of this study.

- To overcome the problem of high aggregation of sector and product groups in IO tables it is possible to disaggregate products and sectors in the Supply and Use Tables and/or IO tables in more detailed categories. In this study, LCI data and MFA[23] is used to refine such disaggregation.
- Due to the fixed technical coefficients in IO models, caution is required when modelling circularity scenarios. The static and linear nature of the EEMRIO model prevents the inclusion of dynamic responses of an economy such as price changes or rebound effects (Wiebe et al., 2018). It requires that any induced or rebound effects need to be exogenously included in the modelling by explicitly modelling. Induced effects refer to secondary economic effects resulting from changes in spending or investments patterns caused by an initial change in economic activity[24]. As such, circular economy scenarios in EEMRIO do not capture the volume effects on prices as well as price effect on the use of certain products (Aguilar-Hernandez et al., 2018). While this is not addressed in this chapter, Section 6 concerning the application of the FIDELIO model is used to complement the limitation of this model.
- As we model scenarios in the future, it is expected that the energy system will change as well following the expected or desired trends. Such information is not present in the chosen database, therefore, the Global Energy and Climate Outlook (GECO) is used to create the prospective EEMRIO tables described in Section 5.1.4. This ensure that the assessment of prospective impacts is aligned with the previous modelling in LCA and LCC described in Section 4. GECO was chosen due to the comprehensiveness of the provided information that exceeds GDP, population, and the composition of the energy sector by providing a

[23] Notice that while the MFA data refers to 'Europe', the IO analysis has been performed considering EU27. The MFA data has been applied to the flows relative to the 27 MSs although the masses refer to an enlarged geographical scope. The MFA data used was considered as the best available and suitable for the types of analyses performed in this study. Nevertheless, future efforts should be placed in replicating the MFA considering only the 27 MSs.

[24] This includes shifts in employment levels as well as changes in firms operating surpluses. Referencing the circular flow of income, these effects can have a multiplier effect on the overall economy, amplifying the initial change in economic activity. Circular economy rebound (Zink & Geyer, 2017) refers to unintended environmental impacts that occur because of circular economy interventions.

complete prospective input-output structure for a long-term baseline scenario based on the computable general equilibrium (CGE) model GEM-E3.

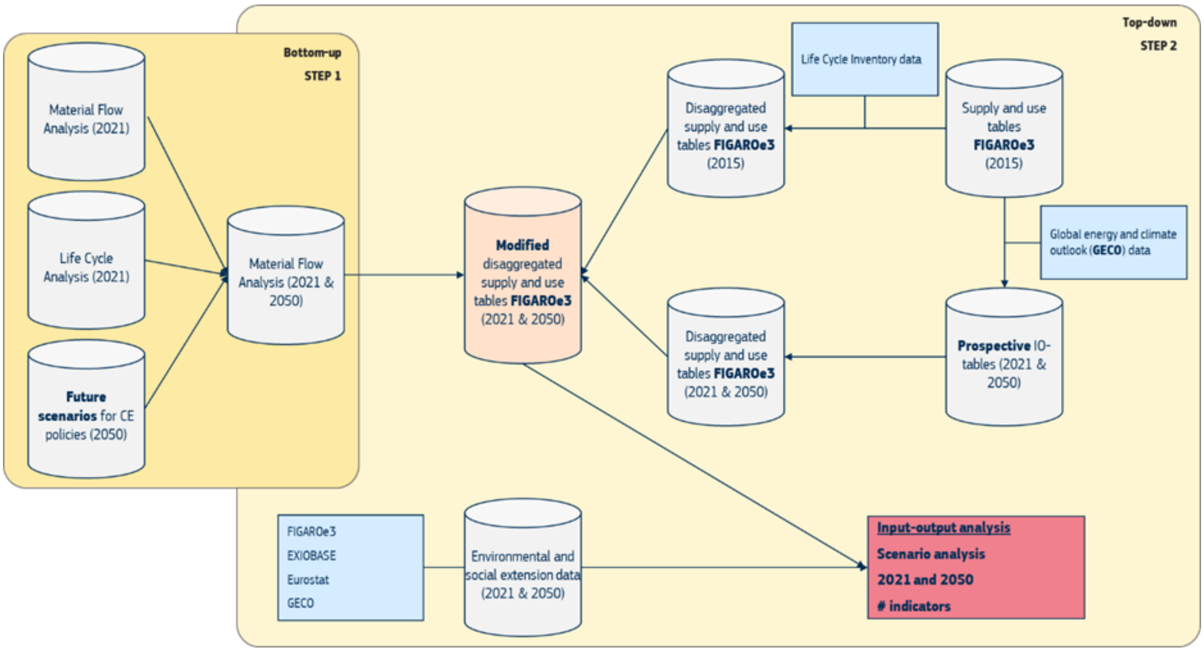
- Additionally, the representation of waste flows in EEMRIO is typically in monetary terms and treated as waste treatment services, which implies that the very physical dimension of waste is not effectively captured and subject to distortions based on the price of those services (Aguilar-Hernandez et al., 2018). This analysis overcomes this limitation, by including a direct link between the MFA (Section 3) and the EEMRIOA. The mass balance of the industry under study is then used to understand the effects of CE across the production network.

So, to overcome the aggregation error of IO tables, a disaggregation of products and sectors in supply and use tables and/or IO tables in more detailed categories provides a solution to overcome the aggregation error. Caution is required when assigning circularity in the future. Due to the fixing of technical coefficients of a circular economy scenario, the IO analysis does not capture the volume effects on prices as well as price effect on the use of certain products (Aguilar-Hernandez et al., 2018). The assessment of prospective impacts relies on exogenous scenarios, where the choice was aligned with the previous modelling in the LCA and LCC. Therefore, the Global Energy and Climate Outlook (GECO) was chosen due to the comprehensiveness of the provided information that exceeds GDP, population, and the composition of the energy sector by providing a complete prospective input-output structure for a long-term baseline scenario based on the computable general equilibrium (CGE) model GEM-E3.

5.1.2 Bottom-up MFA and LCI integration

As indicated in the previous section, the GECO scenarios, LCA and MFA data is used to 1) project energy mix in the future, 2) increase process details of the sector, 3) and model CE levers in Supply and Use Tables. This workflow is visualised in Figure 22 where it is shown the direct use of the material flows and stocks as determined in the MFA. In addition, the details from the LCI-datasets of different processes are used to disaggregate the Supply and Use Tables to improve the granularity and quality of the Input-Output assessment. The assessment is supported by Excel-files and an implementation in R-studio. Further details of the methodology are provided in Annex 8.

Figure 22. Workflow from Material Flow Analysis, Life Cycle Inventory, to (prospective) Input-Output Analysis



Source: JRC elaboration

Based on the results from the MFA, a proposal for sector and product disaggregation is made, which in this case concerns ‘Aluminium and aluminium products’ (CPA_C24_E) and ‘Secondary aluminium for treatment, re-processing of secondary aluminium into new aluminium’ (CPA_C24_F). Afterwards, the MFA-results are incorporated into the Supply and Use Tables. Further, the sectors are disaggregated according to the LCIs provided to include elementary exchanges adding resolution and quality to the sector disaggregated. Subsequently, the RAS balanced prospective tables based on GECO-data are generated. At this point, the disaggregated supply and use table is generated to increase the granularity of the model specifically for the aluminium sector’s sectors/products. Next, the model is regionally disaggregated again to return to the initial geographical detail of FIGAROe3. Performing the IO analysis starts by creating the necessary (disaggregated) extension tables and by deriving the industry-by-industry IO tables.

5.1.3 Extension tables

Besides the monetary values, the IO analysis also provides insight into environmental and socio-economic indicators. It does so through extension tables, which are based on existing extensions of FIGAROe3 and from external sources such as official emission statistics and EXIOBASE, in the case of environmental extensions, and other relevant extensions, such as financial costs, employment and issues of resource dependency.

5.1.3.1 Environmental extensions

As in the LCA (Section 4), the Environmental Footprint (EF) method is used, which includes 16 impact categories. Yet, Ionising Radiation and Ozone Depletion are excluded because emissions related to these impact categories are missing. For the disaggregated sectors, the LCI data not only informs on the elementary exchanges to be included in the production recipe (Section 5.1.2), but also on process specific emissions and combustion emissions that are compounded with the upstream and downstream emissions. The emission coefficients are based on Beylot et al. (2019)

who make use of 78 elementary flows to estimate 14 out of the 16 environmental impact categories. Our project partners VITO created a matrix of characterisation factors in the ETC/CE project of the Consumption Footprint indicator commissioned by the European Environment Agency. This envisioned translating the 528 unique environmental extension lines from EXIOBASE v3.8.2 into 14 out of the 16 impact categories of the EF-method requiring a conversion through characterisation factors. The result can also be normalised and weighted into a single factor, as presented in Annex 9. The FIGAROe3 extension table includes emission data by industry on carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases) for 2015 in Gg. The extension data shows the total volume of emissions (in Gg) per sector per geographical area and per household per geographical area. A wide coverage of environmental extensions is available from the EXIOBASE (currently v3.8.2) dataset. The process of matching the EXIOBASE extension with the EF categorisations is described in Annex 9. For impacts like toxicity, however, EXIOBASE includes only a very limited selection of emissions. No information, and, thus, no extension lines, is available in EXIOBASE to estimate the impact categories Ozone Depletion and Ionising Radiation. Another shortcoming of the EXIOBASE is that the end years of the real data in the extension tables vary and are therefore not completely up to date[25]. Therefore, the change in emissions is only based on output volumes and not actual emission data. Some of these data are complemented by the Eurostat Air Emissions Accounts (AEA) by NACE Rev. 2 activity, which include air pollutants and greenhouse gases per sector per geographical area from 1995 until 2022. Note that the dataset is incomplete due to missing data and unavailable data for non-EU countries. For this reason, only the air pollutants for which the AEA data can be supplemented with the EXIOBASE data are retained (total CO_2, CH_4, N_2O, HFC, PFC, NH_3, NO_X, CO, PM2.5, PM10, and NMVOC).

5.1.3.2 Socio-economic extensions

The extension tables of FIGAROe3 show the generation of value added per sector, disaggregated into 9 categories, which comprise taxes, compensations of employees per skill level and different types of operating surpluses. Employment is based on education or occupation, both disaggregated into male and female as well as low-, medium- and high-skilled. Finally, the concept of EU's strategic autonomy is operationalised into the domestic extraction and use of strategic metal ores, as per the CRM 2023 list. Thus, the focus for strategic autonomy is on the demand for **bauxite/aluminium, copper, nickel, PGM's and other non**-ferrous metals. Nevertheless, in this analysis we only report results for bauxite under the different scenarios assessed.

5.1.4 Prospective Multi-Regional Input-Output tables

For the policies considered for the development of the scenarios in the GECO (2023-edition), the reader is referred to the original publication. The scenarios include energy-related policies in the sectors of energy, power, and transport (incl. aviation and maritime), and include GHG-related policies focusing as well on the ETS and non-ETS sectors for certain emission reduction targets.

Economic Multi-Regional Input-Output tables are available, but only for the GECO Reference scenario. The GECO Reference scenario (Baseline GECO 2022) represents a projection of the world

[25] In the version applied in this study, the end years of the extension tables are: 2015 for energy, 2019 all greenhouse gases (nonfuel, non-carbon dioxide are now casted from 2018), 2013 for material use, and 2011 for most others, land, and water.

economy with corresponding energy demand and GHG emissions. The IO tables are supplemented by energy balances (in physical units) and GHG emissions projections. However, the database as well includes main economic indicators (e.g., value added), detailed energy, greenhouse gas and air pollutant emissions balances for several scenarios of the GECO 2023 report (Reference, NDC-LTS and 1.5°C) for 39 world regions and the EU27. A description of how the NDC-LTS scenario was included in the disaggregated Supply and Use Tables is provided in Annex 10.

5.2 Results

5.2.1 Climate Change mitigation

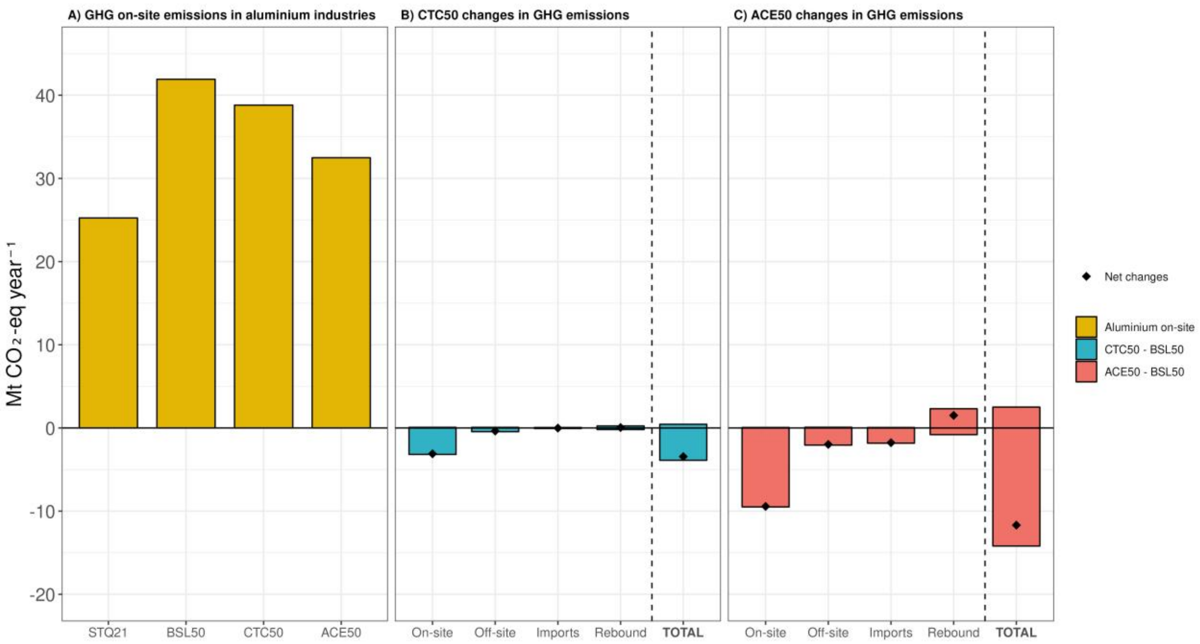
Figure 23 presents the Climate Change impacts of four scenarios: Status Quo (STQ21), Baseline (BSL50), Compliance with selected Targets on Circular Economy (CTC50), and Ambitious Circular Economy scenario (ACE50), measured in million tonnes of CO_2 equivalent (Mt CO_2-eq.). The left-side chart (Figure 23A) shows the on-site emissions[26] in the aluminium industry for each scenario. In the STQ21 scenario, emissions total 25.2 Mt CO_2-eq., which increases by 16.7 Mt CO_2-eq. to 41.9 Mt CO_2-eq. in the BSL50 scenario due to projected increases in virgin material demand. Notice that technologies focused on decarbonising the aluminium production (e.g. smelters or inert anodes) are not modelled as the inclusion of such technologies mainly refers to actions focused on the decarbonisation of the sector rather than on strengthening circularity in the sector. The implementation of selected circular economy targets in the CTC50 scenario leads to a reduction in on-site emissions of 3.1 Mt CO_2-eq. In contrast, the ACE50 scenario triples this reduction, resulting in a total reduction of 9.4 Mt CO_2-eq., which represents 23% of all on-site GHG emissions in BSL50 for the aluminium industries.

Figure 23 A only shows total GHG savings in on-site emissions for the aluminium industries. To provide insights on total GHG savings, that is, from a supply chain perspective (including e.g. emissions related to inputs used by EU industries versus emissions associated with EU imports of aluminium products, or other rebound effects), and regardless of where they occur from a geographic perspective (either in EU or in the Rest of the World). On the other hand, Figure 23 displays in panel B the difference in GHG emissions between the CTC50 and the BSL50 scenarios, and in panel C the difference in GHG emissions between the ACE50 and the BSL50 scenario, while showing the contribution in changes of GHG emissions for on-site emissions in EU, off-site emissions in EU, imports, and rebounds. Specifically, 'On-site' (Figure 23B-C) emissions refer to direct emissions occurring at aluminium industries in the EU to satisfy the EU and Rest of the World (RoW)'s final demand of goods and services; 'Off-site' (Figure 23B-C) refers to emissions from all other EU industries to satisfy the EU and RoW's demand, specifically, it represents upstream GHG emissions in the aluminium supply chain occurring in industries located in the EU and providing inputs to the EU aluminium industries; 'Imports' (Figure 23B-C) refers to emissions occurring in the RoW to satisfy the EU's demand; 'Rebound' (Figure 23B-C) GHG emissions refer to emissions occurring in the RoW, which are related to substitution effects of EU exported aluminium products that are being replaced by non-EU exporters for satisfying ROW demand (which remains constant across scenarios); and, 'TOTAL' (Figure 23B-C) refers to the sum of 'On-site', 'Off-site', 'Imports',

[26] On-site emissions include process and combustion emissions of the aluminium industries only.

and 'Rebound' GHG emissions. As shown in Figure 23B-C, burdens (values above the zero line) and savings (values below the zero line) may occur for 'On-site', 'Off-site', 'Imports', and 'Rebound' emissions; therefore, the 'Net change' is calculated for each contributor to the final result and for the 'TOTAL' itself. Figure 23B shows that the reductions in the CTC50 scenario compared to the BSL50 scenario are related almost entirely to 'On-site' emissions changes as a consequence to the increase in recovery of aluminium scrap. Figure 23C shows that the reductions in the ACE50 scenario compared to the BSL50 scenario are also primarily driven by the fall in 'On-site' emissions. This corresponds to approx. 81% of the 'TOTAL' emission savings (-11.7 Mt CO_2-eq.). As for the remaining 19%, 'Off-site' emissions contribute with an additional 2.0 Mt CO_2-eq. saving, which accounts for up to 17% of the 'TOTAL' due to the use of less carbon-intensive inputs in the supply chain. The remaining 2% reduction of the 'TOTAL' occurs in industries located in the RoW. Specifically, 'Rebound' emissions increase to 1.5 Mt CO_2-eq ('Net changes' in Figure 23C) due to increased production in other countries to replace EU exports of aluminium products (as RoW demand remains constant across scenarios). This basically offsets the GHG savings obtained from decreased imports to the EU economy ('Imports'; -1.8 Mt CO_2-eq., as 'Net changes' in Figure 23C).

Figure 23. On-site GHG emissions in aluminium industries and changes in total GHG emissions for the CTC50 and ACE50 scenarios relative to the BSL50 scenario

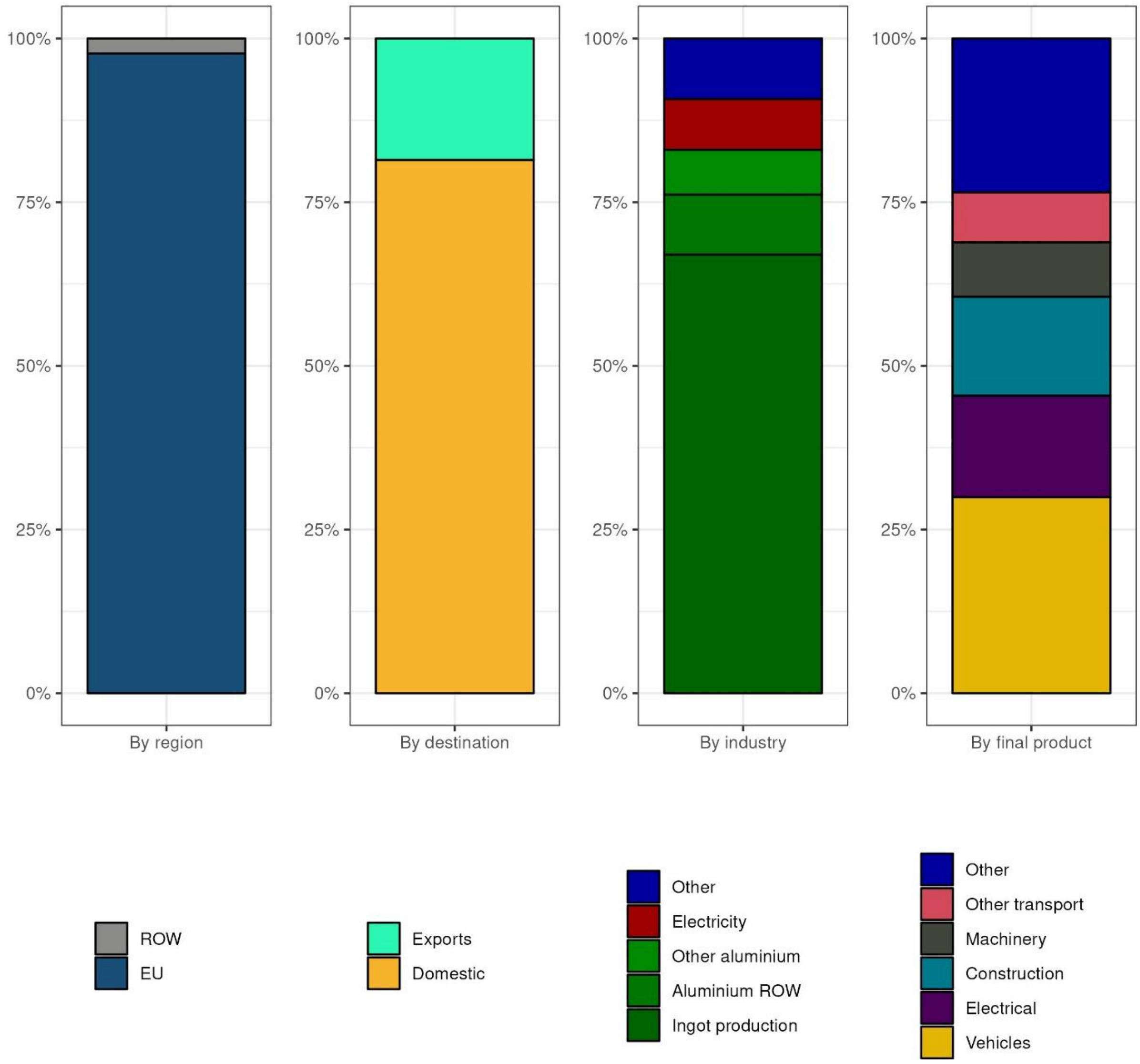


Note: Panel A) displays the on-site GHG emissions of the EU aluminium industry for the Status Quo (STQ21), Baseline (BSL50), Compliance with selected Targets on Circular Economy (CTC50) and Ambitious Circular Economy (ACE50) scenarios; Panel B) displays the changes in GHG emissions between the CTC50 and BSL50 scenarios (CTC50-BSL50); Panel C) displays the changes in GHG emissions between the ACE50 and BSL50 scenarios (ACE50-BSL50). 'On-site' GHG emissions refer to direct emissions occurring at aluminium industries in the EU to satisfy the EU and Rest of the World (RoW)'s demand; 'Off-site' GHG emissions refer to emissions from all other EU industries to satisfy the EU and RoW's demand; 'Imports' GHG emissions refer to emissions occurring in the RoW to satisfy the EU's demand; 'Rebound' GHG emissions refer to emissions occurring in the RoW, which are related to substitution effects of EU exported aluminium products that are being replaced by non-EU exporters for satisfying ROW demand (which remains constant across scenarios); 'TOTAL' GHG emissions refers to the sum of 'On-site', 'Off-site', 'Imports', and 'Rebound' GHG emissions. Notice that the contribution of 'On-site', 'Off-site', 'Imports', and 'Rebound' GHG emissions can be a burden (above the zero line) or a saving (below the zero line) for Climate Change. The net change is displayed with a black solid diamond in the figure. All values are expressed as Mt CO_2-eq year^{-1}

Source: JRC elaboration

Figure 24 further decomposes the changes between the BSL50 and the ACE50 scenarios to provide insight into the regions, destinations, industries, and final goods (or services) driving the net reduction of 11.7 Mt CO_2-eq. between the two scenarios. As expected from Figure 23, mostly all net GHG savings occur in the EU. The data also reveals that most of the impact (81%, 'Domestic' in Figure 24) is driven by final use of products in the EU, whereas the remaining 19% relates to EU exports to the RoW ('Exports' in Figure 24). Furthermore, when focusing on the aluminium industry, the main activity contributing to the savings is 'Ingot production', which accounts for 67% of the net reduction, followed by RoW production of aluminium products (approx. 10%, 'Aluminium ROW' in Figure 24), and electricity generation with an 8% share ('Electricity' in Figure 24). In total, the EU aluminium industries (herein intended as the sum of 'Ingot production' in the EU and 'Other aluminium' industries in the EU) explain 74% of the savings when looking at the industry decomposition. Finally, when focusing on the decomposition of the net GHG savings between the ACE50 and the BSL50 scenario, it is possible to identify what final products (or services) mainly contribute to it. The results displayed in Figure 24 show that the manufacture of motor vehicles, trailers, and semi-trailers ('Vehicles' in Figure 24) is the primary driver of the changes, accounting for 30% of the net savings. When considered together with the manufacture of other transport equipment ('Other transport' in Figure 24), they explain 38% of the net savings. The transport industry is followed by the manufacture of electrical machinery and apparatus n.e.c. ('Electrical' in Figure 24) and the construction industry ('Construction' in Figure 24) with 16% and 15%, respectively, and the manufacture of machinery and equipment n.e.c. ('Machinery' in Figure 24) with 8% only.

Figure 24. Decomposition of the changes between the ACE50 and the BSL50 scenarios relative to the net reductions in GHG emissions



Note: The decomposition of the changes refers to net GHG savings as percentage of origin (EU vs. RoW, or ROW in the figure), destination (domestic consumption vs. exports to the RoW), industry, and final good or service. Only contributions above 5% are shown individually

Source: JRC elaboration

5.2.2 Resource dependency

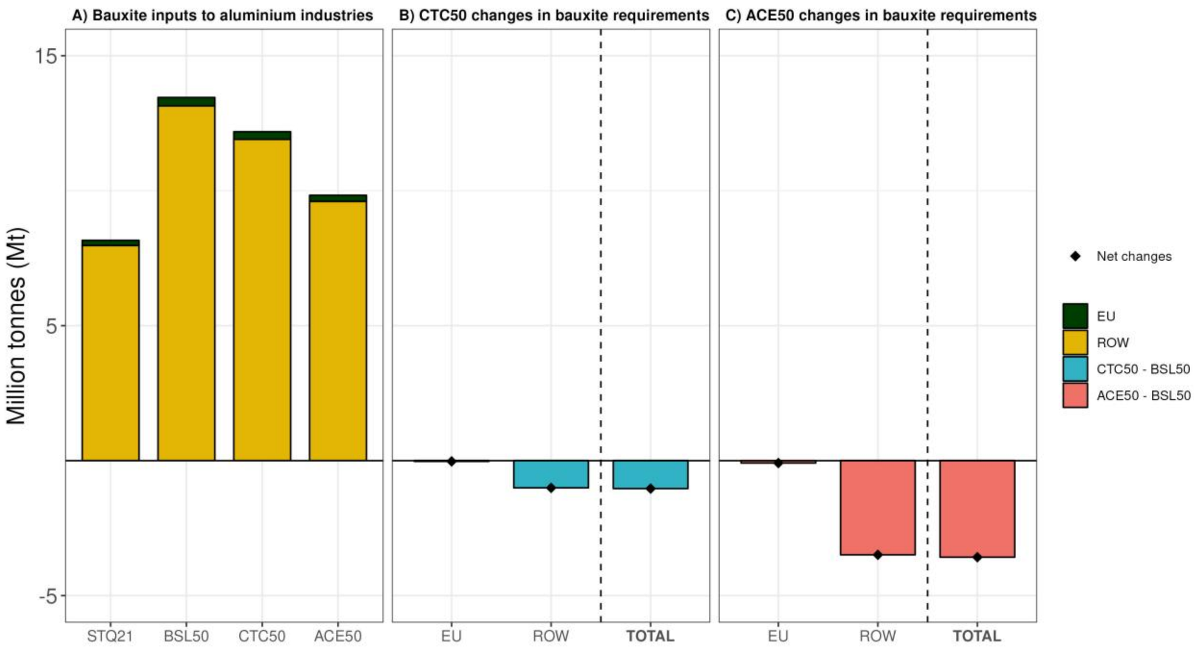
The EEIOA provides results on the amount of bauxite extracted in the different scenarios as well. As explained in Section 1.2, bauxite is needed to produce virgin aluminium, and this represents a scarce resource in EU that is mostly supplied by third countries. The impact category 'Resource dependency' can therefore provide valuable information on the changes in requirements for the aluminium industry (expressed as Mt), but also insights on whether the bauxite is EU- or RoW-sourced.

Figure 25A presents the bauxite direct inputs to aluminium industries in the EU in the STQ21, BSL50, CTC50, and ACE50 scenarios, measured as million tonnes (Mt). In the STQ21 scenario, bauxite input requirements to the EU aluminium industry total 8.2 Mt, which increase by 65% to

13.5 Mt in the BSL50 scenario consequently to increased demand for aluminium. The implementation of selected circular economy targets in the CTC50 scenario leads to a reduction in bauxite inputs of 1.3 Mt due to increased recycling and recirculation of resource. Further, the ACE50 scenario increases this reduction of bauxite inputs to the EU aluminium industry to 3.6 Mt, corresponding to a reduction of 27% compared to the BSL50 scenario. In all scenarios, EU extractions are negligible ('EU' in Figure 25A), with almost all bauxite supplied by the RoW ('ROW' in Figure 25A) .

Similarly to the analysis for Climate Change, Figure 25B-C shows total changes in bauxite requirements from a supply chain perspective, including both direct inputs and upstream bauxite extractions needed for inputs used by EU industries (e.g. imports of ingots, semis, etc.). This analysis compares the CTC50 scenario with the BSL50 scenario (Figure 25B), and the ACE50 scenario with the BSL50 scenario (Figure 25C). The total savings in the CTC50 and ACE50 scenarios relative to the baseline BSL50 scenario amount to 1.0 Mt and 3.6 Mt, respectively. These figures are similar to the on-site savings (Figure 25A), suggesting that, for the specific case of bauxite extractions, most of the savings are attributed to the direct imports of the mineral by EU aluminium industries. However, it is worth noting that, in this case and in contrast to the example of Climate Change, rebound effects due to the replacement of EU (reduced) demand were not considered. The focus here is solely on the EU's material dependency.

Figure 25. Bauxite inputs to aluminium industries and changes in bauxite requirements for the CTC50 and the ACE50 scenarios compared to the BSL50 scenario

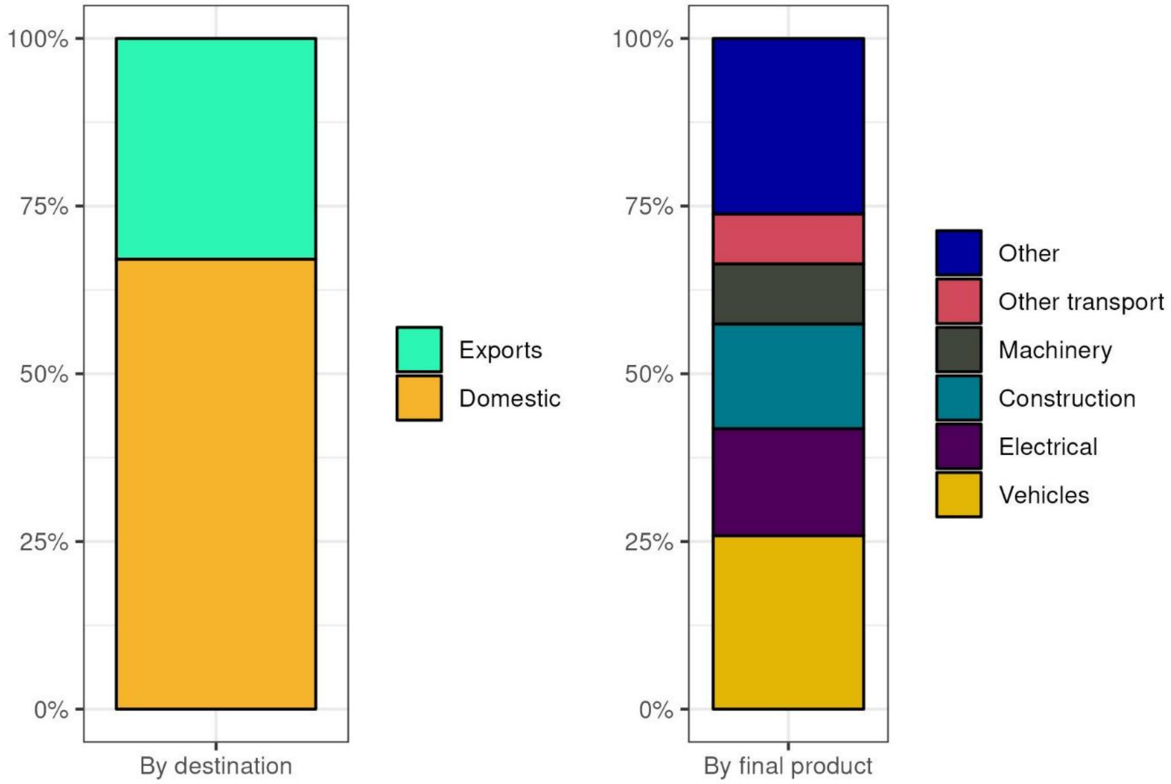


Note: Panel A) displays the bauxite inputs to aluminium industries in the EU in the Status Quo (STQ21), Baseline (BSL50), Compliance with selected Targets on Circular Economy (CTC50) and Ambitious Circular Economy (ACE50) scenarios; Panel B) displays the changes in bauxite requirements between the CTC50 and the BSL50 scenarios; Panel C) displays the changes in bauxite requirements between the ACE50 and the BSL50 scenarios. 'EU' refers to the extraction of bauxite within the EU, 'ROW' refers to the extraction of bauxite within the Rest of the World, 'TOTAL' refers to the sum of 'EU' and 'ROW'. Notice that the 'Net changes' are calculated as the sum of burdens (values above the zero line), and savings (values below the zero line). All values are expressed as Mt

Source: JRC elaboration

Figure 26 provides information on the decomposition of the total net change in bauxite requirements to the EU aluminium industry between the ACE50 and the BSL50 scenarios (i.e. 3.6 Mt) 'By destination' and 'By final product' (or service). The data 'By destination' shows that 67% of the total net reduction is attributed to decreased EU domestic consumption ('Domestic' in Figure 26), while 33% of the reduction is due to lower EU exports of aluminium products to the world ('Exports' in Figure 26). The data 'By final product' shows that manufacture of motor vehicles, trailers, and semi-trailers ('Vehicles' in Figure 26) is the primary driver of the change, accounting for 26% of the total net deduction. When considered together with the manufacture of other transport equipment ('Other transport' in Figure 26), they explain 33% of the net reduction. Similarly to the decomposition of the net savings obtained for Climate Change when comparing the ACE50 and the BSL50 scenarios (Figure 24), this is followed by the manufacture of electrical machinery and apparatus (n.e.c.) ('Electrical' in Figure 26) and the construction industry ('Construction' in Figure 26), each accounting for 16% of the bauxite resource savings.

Figure 26. Decomposition of the changes in bauxite requirements to the EU aluminium industry between the ACE50 and the BSL50 scenario



Note: decomposition of the changes in bauxite requirements by destination (domestic consumption, 'Domestic', vs. exports from the EU to the world, 'Exports'); decomposition of the changes in bauxite requirements by final product (or service)

Source: JRC elaboration

Finally, although the EEIOA model implemented was not specifically designed to assess the impact of energy demand resulting from CE policies, Table 4 provides a rough indication of the changes in purchases of selected energy products when comparing the ACE50 and BSL50 scenarios for the EU economy, while Table 5 focuses on changes in the energy inputs to the aluminium industry. The results suggest that circular economy policies have an impact on reducing energy dependencies, with the greatest impact observed on electricity and other fossil fuels, when focusing on the requirements of the sector in focus.

Table 4. Changes in selected products demand in ACE50 in comparison to BSL50 for the total EU economy

Selected product	Quantity reduced	Unit	% Relative to total EU demand
EU electricity production	-12 547	GWh	-1.1%
EU heat production	-7 875	TJ	-0.15%
Coal and lignite, extraction of peat	-19 720	TJ	-0.69%
Crude petroleum	-8 970	TJ	-0.08%

Natural gas	-48 964	TJ	-0.34%
Other fossil fuels	-412	TJ	-0.09%

Note: The relative reduction is calculated as the reduction of the ACE50 scenario with respect to the BSL50 scenario over the total EU demand in the BSL50 scenario

Source: JRC elaboration

Table 5. Changes in selected products demand in ACE50 in comparison to BSL50 for the aluminium industries

Selected product	Quantity reduced	Unit	% Relative to the aluminium industry demand
EU electricity production	-11 345	GWh	-22%
EU heat production	-7 724	TJ	-11%
Coal and lignite, extraction of peat	-15 916	TJ	-10%
Crude petroleum	-380	TJ	-6%
Natural gas	-4 173	TJ	-7%
Other fossil fuels	-162	TJ	-22%

Note: The relative reduction is calculated as the reduction of the ACE50 scenario with respect to the BSL50 scenario over the total demand in the aluminium industry in the BSL50 scenario

Source: JRC elaboration

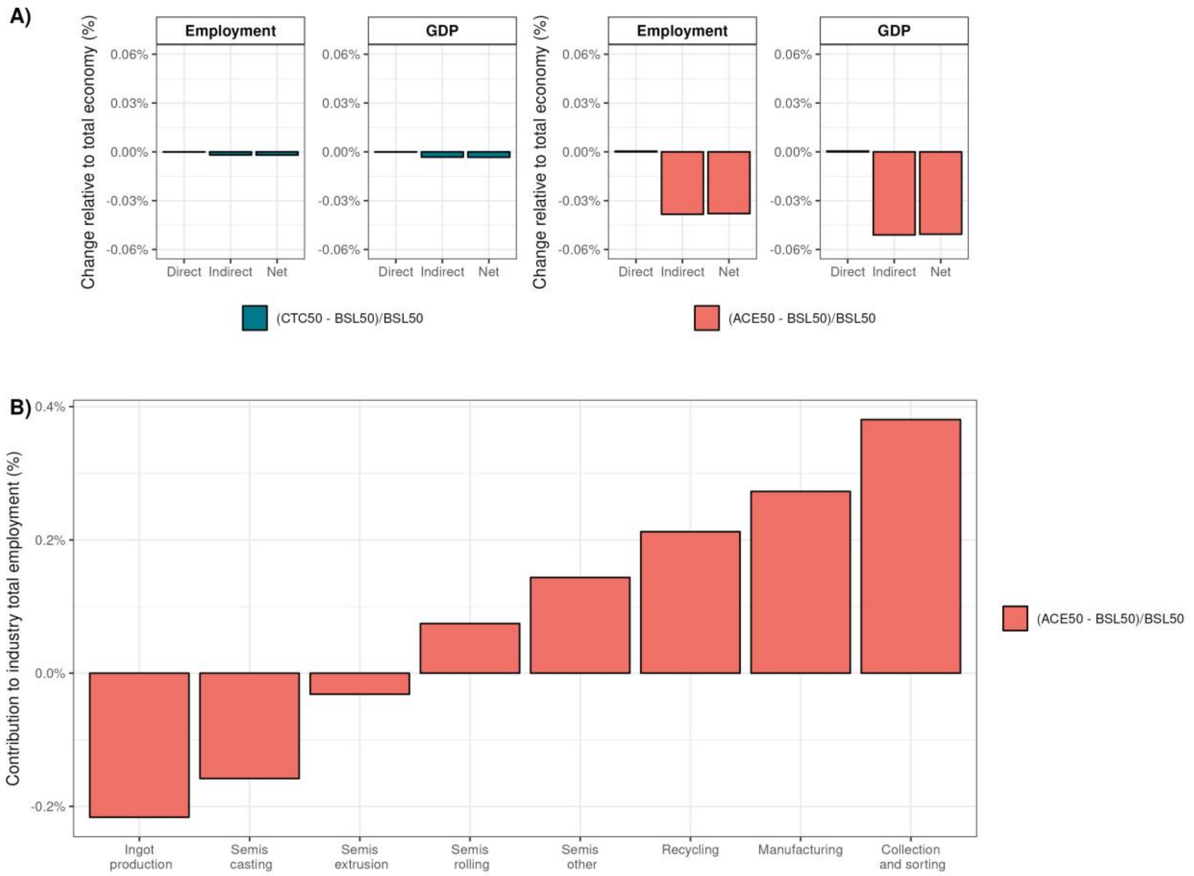
5.2.3 Employment and value added

Figure 27 provides information on the re-allocation of employment and GDP between the Compliance with selected Targets on Circular Economy and the Baseline scenarios (CTC50-BSL50) and between the Ambitious Circular Economy and the Baseline scenarios (ACE50-BSL50) in relative terms compared to the total economy. The results in Figure 27A indicate that at the macro-level, the CTC50 scenario has a negligible impact on both total employment and GDP ('Net' in both Employment and GDP). In contrast, the ACE50 scenario shows a decrease of approximately 0.04% in total employment and 0.05% in GDP ('Net' in both Employment and GDP).

In addition, the results suggest that there is no net impact on the aluminium industry, with the number of jobs remaining the same in both scenarios ('Direct' in Employment and GDP under the CTC50 and ACE50 scenarios when compared with the BSL50 scenario). It is worth noting that the EEIO modelling is a linear model that does not account for changes in labour productivity and instead assumes an equal number of jobs per unit of output for all aluminium industries. Moreover, the re-allocation of productive factors to, for example, service sectors is also not included. However, it does capture changes in the economy, as it adjusts to a new supply and demand balance, which has implications for supply chain configurations.

Figure 27B provides insight into why there is no net impact on the aluminium industry when focusing on Employment effects. It is evident that there is an offsetting effect between different industry activities. Some activities, such as ingot production and casting of semi-finished products, support fewer jobs, resulting in decreases of 0.22% and 0.16%, respectively, relative to the industry total. In contrast, others create more jobs, with the most notable cases being collection and sorting, manufacturing, and recycling, which see increases between 0.2% and nearly 0.4% in jobs.

Figure 27. Changes relative to the total economy in Employment and GDP, and changes in the employment of the aluminium industry in the ACE50 scenario compared to the BSL50 scenario



Note: Panel A) displays the changes in employment and gross domestic product (GDP) between the Compliance with selected Targets on Circular Economy and the Baseline scenarios (CTC50-BSL50) (left), and between the Ambitious Circular Economy and the Baseline scenarios (ACE50-BSL50) (right) for direct jobs and GDP ('Direct') contribution in the EU aluminium industry, indirect jobs and GDP ('Indirect') in other industries in the supply chain, and net changes ('Net') in comparison to the total economy; Panel B) displays the changes in of employment in the Ambitious Circular Economy relative to the Baseline scenarios (ACE50-BSL50)/BSL50 for specific aluminium industries in comparison to the total industry in 2050. All values are expressed as percentages [%]

Source: JRC elaboration

6 Dynamic macroeconomic modelling

The transition from a linear to a circular economy interferes in complex systems of economic interactions. Comprehensive modelling approaches capable of capturing the dynamic complexity are essential for evaluating transition pathways. This study follows an integrated approach that combines MFA (Section 3), LCA and LCC (Section 4), EEIOA (Section 5) and dynamic macroeconomic modelling. The Fully Inter-country Dynamic Econometric Long-term Input-Output (FIDELIO) model developed by the JRC is applied to add to the insights of the other methods.

In this chapter, before the implementation of CE scenarios in FIDELIO, an general overview over dynamic modelling approaches is provided (Section 6.1), followed by the results obtained (Section 6.2), and discussing some of the limitations related to FIDELIO (Section 6.3).

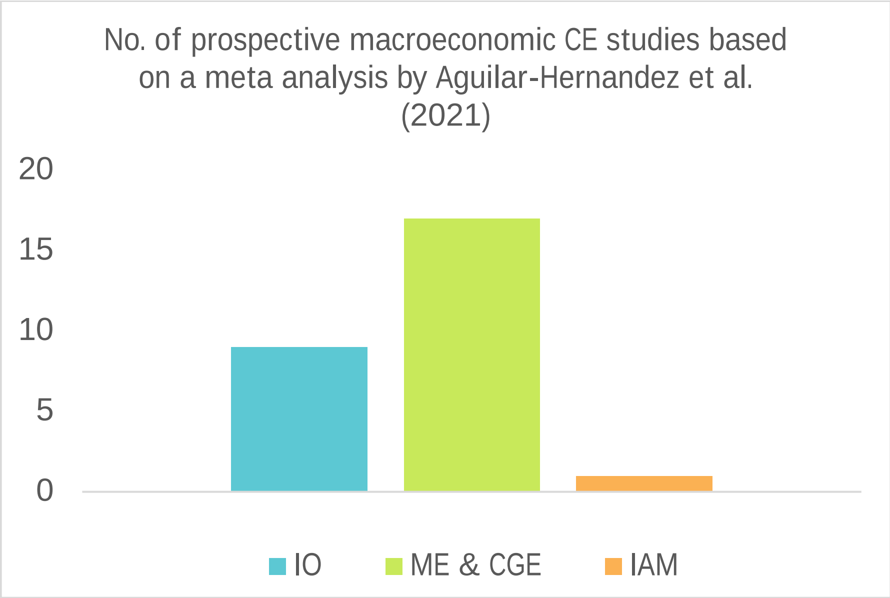
6.1 Methodology

The circular flow of income is a foundational concept in economics that illustrates how money circulates through an economy, highlighting the interactions between households, firms, governments and financial institutions (Miller & Blair, 2022). Dynamic economic modelling captures the relationships between different agents in an economy. While IOA covers the relationship of the final demand to industries, dynamic modelling approaches such as FIDELIO extend the representation of economic relationships by covering flows such as from businesses to households in form of wages, or by linking government spending to taxation of firms. They therefore cover a wider range of economic interactions and, building on these dynamics, they can be applied for prospective studies.

In a meta-analysis, (Aguilar-Hernandez et al., 2021) found that most prospective macroeconomic studies of the CE are centred on dynamic approaches such as macroeconometric analysis (ME), computable general equilibrium (CGE) models and integrated assessment models (IAM) as shown in Figure 28. While IOA is mainly based on retrospective data, several studies that calibrate IO tables for prospective stages of production and consumption based on exogenous scenarios have been developed (Wiebe et al., 2019); nevertheless, CGE remains the most common tool for prospective CE research (Aguilar-Hernandez et al., 2021).

The data core of CGE models is set up through a social accounting matrix that in its properties is comparable to Input-Output Tables (Miller & Blair, 2022). The reactions of agents in the economy are modelled based on elasticities often assuming uniform agents acting on perfect rationality and perfect information for cost-optimising behaviours (Böhringer & Rutherford, 2015). On the supply side, constant elasticities of substitution (CES) are applied between the production factors materials, capital and labour. On the demand side, the price elasticity of goods and services allow substitutions depending on relative price changes (McCarthy et al. 2018). McCarthy et al. (2018) found that the economic sectors included in CGE models applied for CE research differed between 15 and 40 sectors.

Figure 28. Overview over prospective macroeconomic CE studies based on Aguilar-Hernandez et al. (2021)



Note: The following acronyms are used: 'CGE' Computable General Equilibrium model; 'IAM' Integrated Assessment Model; 'IO' Input output; 'ME' Macroeconomic analysis

Source: JRC elaboration

While CGE models build on a micro foundation rooted in neoclassical equilibrium theory, macroeconometric models are primarily based on empirical data relying on historical time-series to estimate parameters and relationships between economic variables over time. ME relies on statistical methods to determine the interdependencies between variables, helping in understanding how external shocks impact the economy. Building on behaviours observed in historical data, the models assume prospective pathways will follow historical patterns. Compared to ME, the theoretical assumptions of CGE on cost-optimizing behaviour are less time sensitive and macroeconometric models are therefore often applied primarily for the short and mid-term. With 43 economic sectors in 71 regions, the macro econometric model E3ME is in line with the level of detail of CGE models used in CE research. The model has been applied to review employment impacts of CE interventions until 2030 (European Commission, 2018).

Dynamic economic models have advantages over IOA in the representation of economic interactions and a wider range of indicators. They are well suited to highlight rebound effects of the CE. Zink & Geyer (2017) coined the term 'circular economy rebound' through which unintended environmental impacts follow CE interventions. This can be the case due to insufficient substitutability between primary and secondary products because of quality degradation leading to a separate market for secondary goods additional to the primary market without replacing it. The second mechanism is due to price effects, when lower quality secondary goods decrease costs compared to their primary counterparts. This can lead to either an increase in production or an income effect, depending on whether the benefit is captured by firms or passed on to final demand (Zink & Geyer, 2017). The quantification of rebound effects is often omitted in CE impact assessments (Donati et al., 2020; Wiebe et al., 2019) but can be assessed using dynamic models.

6.1.1 FIDELIO: Model description

FIDELIO is a global demand-driven dynamic macroeconomic model that combines elements of Input-Output Analysis, macroeconometric analysis and computable general equilibrium modelling. It is based on Eurostat's official FIGARO Supply and Use Tables (SUT) covering 64 industries and products in 46 countries and regions, with 2015 as the base year. The model builds upon the disaggregated Supply and Use Tables described in Section 5.1. Based on FIGAROe3, 'Electricity, gas, steam and air conditioning supply' is extended into 14 industries covering 12 types of electricity generation, electricity transmission and distribution, and gas, steam and hot water supply. The 14 energy industries produce a common product, resulting in a full resolution of 77 industries and 64 products in FIDELIO. The development of FIDELIO started with a first expert workshop in 2006 and is currently developed in its fourth version at the JRC. FIDELIO 4 is structured in modules to increase transparency and traceability of macroeconomic effects. Thereby, the model is extended step by step with blocks of equations. Starting with a static Supply and Use Table model using a Leontief approach, the second module adds equations for investment dynamics. The third module adds consumption dynamics, and the full model includes price dynamics. The use of the full model is the most realistic due to its comprehensive representation of the economy and economic interactions. A detailed description of FIDELIO 4, including all equations, will be available in the forthcoming model documentation (Rocchi et al., 2025).

6.1.2 FIDELIO: Modelling approach

The modelling approach is divided into two parts. First, shocks derived from the bottom-up LCA model are processed in a way that is suitable for their implementation in FIDELIO. Second, the shocks are implemented in the BSL50, CTC50 and ACE50 scenarios in FIDELIO. Using all the individual FIDELIO modules was beyond the scope of this study, and it is therefore limited to the full FIDELIO model for the most comprehensive representation of economic interactions.

6.1.2.1 Processing shocks of the bottom-up model

As a starting point, the EU-wide levers from the bottom-up model are assigned to their respective matrix, product, industry or end-use category in the FIGARO Supply and Use Tables (SUT). Due to the missing representation of stocks in the SUT data, only flows from the bottom-up model are implemented. An interface between the MFA/LCA bottom-up model and FIDELIO was developed, to effectively bridge the different spatial, sectoral and temporal granularity of the methods.

- Spatial: The granularity of the MFA/LCA bottom-up model perspective is aggregated spatially at the EU level, while FIDELIO uses country-specific data. To implement the CE levers in FIDELIO from the bottom-up models, their outputs must be distributed to the national level. This was done by aggregating the EU wide market in the FIGARO SUT and calculating national market shares of the 27 Member States. The shares are applied as a weighting factor to distribute the EU-wide shock to the national level.

- Sectoral: While the MFA/LCA bottom-up model includes a detailed representation of stocks and flows in different production stages as well as recycling industry, the sectoral granularity of FIDELIO is less comprehensive. To map the physical flows in the MFA to the monetary flows of FIDELIO, the data of the MFA is aggregated to a level compatible with the broader sectoral flows of FIDELIO. Where the flows in the MFA/LCA bottom-up model (e.g. aluminium products) still represent only a fraction of a broader sector in FIDELIO (e.g. ‘Basic metals’), a market penetration rate was calculated using the highly disaggregated IO table FIGAROe3.

The market penetration rate was then applied as a second weighting factor to bridge between the different sectoral granularities. This approach is adapted from Donati et al. (2020).

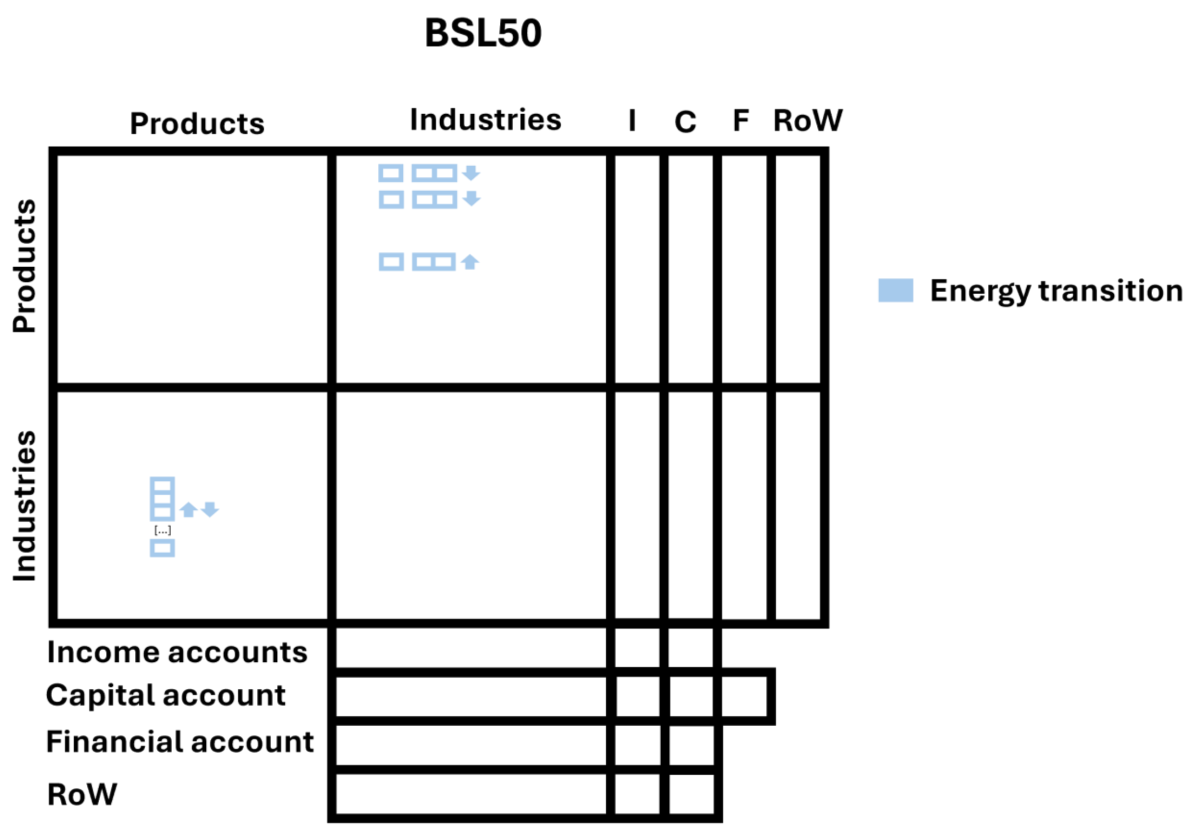
- Temporal: FIDELIO uses yearly data while data from the bottom-up MFA/LCA model is available for the status quo year 2022 and the target year 2050. For implementing bottom-up scenarios from the MFA/LCA model, interpolation is necessary. In this study, an S-shaped logistic growth function is used to interpolate values from the bottom-up model. This function is common for modelling diffusion processes and begins with exponential growth, that slows until a saturation point is reached (Sterman, 2000). For this study, it describes the implementation level of the applied levers between 0% to 100%, accounting for full implementation between 2030 and 2050.

By combing both weighing factors and interpolating for annual time steps, the changes are distributed to the national level. These steps are repeated for all relevant flows of the bottom-up model. The relative change in physical units of the bottom-up model is applied as a likewise relative change in the monetary units of FIDELIO. This simplifies the process and avoids price uncertainties. However, it is possible to use this approach by monetising the physical quantities first and then adding an additional step to adjust for differences in national price levels.

6.1.2.2 BSL50

In the BSL50 scenario, three main trends are included based on the NDC-LTS scenario from the Global Energy and Climate Outlook 2023: economic growth, energy transition, and electrification. Thereby, the national GDP growth rates were adjusted to follow the GECO 2023. Energy is represented in FIDELIO by the product 'Electricity, gas, steam and air conditioning' (CPA_D35), co-produced by 14 disaggregated industries of D35, and 'Coke and refined petroleum products' (CPA_C19) that is mainly produced by the industry 'Manufacture of coke and refined petroleum products' (C19). Decarbonisation is represented in the BSL50 scenario by including two main trends: phase-out of fossil fuels in the production of electricity and electrification, as illustrated in Figure 29.

Figure 29. Implementation of the energy transition in the BSL50 scenario



Note: C: Capital account; F: Financial account; I: Income account; RoW: Rest of the World

Source: JRC elaboration

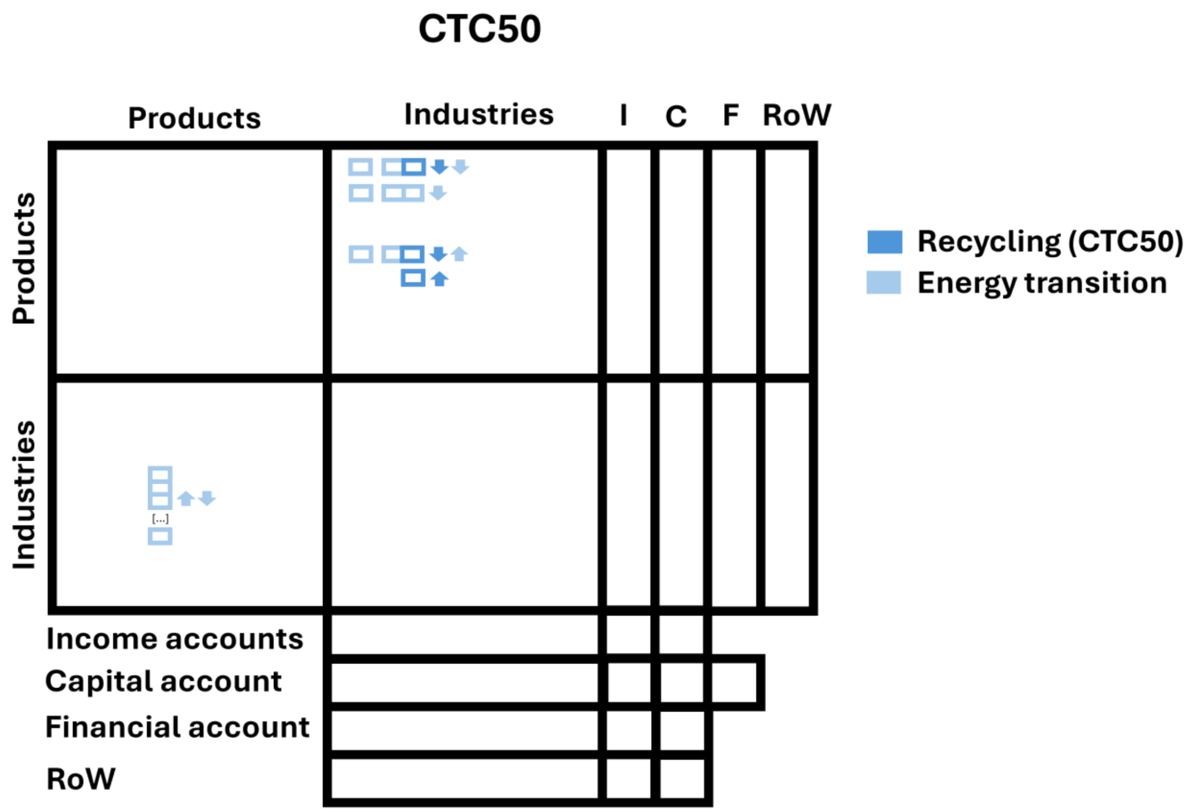
The transition away from fossil fuel-based electricity is reflected by lowering their production share in the supply matrix following the energy shares of the GECO NDC-LTS scenario. Electricity is co-produced by 12 main industries in FIDELIO representing fossil and renewable energy carriers. Additionally, FIDELIO covers the transmissions and distribution of electricity in one industry and gas, steam and heat in another industry. The electrification of the energy sector is included by increasing the shares of electricity production and transmission while lowering that of gas, steam and heat. The ratio between electricity production and transmission were thereby kept static. In addition, the energy consumption of the energy intensive industries steel, aluminium, cement and concrete, and plastics were adjusted using data from GECO 2023. This was done by adjusting the intermediate use of the industries 'Basic metals' (C24), 'Other non-metallic mineral products' (C23) and 'Chemicals and chemical products' (C20) based on the respective market penetration rates of the materials in these sectors, which are based on the highly disaggregated IO table FIGAROe3. Following the data from GECO 2023, this included a phasing-out of fossil fuels such as 'Coke and refined petroleum products' (C19) and 'Mining and Quarrying' (B), while increasing the consumption from 'Electricity, gas, steam and air conditioning' (D35). The energy expenditure in the intermediate input is thereby kept constant, and energy efficiency or an increase in energy expenditure, for example for green hydrogen, is not explicitly considered here and can be investigated more closely in the future.

Overall, the Baseline scenario covers electrification using an energy mix primarily from renewable energies for import industries and final uses. The GECO NDC-LTS scenario relies on increases in energy efficiency for agriculture, industries and services plus technologies such as carbon capture and storage (CCS) to reach European net zero goals in 2050. A full replication of the GECO analysis using FIDELIO was considered out of the scope of this study and, therefore, net zero is not achieved in the BSL50 scenario in FIDELIO. The BSL50 scenario in the dynamic modelling for this study focuses on main aspects, such as phasing out fossil fuels and electrification of key sectors.

6.1.2.3 CTC50

In the CTC50 scenario an increase in secondary material is added on top of the decarbonisation modelled in the BSL50 scenario (modelled as explained in Section 6.1.2.2). In the CTC50 scenario 'Mining products' (CPA_ B) are substituted with waste services (CPA_E37-E39) in the intermediate use of 'Basic metals' (C24) following increased recycling to meet selected EU targets (based on bottom-up results from the MFA and LCA; see Section 3.2 and Section 4.5, respectively). The decrease in 'Mining products' (CPA_ B) is counterbalanced by a proportional increase in waste services (CPA_E37-E39), assuming the same price. Given the large uncertainties in forecasting future resource prices, this is considered a feasible approach (Wiebe et al., 2019). To consider the difference in energy consumption between primary and secondary aluminium production, the intermediate use of 'Electricity, gas, steam and air conditioning' (CPA_D35) is reduced according to the life cycle inventory. Figure 30 illustrates the implementation of changes in the production inputs of the 'Basic metals' industry column.

Figure 30. Implementation of selected policy targets in the CTC50 scenario



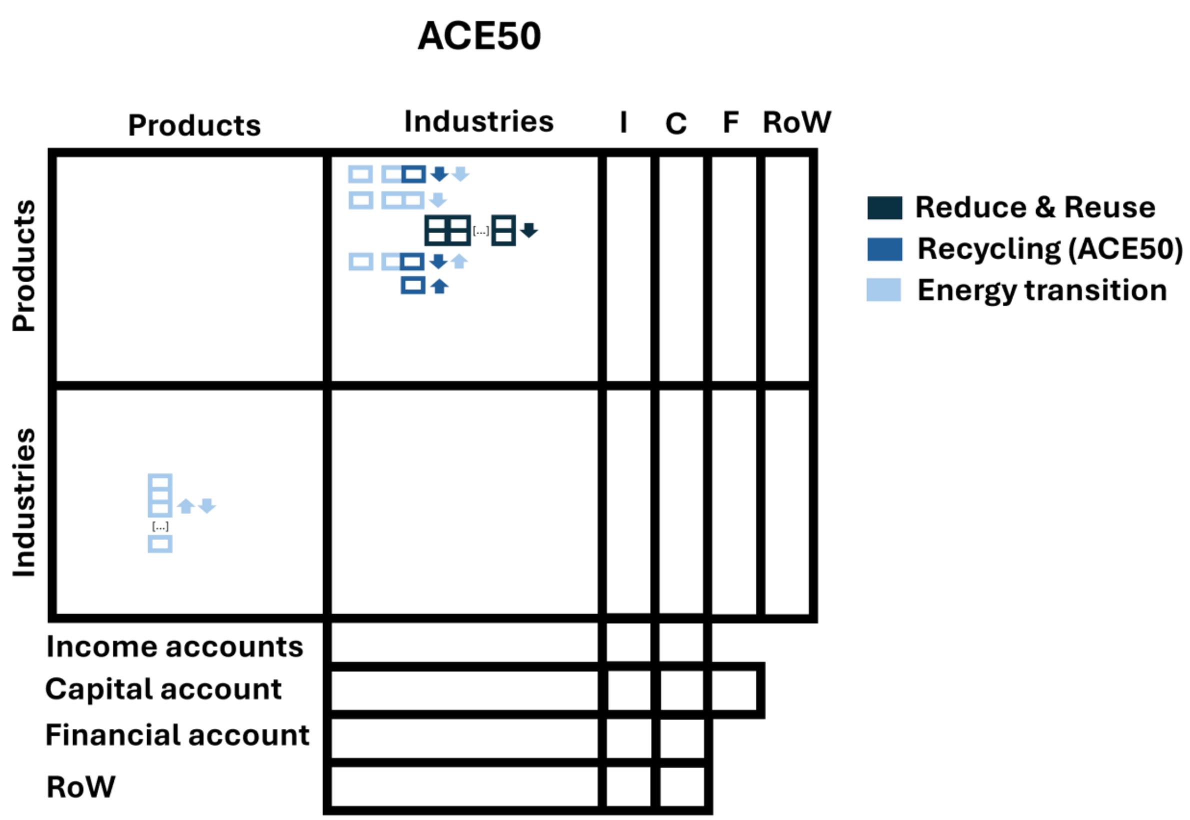
Note: Implementation of the policy targets (i.e. the shocks). C: Capital account; F: Financial account; I: Income account; RoW: Rest of the World

Source: JRC elaboration

6.1.2.4 ACE50

In the ACE50 scenario reductions in pre-consumer scrap production and the extension of the lifetime of aluminium finished products are added to the decarbonisation implemented in the BSL50 scenario. Furthermore, building on the CTC50 scenario implementation (see Section 6.1.2.3), the amount of scrap entering recycling is also included based on the bottom-up results of the MFA and the LCA (see Section 3.2 and Section 4.5, respectively). The calculation of the market penetration rates and the implementation of the CE levers in FIDELIO is detailed in Annex 11 and illustrated in Figure 31.

Figure 31. Implementation of CE levers in the ACE50 scenario



Note: Implementation of the CE levers (i.e. the shocks). C: Capital account; F: Financial account; I: Income account; RoW: Rest of the World

Source: JRC elaboration

The shocks cover the intermediate use ‘Basic metals’ (CPA_C24) and ‘Fabricated metals’ (CPA_C25) in the industries ‘Manufacture of electrical equipment’ (C27), ‘Manufacture of machinery and equipment n.e.c.’ (C28), ‘Manufacture of motor vehicles, trailers and semi-trailers’ (C29), ‘Manufacture of other transport equipment’ (C30), ‘Manufacture of furniture; other manufacturing’ (C31_32) and ‘Construction’ (F). ‘Basic metals’ (CPA_C24) refers to the production of basic metals such as steel, aluminium, copper and other metals that are produced by melting, casting and other primary metalworking processes. These products are usually unprocessed and serve as the starting material for further industrial applications, while ‘Fabricated metals’ (CPA_C25) covers the manufacture of metal products made from these basic metals. The focus here is on the further processing and refinement of metals into finished products such as vehicles or consumer durables. The share of aluminium products in ‘Fabricated metals’ (CPA_C25) is estimated using data from

FIGAROe3 to determine the national market penetration rates of the CE levers in the ACE50 scenario. The use of 'Basic metals' (CPA_C24) and 'Fabricated metals' (CPA_C25) is reduced for the respective industries based on the market penetration rates for aluminium products as weighing factors.

6.2 Results

The results for GDP, value added, trade, and employment obtained by using the dynamic macro-economic modelling FIDELIO are presented in Sections 6.2.1- 6.2.3. The results are presented relative to the BSL50 scenario, which is taken as benchmark. Therefore, the difference between BSL50 and the CTC50 and the ACE50 scenario is to be interpreted as the additional effect incurred by the implementation of the targets and by the full-fledge implementation of the CE levers investigated, respectively.

Notice that we report the results both as total absolute decrease (e.g. billion EUR) and relative decrease (%) compared with the baseline. The two offer complementary but different information: while the total decrease (e.g. in GDP or Value Added) is strongly correlated to the size of a region or industry in the baseline, the percentage should be rather interpreted as an impact intensity and, as such, identifies the most affected regions or sectors, regardless of the size.

6.2.1 Gross Domestic Product and Value Added

The results obtained for the changes in the Gross Domestic Product (GDP) as a consequence to the attainment of selected policy targets and the CE levers with respect to the BSL50 scenario are presented in Figure 32. Associated changes in Gross Value Added (GVA) for the EU industry are presented in Figure 33.

Focusing on the EU, the changes in GDP are negligible for the CTC50 (ca. EUR 1 billion difference, or 0.0036% relative change), while for the ACE50 scenario there is a decrease of ca. EUR 9 billion relative to the BSL50 scenario, corresponding to a 0.05% decrease. The largest contributions to the EU GDP loss are observed for Germany, France and Italy, with decreases in the order of EUR 1.1-1.7 billion relative to the BSL50 scenario, corresponding to a relative reduction of 0.040-006% (see Figure 32a and Figure 32b). Regarding non-EU countries, negligible differences in GDP can also be observed, both for the CTC50 (EUR 0.2 billion difference to the BSL50 scenario, corresponding to a 0.00023% relative reduction) and for the ACE50 scenario (EUR 7 billion difference to the BSL50 scenario, corresponding to a 0.0073% relative reduction). The non-EU countries most affected are, a part from Rest of the World (RoW), China, the USA, Russia and the UK, with decreases compared to the BSL50 scenario in the order of EUR 0.33-1.55 billion or 0.0032-0.028% relative reduction (see Figure 32c and Figure 32d). Overall, the results of the modelling show also for non-EU countries that the general trend of GDP decline is limited, both in the CTC50 and in the ACE50 scenario.

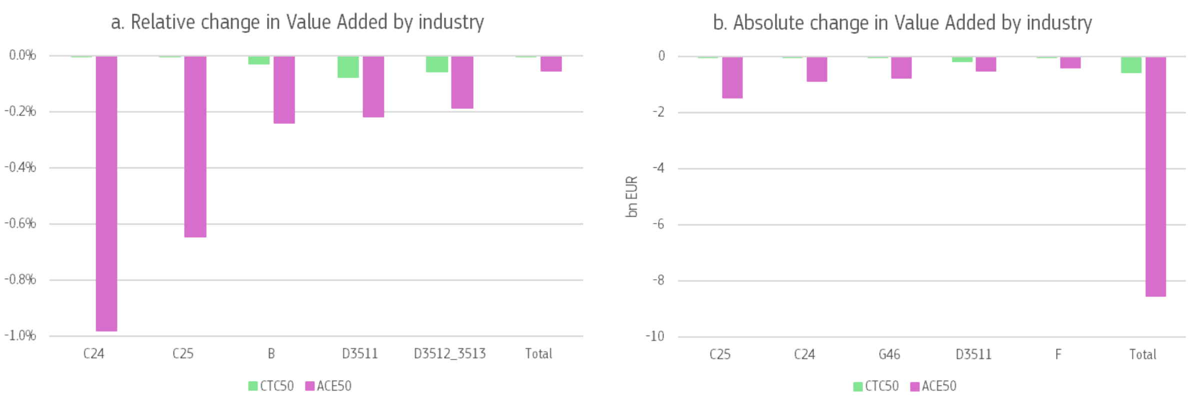
With respect to changes in the Value Added at EU level, the results obtained in the CTC50 scenario are negligible, while in the ACE50 scenario the industries mainly affected are 'Manufacture of fabricated metal products, except machinery and equipment' (C25), 'Manufacture of basic metals' (C24), 'Wholesale trade, except of motor vehicles and motorcycles' (G46), 'Production of electricity' (D3511), and 'Construction' (F), with decreases compared to the BSL50 scenario in the order of EUR 0.50-1.5 billion or 0.051-0.98% (see Figure 33a and Figure 33b).

Figure 32. Absolute and relative change in GDP in EU and non-EU country

Note: Panel a) Relative change in GDP per EU country expressed as percentages for the CTC50 and the ACE50 scenario; Panel b) Absolute change in GDP per EU country expressed as billion EUR for the CTC50 and the ACE50 scenario; Panel c) Relative change in GDP per non-EU country expressed as percentages for the CTC50 and the ACE50 scenario level; Panel d) Absolute change in GDP per non-EU country expressed as bn EUR for the CTC50 and the ACE50 scenario

Source: JRC elaboration

Figure 33. Absolute and relative change in value added by industry in EU



Note: Panel a) Relative change in Value Added for the EU at industry level expressed as percentages for the CTC50 and the ACE50 scenario; Panel b) Absolute change in Value Added for the EU at industry level expressed as billion EUR for the CTC50 and the ACE50 scenario

Source: JRC elaboration

Furthermore, at the global scale, the European GDP corresponds to approx. 14% of the global GDP (approx. EUR 110 trillion in 2050). The CTC50 scenario results in a relative reduction of the global GDP of 0.001% (EUR 1 billion), while the ACE50 scenario of 0.01% (EUR 16 billion), losses that are also negligible. Overall, the results of the modelling show that the general trend of GDP decline is limited and the EU's position in the global economy is not negatively affected by the attainment of selected policy targets nor by the implementation of the CE levers.

6.2.2 Trade

The results obtained for the changes in Trade as a consequence to the attainment of selected policy targets and CE levers with respect to the BSL50 scenario are presented in Figure 34.

In the BSL50 scenario the total amount of EU imports amounts to EUR 3 391 billion, while for the CTC50 scenario to ca. EUR 3 391 billion, and for the ACE50 scenario EUR 3 387 billion. With respect to exports, in the BSL50 the total amount of EU exports equals EUR 4 350 billion, while for the CTC50 to ca. EUR 4 350 billion, and for the ACE50 scenario ca. EUR 4 350 billion. This corresponds for the EU in a surplus in trade balance[27] of EUR 959 billion in the BSL50 scenario, EUR 960 billion in the CTC50 scenario, and EUR 963 billion in the ACE50 scenario. Considering the difference between the CTC50 and the ACE50 with the BSL50 scenario, an increase in trade balance of EUR 0.20 billion in the CTC50 scenario and of EUR 3.9 billion in the ACE50 scenario are calculated. This means that the attainment of selected policy targets and the implementation of CE levers incur an increase in EU trade surplus (less demand for imports mainly, with exports proportionally less, or not, affected).

The increased surplus for the EU in both the CTC50 and the ACE50 scenario are due to changes in trade patterns, overall inferring a reduced dependency from non-EU countries. Focusing on the trade partners, in the CTC50 scenario the main changes are observed for Russia, Norway and the USA with a surplus in trade balance in the order of EUR 0.040-0.018 billion or 0.0037-0.11% relative to the BSL50 scenario. For the ACE50 scenario, the main changes are observed for China, Russia, the USA, and the UK with a surplus in trade balance in the order of EUR 0.33-0.50 billion or 0.074-3.0% relative to the BSL50 scenario (see Figure 34a and Figure 34b). Specifically, Norway, Russia, China, and the USA are amongst the main countries from which the EU imports ingots, semi-finished and finished products. The implementation of the CTC50 and the ACE50 would result in an increased autonomy. Indeed, the sector mainly affected in non-EU countries refers to 'Mining and quarrying' (B).

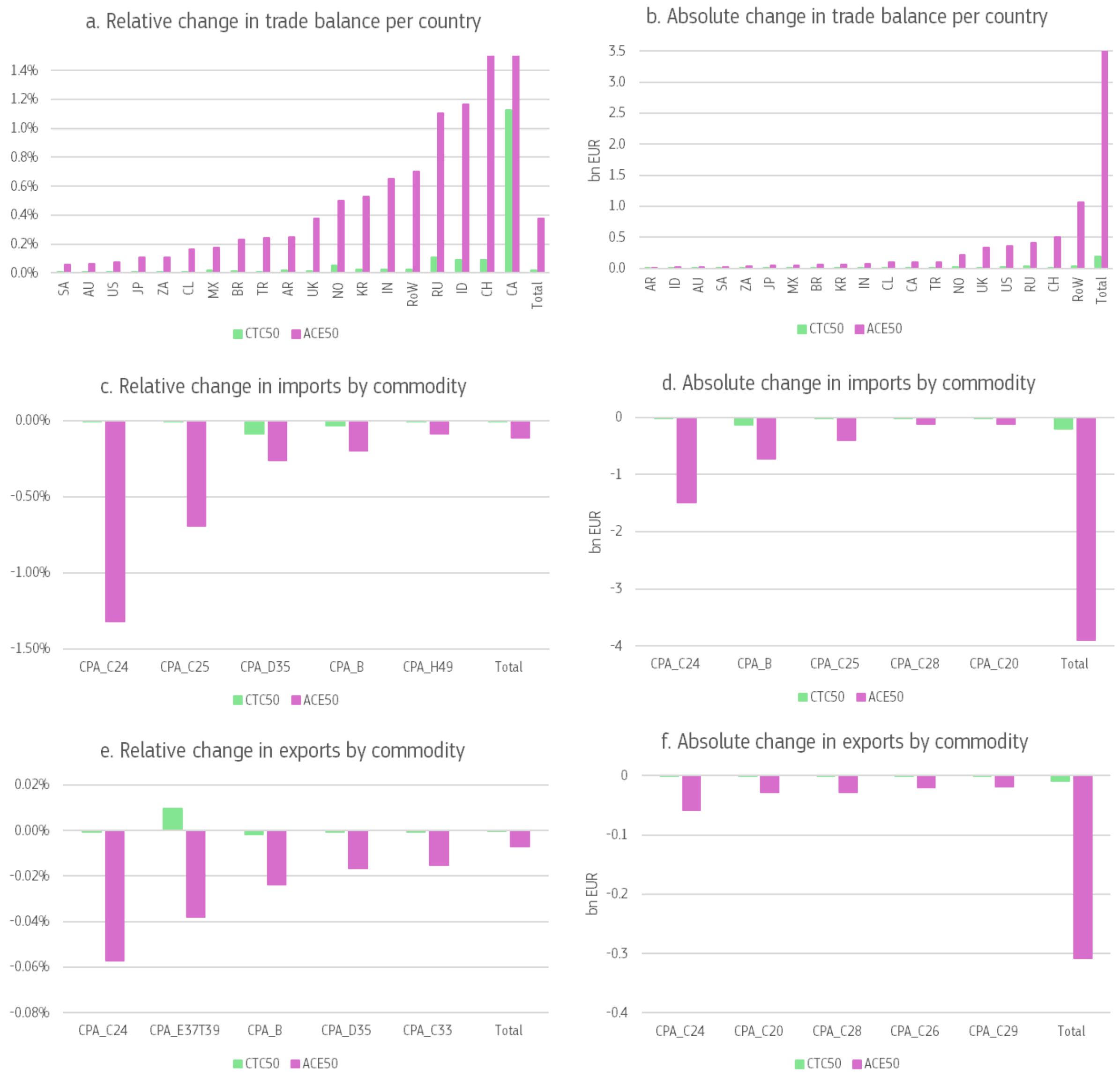
With respect to what is imported in the EU, Figure 34c and Figure 34d show what commodities are mainly affected by the changes implemented in the CTC50 and ACE50 scenarios when compared to the BSL50 scenario. Negligible decreases are observed for the CTC50 scenario, while for the ACE50 scenario, the main commodities affected are 'Basic metals' (CPA_C24), 'Mining and

[27] The trade balance is calculated as *Trade balance = Exports – Imports*.

quarrying' (CPA_B), 'Fabricated metal products, except machinery and equipment' (CPA_C25), and 'Machinery and equipment n.e.c.' (CPA_C28) in the order of EUR 0.11-1.5 billion or 0.077-1.3% relative reduction.

Finally, Figure 34e and Figure 34f show what EU exported commodities are mainly affected by the implementation of the CTC50 and ACE50 scenarios as opposed to the BSL50 scenario. Negligible increases and decreases are observed for the CTC50 scenario, while for the ACE50 scenario, the main goods decreasing their exports are 'Basic metals' (CPA_C24), 'Chemicals and chemical products' (CPA_C20), 'Machinery and equipment n.e.c.' (CPA_C28), 'Computer, electronic and optical products' (CPA_C26), and 'Motor vehicles, trailers and semi-trailers' (CPA_C29) in the order of EUR 0.018-0.058 billion or 0.0058-0.057% relative reduction.

Figure 34. Relative and absolute changes in trade balance by country, and imports and exports by commodity



Note: Panel a) Relative change in trade balance with non-EU countries expressed as percentages for the CTC50 and the ACE50 scenario; Panel b) Absolute change in trade balance with non-EU countries expressed as billion EUR for the CTC50 and the ACE50 scenario; Panel c) Relative change in EU imports by commodity expressed as percentages for the CTC50 and the ACE50 scenario; Panel d) Absolute change in EU imports by expressed as billion EUR for the CTC50 and the ACE50 scenario; Panel e) Relative change in EU exports by commodity expressed as percentages for the CTC50 and the ACE50 scenario; Panel f) Absolute change in EU exports by commodity expressed as billion EUR for the CTC50 and the ACE50 scenario

Source: JRC elaboration

6.2.3 Employment

The results obtained for the changes in Employment because of the attainment of the policy targets and the CE levers with respect to the BSL50 scenario are presented in Figure 35.

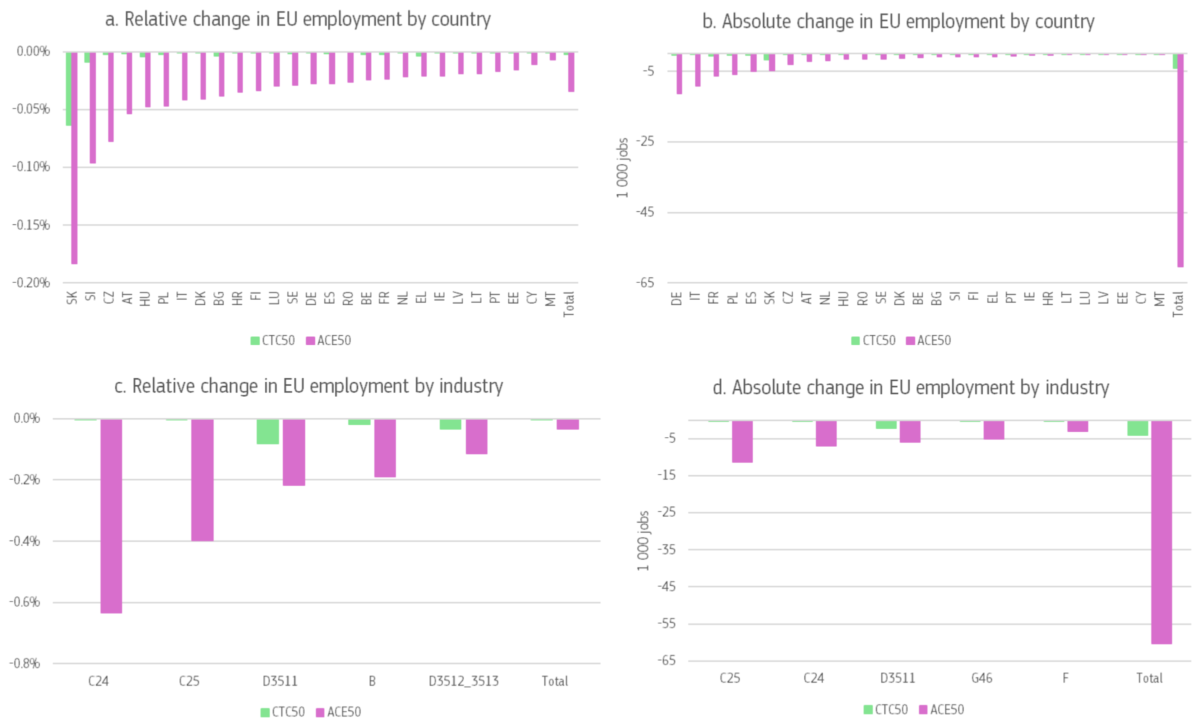
The total number of jobs in the 2050 scenarios is approx. 177 million jobs. The difference between the CTC50 and the BSL50 scenario highlights a reduction in employment of 4 000 jobs (corresponding to a 0.0022% relative reduction, not shown in Figure 35), while in the ACE50 scenario of 60 000 jobs (corresponding to a 0.034% relative reduction, not shown in Figure 35).

In the CTC50 scenario, the main differences in the reduction of number of jobs are observed for Slovakia, France, and Germany in the order of 345-1 666 jobs or 0.0008-0.063% relative reduction. In the ACE50 scenario more pronounced losses are observed for Germany, Italy, and France in the order of 6 300-11 000 jobs or 0.024-0.041% relative reduction (see Figure 35a and Figure 35b). Germany, France and Italy are amongst the main countries within the European aluminium supply chain. Within the EU, Slovakia is producing 9% of the vehicles and is strongly embedded through upstream linkages to automotive industries in other EU countries (Rueda-Cantuche et al. 2024) (Rueda Cantuche et al., 2024). This can explain its sensitivity for shocks in the automotive industry. Hence, a reduction in the sector would impact negatively from an employment perspective.

With respect to the industries mostly affected by reductions in employment, the results for the CTC50 scenario show that the main losses compared to the BSL50 scenario are incurred by 'Electricity, gas, steam and air conditioning' (D3511) and 'Construction' (F) in the order of 250-2 200 jobs), while an increase of 200 jobs is observed for 'Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services' (E37T39, not shown in Figure 35) due to, among the others, an increase in recycling in the CTC50 compared to the BSL50 scenario. In the ACE50 scenario, the main reductions in employments are observed for 'Manufacture of fabricated metal products, except machinery and equipment industry' (C25), 'Manufacture of basic metals' (C24), 'Electricity, gas, steam and air conditioning' (D3511), 'Wholesale trade, except of motor vehicles and motorcycles' (G46), and 'Construction' (F) in the order of 3 000-11 400 jobs or 0.054-0.63% relative reduction. As opposed to the CTC50 scenario, decreases in 'Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services' (E37T39, not shown in Figure 35) are observed, although very limited.

The modelling results show overall a negative trend in job demand. It is important to note that amongst the levers herein studied the extension of the lifetime of products via repairing and remanufacturing requiring skilled workers, changes in design of products to improve recyclability and new sorting technologies both requiring research and development, are considered. Nevertheless, the creation of jobs related to the mentioned activities are not modelled. Hence, the results do not fully represent the consequences of attaining policy targets and implementing CE levers.

Figure 35. Relative and absolute changes in EU employment by country and industry



Note: Panel a) Relative change in employment by EU country expressed as percentages for the CTC50 and the ACE50 scenario; Panel b) Absolute change in employment by EU country expressed as 1 000 jobs for the CTC50 and the ACE50 scenario; Panel c) Relative change in EU employment by industry expressed as percentages for the CTC50 and the ACE50 scenario; Panel c) Absolute change in EU employment by industry expressed as 1 000 jobs for the CTC50 and the ACE50 scenario

Source: JRC elaboration

6.3 Limitations

Decarbonisation in this study is focused on the energy sector and four energy-intensive industries, namely steel, aluminium (the industry in focus), cement and plastics. The electrification of service sectors such as transport and residential energy use, as well as energy efficiency and the market diffusion of carbon capture technologies or green hydrogen were considered as out of scope. The analysis with FIDELIO in the BSL50 scenario therefore lacks the depth of the energy transition in the Global Energy and Climate Outlook 2023 and should be further investigated to examine the long-term contributions of the CE in more detail. An integrated approach combining FIDELIO with an energy system model at the appropriate spatial and sectoral level of detail, as recommended by Elberry et al. (2024), and an MFA or LCA model to track stocks and flows of the evolution towards a CE would be a way forward, allowing to build on the specific strengths of the different types of modelling.

The dynamic modelling approach is consistent with the EEIOA, where shocks are implemented in the intermediate use matrix. However, this approach treats CE interventions as cost reductions. While the literature on CE rebound effects suggests that cost reductions through CE are likely and can lead to environmental rebound effects (Zink & Geyer, 2017), CE usually requires more services, which may partially counteract the cost reductions. This study used a combined approach of life cycle assessment, material flow analysis and macroeconomic modelling. While this approach is rich in information on stocks and flows of aluminium, additional data inputs are required to consider repair and rental services, as well as research and development activities, which are important for longer product life, intensification of use and material efficiency. However, robust economic data for services were not available and were not specifically collected in this study. The consideration of this system boundary is important for the interpretation of economic indicators, such as GDP or employment, that do not include the increase in services required by the CE and should therefore be considered as a lower bound after technical optimisation of product design and processes to reduce material use. In addition to the costs of services, investment costs for additional recycling infrastructure, repair and refurbishment infrastructure and research facilities should be covered in more detail in the future. Future research projects can highlight these in more detail by adding data on life cycle costs, capital expenditure (CAPEX) and operating and maintenance expenditure (OPEX). This study highlights the potential to reduce industrial demand for aluminium rather than social innovations and impacts of behavioural change of consumers. Combining FIDELIO with a modelling approach that goes beyond the MFA inputs would allow scenarios of consumer behaviour change to be explored in more depth, broadening the scope of this study from technical optimisation to social innovation. This can be achieved, for example, through system dynamic or agent-based modelling approaches.

The study is limited to the sectoral granularity of FIDELIO. Although the level of detail is comparatively high compared to other dynamic macroeconomic models used for CE analysis, there is a bias due to aggregation error. For example, the mining sector (NACE B) includes both energy extraction, such as coal, gas and oil, and non-energy extraction, such as iron ore. Therefore, modelling a reduction in the use of iron ore by reducing mining inputs of the commodity CPA B will also lead to a reduction in energy inputs. Another aggregation error is found in industry E37T39, which includes GHG-intensive processes such as waste incineration or processing of sewage sludge, in addition to the collection and processing of secondary materials. A further disaggregation of FIDELIO for non-energy mining and a differentiation of the waste streams for processing of secondary materials, incineration, landfilling or sewage services would help to better capture the changes due to the CE. This can be based on the highly disaggregated IO table FIGAROe3, following the example of the disaggregated energy sector used for this study. For the mining sectors, data quality checks can be carried out using the OECD's Inter-Country Input-Output tables (ICIO), which distinguish between energy and non-energy mining as well as mining support services. A CE sector specific disaggregated version of FIDELIO would allow future CE research projects to reduce the aggregation bias in FIDELIO. However, in dynamic economic modelling, an increased number of industries in models comes at the cost of reduced data reliability (Duchin & Levine, 2016; Hu et al., 2023). The data available for parameter validation is retrospective, spatially limited, and restricted to a unique setting, leading to limitations on the total number of industries used in dynamic macroeconomic models (Duchin & Levine, 2016). The trade-off between the benefits of higher sectoral granularity and lower data reliability should be considered when increasing the number of sectors in the model.

FIDELIO allows to use a modular approach. This study was limited to the use of the full model and therefore missed the traceability of macroeconomic spillovers and rebounds that is offered by using the different modules of FIDELIO to track intersectoral, investment, income and price effects. Using all modules would increase the depth of the analysis. A replication of the results using the other modules of FIDELIO can be considered to increase the traceability and transparency of the results.

The trade pattern modelled in the BSL50 scenario of FIDELIO do not mirror the post Ukrainian-war situation. Therefore, in the changes in trade balances and patterns, it is expected to see less reduction following CE levers for Russia as a consequence to the implementation of existing European sanctions.

7 Synthesis and discussion

The results obtained via LCA, EEIOA, and dynamic macroeconomic modelling and key insights are synthetised in Section 7.1. Possible policy actions that would be needed to activate the CE levers investigated in this study are presented in Section 7.2.

7.1 Impacts of CE: Synthesising bottom-up and macro-analyses

7.1.1 Climate change mitigation and other environmental effects

Our results indicate that the potential of CE to mitigate climate change, additional to what would be achieved by solely the decarbonisation of the energy sector, lies between 12-14 Mt CO_2-eq. (year 2050; Figure 36). The two analyses show comparable results, with the ones obtained via EEIOA in the lower end of the range as they include rebound effects related to increased production in third countries due to reduced exports. If these effects would be excluded, as they are in the boundaries of the LCA, then both analyses would show a yearly reduction of approx. 14 Mt CO_2-eq. (year 2050).

Figure 36. Greenhouse gas emission savings for the aluminium sector in the ACE50 scenario and breakdown into the Reduce, Reuse, and Recover clusters

Note: All values are expressed in Mt CO_2-eq and relative to the BSL50 scenario

Source: JRC elaboration

The higher granularity of the LCA allows for showing the effects of the individual CE levers. The Reduce lever, which is focused on decreasing pre-consumer scrap, contributes with limited reductions of 1 Mt CO_2-eq. Moderate climate change mitigation effects were expected as production processes are already highly optimised, but also because pre-consumer scrap has high economic value and is easy to sort, hence it is already fully recycled (European Aluminium, 2020). Levers that entail reducing the demand for aluminium ultimately substituting it with other materials were not considered. Indeed, the demand for aluminium is project to increase (see, for example, European Aluminium, 2020) and it is expected that aluminium will substitute other materials (e.g., steel in cars). The Reuse cluster contributes with a reduction of 11 Mt CO_2-eq., where extending the lifetime of aluminium-containing finished products across all sectors with a lifespan greater than 1 year appears as an impactful lever. The Recover cluster contributes with a reduction of 6 Mt CO_2-eq. with levers targeting high-quality closed loop recycling as the most impactful ones. Indeed, both L(5) (‘Improved waste sorting and scrap quality’) and L(7) (‘Expansion of deposit return systems’) strive to achieve closed-loop recycling by establishing an alloy-to-alloy separation, which is rather limited in Europe and that appears as a key feature to avoid downcycling of wrought aluminium into cast aluminium of which a surplus in supply is forecasted by several scholars (Bertram et al., 2017; van den Eynde et al., 2022). Moreover, a better use of the scrap would also contribute in decreasing the dependence on virgin aluminium (European Aluminium, 2020; Georgitzikis et al., 2021).

Deriving and reporting 'percentages of reduction' (e.g. GHG reduction in %) from these figures may be misleading, as the values depend on the reference of comparison chosen, i.e. from how the boundaries of the system, for which the emissions are quantified, are defined. Taking the boundary of the LCA as an example, the results of the bottom-up assessment indicate that the CE levers studied achieve an additional impact reduction on the impact category Climate Change equal to 14% relative to that of the Baseline scenario, i.e. what would be achieved only via decarbonisation of the energy sectors. In the scope of the LCA both on-site and off-site emissions are included, while the EEIOA results can provide insights on EU on-site emissions for the sector under study. As technologies focused on reducing on-site emissions (e.g. switching from carbon anodes to inert ones) were not included in this study and since an increase in the demand for aluminium is forecasted in 2050, the results of the EEIOA highlight an increase in on-site emissions in the Baseline scenario of 66% relative to the Status Quo scenario. Nevertheless, in the Ambitious Circular Economy scenario a reduction of 22% relative to the Baseline scenario is calculated due to reduced demand for aluminium and replacement of virgin aluminium with high-quality scrap.

Our findings further indicate that the CE levers studied incur a reduction of the impacts on all the environmental impact categories considered other than the Climate Change one, and no trade-offs are observed upon implementing the Ambitious Circular Economy scenario.

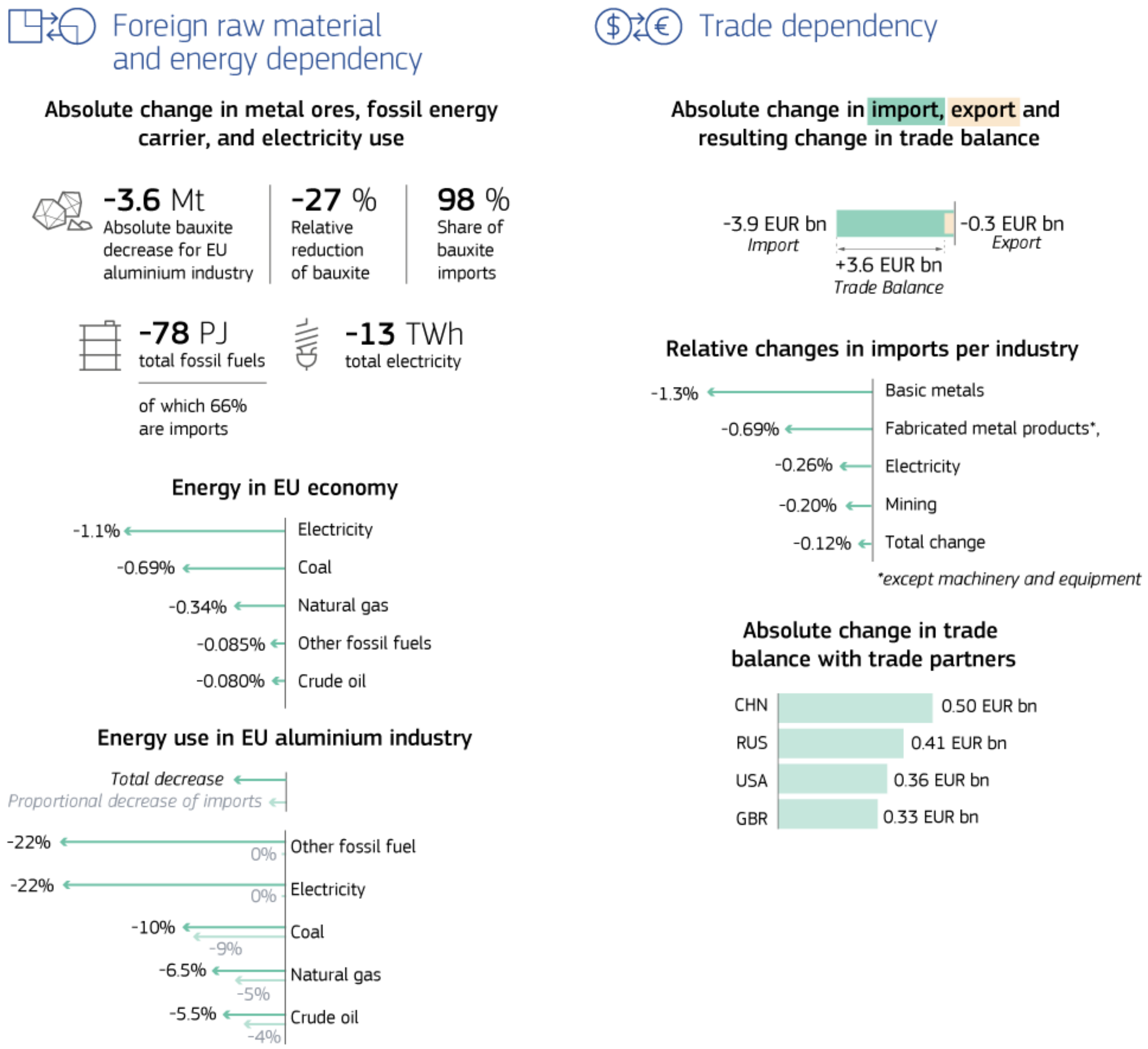
7.1.2 Resource and trade dependency

The full implementation of all CE levers (ACE50 scenario) leads to a decrease relative to the Baseline scenario in EU demand for bauxite of 3.6 Mt, representing 27% of all bauxite mineral requirements in BSL50, of which the large majority is supplied by countries other than the EU. These figures are calculated via EEIOA and only account for the direct bauxite input requirements of the EU aluminium industry for maintaining the EU final demand and EU exporting sector. If inter-country and inter-sector spillover effects are accounted for, then a reduction of 11% in the ACE50 scenario relative to the BSL50 scenario is observed.

For the European aluminium sector, the implementation of CE levers corresponds to a reduction in demand for energy products. Relative to the Baseline scenario, it is calculated that the electricity use would decrease by 22% according to EEIOA results. With respect to the use of fossil fuels, it is quantified via EEIOA a reduction in the demand for coal (10%), crude oil (6%), natural gas (7%), and other fossil fuels (22%) relative to the Baseline scenario. These demand reductions mostly affect imports; indeed, imports represent approx. 87% of the total reduction in fossil energy carriers (Figure 37).

The reduction in resource dependency reflects decreased imports from foreign regions. The results of the dynamic macroeconomic modelling suggest that the implementation of all CE levers (ACE50 scenario) by 2050 increases the trade balance of the EU by annual EUR 3.6 billion. This is related to reduction of imports (EUR 3.9 billion) from China, Russia, USA and the UK. The imported commodities most affected in absolute terms relative to the Baseline scenario (cumulatively approx. EUR 2.6 billion) are 'Basic metals', 'Mining and quarrying', and 'Fabricated metal products, except machinery and equipment'. Exports from the EU are also reduced, although to a much lesser extent (EUR 0.3 billion relative to the Baseline scenario) (Figure 37). This result is to be taken with much caution as it is affected by the assumptions made on cost-neutrality of some of the CE levers applied. On top, the increase of economic output (employment and GVA) from repair and research services was not thoroughly investigated and only approximately modelled, assuming that the reduction of economic input in manufacturing would be diverted to repair and research, *ceteris paribus*. However, this is only an assumption, and more research is needed on this aspect to improve accuracy of distribution within and across sectors.

Figure 37. Effects of CE levers with respect to the BSL50 scenario on resource and trade dependency for the aluminium sector

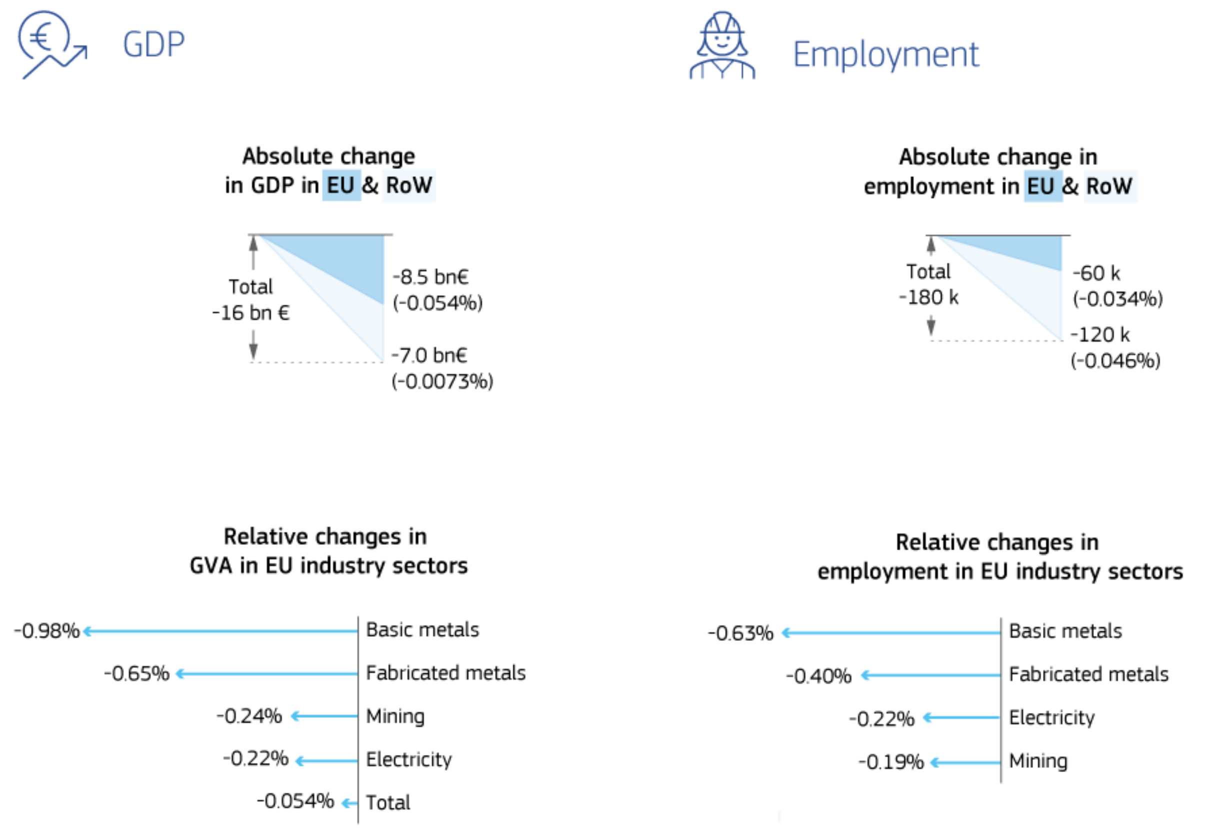


Source: JRC elaboration

7.1.3 Socio-economic effects

As a result of the implementation of CE levers in the aluminium sector, we calculate a decrease in jobs and value added. The decrease in value added is in the order of 0.054% of GDP across the entire EU economy relative to the Baseline scenario, while the decrease in job requirements is in the order of 0.034% across the entire EU economy relative to the Baseline scenario (Figure 38).

Figure 38. Effects of the CE levers relative to the BSL50 scenario on GDP and employment for the aluminium sector



Source: JRC elaboration

The most affected industries in relative terms are 'Basic metals' (-0.63% in employment, -0.98% in GVA), 'Fabricated metal products, except machinery and equipment' (-0.40% in employment, -0.65% in GVA), 'Mining and quarrying' (-0.19% in employment, and -0.24% in GVA), and the 'Electricity, gas, steam and air conditioning' (-0.22% in employment, -0.22% in GVA). All values are obtained via the dynamic macroeconomic modelling.

The decrease in GVA in the EU aluminium sector corresponds to 1:17[28] the decrease in direct GHG emissions in the same sector, suggesting a strong decoupling of economic growth and GHG emissions incurred by CE.

As for costs, we only estimated non-discounted life cycle costs which offer a limited representation of the actual costs incurred by the economic system because of the CE levers studied. Recover levers, based on the static (i.e. EEIOA) and dynamic macroeconomic modelling analyses, increase the economic output mainly following increases in cost for collection, sorting, and recycling while maintaining industry production and final consumption unchanged, aligning with the life cycle costing results. However, no robust information was found to duly account for the technology investments and operational costs incurred by a shift towards high-quality recycling. For Reuse and

[28] The ratio is calculated as: the relative change in EU territorial emissions relative to the baseline, and the relative change in EU territorial GVA relative to the baseline. Both relative changes are calculated based on the EEIOA results.

Reduce levers, on the other hand, no robust information on investment and operational costs could be found.

7.1.4 Key insights

The aluminium sector is considered as a circular one; however, the aluminium supply chain would benefit from additional efforts implemented at collection, sorting and recycling for sectors other than packaging. Indeed, the results highlighted that maintaining alloys families separated to ensure closed-loop recycling and reduce scrap surplus is key, considering also the predicted oversupply of cast aluminium alloys. Nevertheless, this requires additional investments in collection, dismantling practices and sorting technologies able to separate different alloys to preserve quality. Reducing the amount of virgin aluminium can on the one hand decrease GHG emissions and, on the other one, increase the independence of this critical and strategic material for EU decarbonisation. Lifetime extension practices have similar effects but require additional changes in business models (e.g. repair services), the costs and employment of which were not duly accounted for in this study.

7.2 Potential policy instruments to foster CE in the aluminium sector

The transition to a circular economy (CE) is a multi-level and multi-stakeholder long-term process that requires a well-aligned strategic direction and a carefully designed operational framework. The CE could contribute to mitigating resource and environmental constrains in the EU by addressing aspects of the climate and resource crisis, enhancing competitiveness in a global environment, strengthening the strategic autonomy of the EU, without diminishing the quality of life of EU citizens nor shifting environmental burdens elsewhere. This diversity of CE objectives causes considerable complexities for policymakers, since multiple policy objectives need to be fulfilled at the same time. Since there is no single policy instrument that would be equally suited for all problem areas, goals, actors, type of resources, life-cycle stages, etc., a systems perspective would be required to prevent problem shifting, conflicting aims and incoherence among policy fields and implementation levels (Wilts & O'Brien, 2019).

It is widely recognised that supporting sustainability transitions, such as the CE transition, requires a consistent combination of strategies and accompanying instruments in so-called policy mixes (Sovacool et al., 2025). Within a policy mix, the synergies between various policy instruments are intended to address the complex challenges of CE more holistically, leveraging their strengths to target different aspects of a problem at different levels. A coordinated policy mix approach aims at mitigating potential conflicts or redundancy between policy instruments, ensuring coverage of various dimensions of the issue and enhancing the overall effectiveness of the applied policies (Howlett & Rayner, 2007; Rogge & Reichardt, 2016).

The EU aluminium sector consists of an extensive multi-actor value chain, extending both within and outside the EU, and involving economic and societal actors at regional, national and international levels. It becomes evident that a CE transition of the sector needs a systemic (holistic) policy approach, designing a balanced policy mix targeting all CE clusters and actors involved.

7.2.1 Policy mixing principles

The three main reasons for adopting a policy mix approach can be summarised as multiple market failures (including transaction costs and information asymmetries), governance constraints, and behavioural factors (Bouma et al., 2019). Therefore, an effective design of a policy mix intervention requires a good understanding of the market, governance and behavioural failures that need to be tackled for the intended policy mix to have the desired effect. A policy mix approach should exhibit certain design characteristics to achieve a high level of efficacy in addressing the targeted problem(s). These characteristics are consistency, coherence, comprehensiveness, credibility, and congruence (Howlett & Rayner, 2007; Rogge & Reichardt, 2016).

Consistency refers to 'how well the elements of the policy mix are aligned with each over, thereby contributing to the achievement of policy objectives' (Rogge & Reichardt, 2016). Single instruments in a policy mix can be considered as consistent when they function synergistically to support a policy objective. This implies the elimination of contradictions between instruments and the existence of synergies within and between the elements of the policy mix. While consistency focuses on the contents of the mix, the term coherence focuses on the design policy process dimension (OECD, 2016). Consistency and coherence in a policy mix can be fostered by combining primary with supportive instruments. Primary instruments are mainly used to achieve a defined policy objective. Supportive instruments are used to minimise or mitigate unintended negative side effects of primary measures and, therefore, to increase their acceptability and feasibility (Rogge & Reichardt, 2016). Credibility refers to the extent to which a policy mix is considered reliable, which may be affected by several factors, such as the commitment from political actors, the consistency of the instrument mix, and the competence of the implementing authorities (Rogge & Reichardt, 2016). Comprehensiveness refers to the '…the degree to which the instrument mix addresses all market, system and institutional failures, including barriers and bottlenecks' (Rogge & Reichardt, 2016). Congruence among instruments and (socio-economic) goals means the compatibility between the strategic objective of a policy goal and the design of the policy mix to achieve the intended outcomes (Howlett & Rayner, 2007)

In order to effectively respond to the specific context of a policy vision in a long-term perspective, the development of policy mixes needs to consider the following (Howlett & Rayner, 2007; Rogge & Reichardt, 2016):

- The full range of policy instruments (types of instruments, see Section 7.2.3);
- The full cost of policies (including implementation, transaction and compliance costs);
- Avoiding negative interactions between single policies (i.e. instruments already in place and new ones) and emphasising mutual benefits and potential with existing policies;
- The potentially negative side-effects of the instruments on the target groups, e.g. issues of competitiveness in industry or adverse effects on lower income households;
- The political processes during the design and implementation of the mix.

A comprehensive policy mix needs to go beyond just combining the individual policy instruments statically. In a policy mix, the long-term qualitative strategic objectives and short- to mid-term quantitative targets should be combined in a time-dynamic approach to effectively achieve the overall goals. A policy mix design also requires forward-looking strategic planning (foresight), by relating different policy instruments in a time sequence that enables the optimisation of synergistic effects while minimising the unintended negative side effects (Ekvall et al., 2016).

Moreover, the literature on policy mixes for sustainability transition processes emphasise that change does not materialise by fostering solely new solutions and innovations, but also by putting pressure on incumbents and the established socio-technical configurations, e.g. through phasing out existing measures that reinforce the status quo (Kivimaa & Kern, 2016; Sovacool et al., 2025).

7.2.2 Long-term policymaking considerations

Socio-economic transition processes take a long time and can have variable directions and outcomes, so a necessary strategic vision and appropriate policy instruments must be formulated in advance. The transition to a CE is expected to develop gradually over the following years and the impact assessment modelling in this study foresees anticipated outcomes by the year 2050. In this context, the notion of long-term policy design is coming to prominence. Fundamental elements to consider in long-term policy design include: 1) achieving extended coordination between the actors involved; 2) taking a holistic view on socio-economic and (parallel) political developments; 3) preventing unpredictable outcomes; 4) sustaining a vision for the long-term goals of the policy, without suppressing diversity; and 5) retaining adaptability towards the complex dynamics of change. In order to constructively deal with all these issues in long-term policy guidance, within a short-term context, most approaches to strategic planning pragmatically combine top-down and bottom-up considerations (Voß et al., 2009).

7.2.3 Typology of policy instruments

Policy instruments are the actual tools governments use to implement their policies. Policymakers have the option to select from a wide range of instruments to address a certain policy problem and achieve a desired outcome. A policy instrument constitutes a steering function and provides incentives for achieving a certain policy. Policy instruments can be divided into three types (administrative, economic, and informative) in relation to their nature and into two types (mandatory, voluntary) concerning their implementation mode (Mont & Dalhammar, 2005; Vedung, 1998). Other typologies in literature might include more than three categories and distinguish between, for example, voluntary agreements and self-regulation as separate categories (Gunningham et al., 1998). However, the categorisation that is most consistent among policy sources is presented in Table 6), including also a few indicative examples of related measures per category.

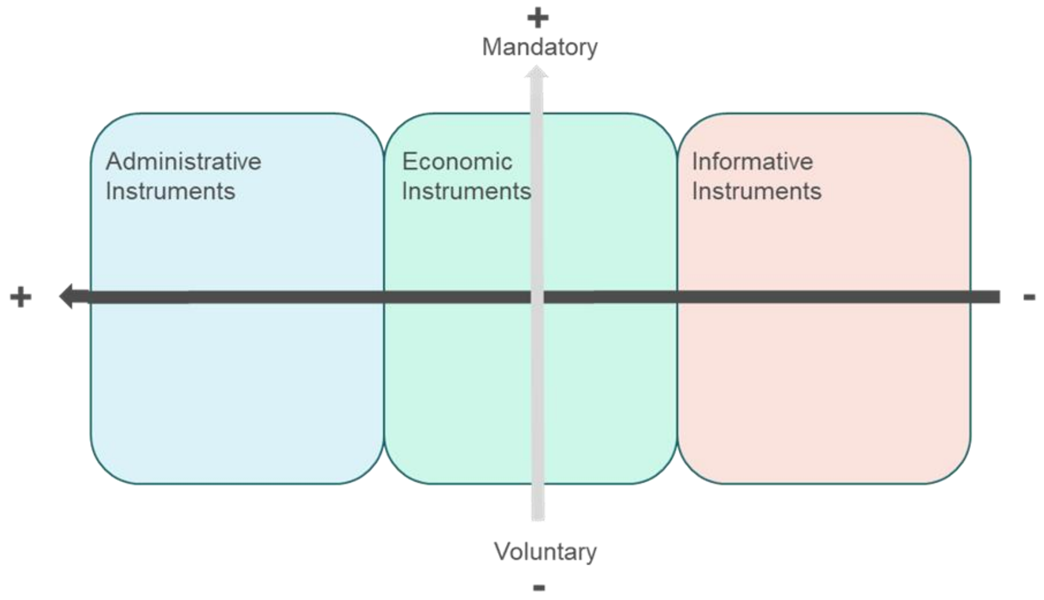
Table 6. Policy instruments typology and examples of measures

	Mandatory	Voluntary
Administrative	e.g. bans, standards, quotas, licences	e.g. standards, agreements between government and industry
Economic	e.g. taxes, fees, tariffs, subsidies	e.g. public procurement, loan guarantees, charges
Informative	e.g. reporting requirements, labelling, education	e.g. certification schemes, awareness raising campaigns, environmental management systems

Source: JRC elaboration

A well-defined command and control administrative policy instrument is typically more effective than a mere informative instrument, which is mostly applied as a supportive instrument. Moreover, the potential effect of a mandatory policy instrument, under monitoring obligations by a competent authority, which is applied throughout a sector or a national context, can be more effective than a voluntary agreement between industry players and a central government authority. In Figure 39, the potential effectiveness of policy instruments according to their typology is illustrated.

Figure 39. Anticipated effectiveness (horizontal line) of policy instruments by type



Source: Own illustration

7.2.4 Life-cycle approach in policymaking

To reduce the risk of burden shifting from one life-cycle stage to another, a wide systems perspective is required in the designing of a policy mix (Ekvall et al., 2016). This implies that the policy mix would target every stage of the life cycle of a process or product to avoid potential counteractive or unintended effects of the selected instruments upstream or downstream the supply chain, while in the meantime striving to achieve synergies between the various policy instruments to reinforce the anticipated outcome of the policy mix (Dalhammar, 2015). Therefore, in the context of CE, a carefully designed policy mix has the potential to result in a strengthened policy framework with a significant influence towards saving resources and increasing the mass and quality of circulated materials and products in the economy. The direct effects of the policy mix would be expected to have higher impact than what a mere combination of the individual policy instruments would be able to achieve, and would target proportionately all life cycle stages (Milios, 2018). Conceptually, a CE policy mix would include a set of complimentary policy instruments applied across the life cycle of materials/products.

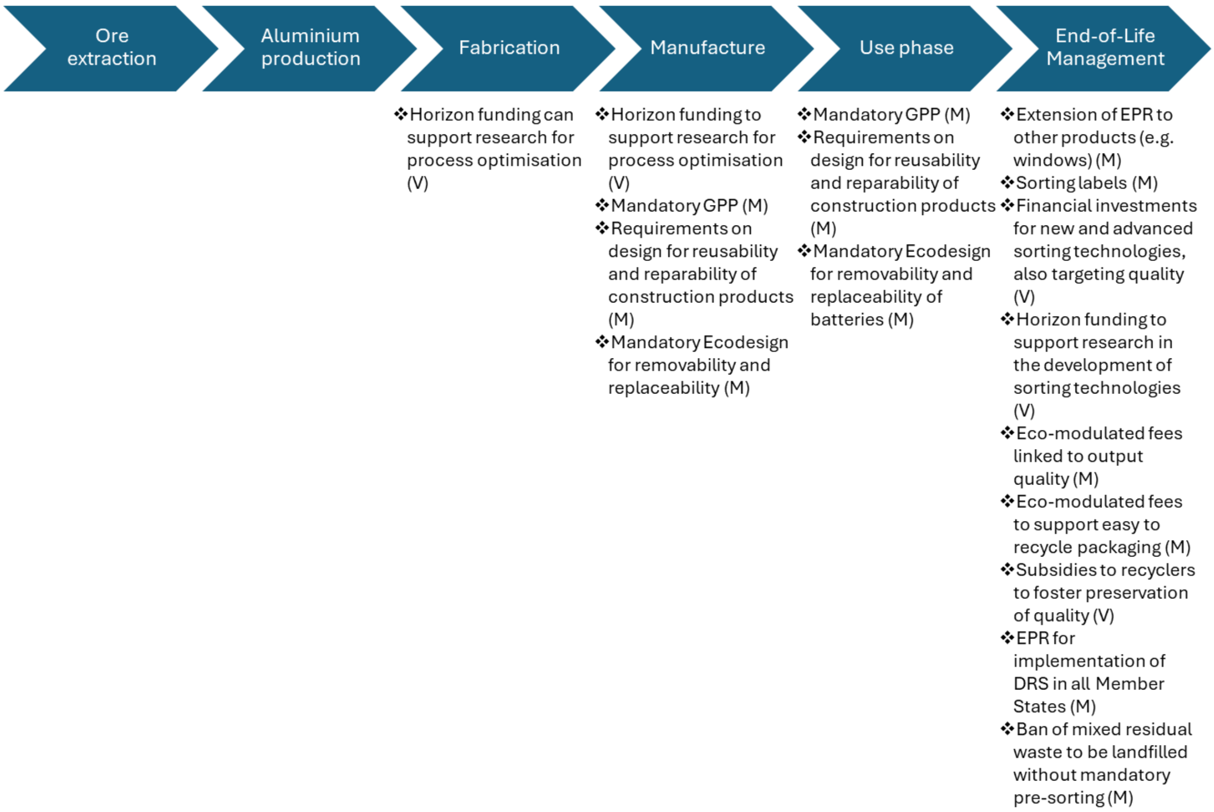
7.3 Policy suggestions to activate the CE levers studied

Table 7 presents a summary of the levers, their quantified effects as reduction of the primary material demand and of climate change mitigation, along with a list of potential policy instruments that can 'activate' the lever. The instruments suggested are also displayed in Figure 40 based on their positioning along the aluminium supply chain.

In total, a mix of eleven policy instruments is suggested, on top of existing policy instruments, to 'activate' the proposed levers investigated in the study. The instruments proposed cover all stages of the material life cycle, except for distribution (not shown for simplicity), ore extraction and aluminium production. It is important to note that advancements in smelting technologies and the use of inert anodes are not herein investigated as these interventions mainly pertain to decarbonisation actions rather than to CE. Nevertheless, research and investments at the production stage are certainly needed to lower direct and indirect emissions of the sector. These policy measures would therefore fall into the stage of aluminium production.

All instruments suggested are mandatory, except for three voluntary ones, namely the use of Horizon Europe, the implementation of financial investments to support the development of new and advanced sorting technologies, and the employment of subsidies for recyclers to foster high-quality recycling. The instruments proposed below are further discussed in Sections 7.3.1-to-7.3.3; notice that increased burdens (either economic or administrative) for industry and/or consumers are not assessed herein.

Figure 40. Summary of the policy instruments suggested to 'activate' the levers analysed in the study and their position along the material supply chain



Note: The distribution stage is not shown for simplicity. DRS: Deposit Return System; EPR: Extended Producer Responsibility; GPP: Green Public Procurement; M: Mandatory; V: Voluntary

Source: Own illustration

Table 7. List of policy instruments that can trigger the effects of the CE levers

R-cluster	Lever	Primary material demand & GHG reduction	Sector affected	Existing policy instruments?		Policy instruments suggested?	
				What	Type of instrument & Lifecycle stage	What	Type of instrument & Lifecycle stage
Reduce	Pre-consumer scrap reduction	-0.1 Mt (2%)[29] 1 Mt CO_2-eq (1%)	All sectors are affected, i.e. building, transport	No specific instrument in place to optimise fabrication and manufacturing processes.	-	Horizon Europe can support research in the optimisation of fabrication and manufacturing processes.	Type: Econ; Voluntary Lifecycle stage: Fabrication, Manufacture
Reuse	Design for reusability	0.4 Mt (10%) 11 Mt CO_2-eq (11%)	Building	Yes, the Green Public Procurement (GPP) for construction products already encompasses criteria on design for reusability.	Type: Admin/Econ; Voluntary Lifecycle stage: Manufacture, Use	Make GPP requirements on design for reusability of construction products mandatory for aluminium-based construction products (e.g. windows). The Construction Product Regulation (CPR) (Regulation EU 2024/3110) is mainly targeting cement, steel, and insulation materials. Requirements for design for reusability and reparability should also be established for aluminium-based construction products.	Type: Admin/Econ; Mandatory Lifecycle stage: Manufacture, Use Type: Inform; Mandatory Lifecycle stage: Manufacture, Use

[29] In this lever, the amount of primary material demand increases compared to the corresponding amount in the Baseline 2050 scenario. Despite this being counterintuitive, this is mathematically correct, and it is influenced by the assumptions made in the mass flow analysis to close the mass balance. Indeed, the import has been re-proportioned according to the shares in the Baseline 2050 scenario.

				Yes, the Ecodesign for Sustainable Products Regulation (ESPR) is expected to deliver on requirements for products' reusability with respect to aluminium intermediate products.	Type: Admin; Mandatory Lifecycle stage: Fabrication		
			Transport	Yes, the End-of-Life Vehicle Regulation proposal (amending Regulations EU 2018/858 and 2019/1020 and repealing Directives 2000/53/EC and 2005/64/EC) already addresses the need to design vehicles that are easy to dismantle, reuse and recover. Yes, the Ecodesign for Sustainable Products Regulation (ESPR) is expected to deliver on requirements for products reusability with respect to aluminium intermediate products.	Type: Admin; Mandatory Lifecycle stage: Manufacturing, End-of-Life Type: Admin; Mandatory Lifecycle stage: Fabrication		
			Machinery and equipment	Yes, the Ecodesign for Sustainable Products Regulation (ESPR) is expected to deliver on requirements for products reusability with respect to aluminium intermediate products.	Type: Admin; Mandatory Lifecycle stage: Fabrication		
			Electrical	Yes, Ecodesign for batteries addressing design for removability and replaceability.	Type: Admin; Voluntary Lifecycle stage: Manufacture, End-of-Life	Make Ecodesign requirements on design for removability and replaceability mandatory.	Type: Admin; Mandatory Lifecycle stage: Manufacture, Use

				Yes, the Ecodesign for Sustainable Products Regulation (ESPR) is expected to deliver on requirements for products reusability with respect to aluminium intermediate products.	Type: Admin; Mandatory Lifecycle stage: Fabrication		
			Consumer durables, Other	Yes, the Waste from Electrical and Electronic Equipment (WEEE) Directive (Directive 2012/19/EU) supports the need for cooperation among producers and recyclers to facilitate re-use, dismantling and recovery of WEEE, its components and materials.	Type: Admin; Mandatory Lifecycle stage: Manufacture, End-of-Life		
				Yes, Green Public Procurement (GPP) and Ecodesign are in place for electronic equipment & ICT, household appliances and address design for reusability and reparability.	Type: Admin/Econ; Voluntary Lifecycle stage: Manufacture, End-of-Life	Make GPP requirements on design for reusability of aluminium-based products mandatory.	Type: Admin/Econ; Mandatory Lifecycle stage: Manufacture, Use
				Yes, the Ecodesign for Sustainable Products Regulation (ESPR) is expected to deliver on requirements for products reusability with respect to aluminium intermediate products.	Type: Admin; Mandatory Lifecycle stage: Fabrication		

	Remanufacturing of automotive components	0.01 Mt (0.2%) 1 Mt CO_2-eq (2%)	Transport, passenger car	Yes, the End-of-Life Vehicle Regulation proposal (amending Regulations EU 2018/858 and 2019/1020 and repealing Directives 2000/53/EC and 2005/64/EC) already addresses the need to design vehicles that are easy to dismantle, reuse and recover.	Type: Admin; Mandatory Lifecycle stage: Manufacture, End-of-Life		
				No, although Green Public Procurement (GPP) on "Transport" is established.	Type: Admin; Voluntary Lifecycle stage: Manufacturing	Mandatory GPP requirements for remanufacturing of vehicle parts.	Type: Admin/Econ; Mandatory Lifecycle stage: Manufacture, Use
				Yes, the Ecodesign for Sustainable Products Regulation (ESPR) is expected to deliver on requirements for products reusability with respect to aluminium intermediate products.	Type: Admin; Mandatory Lifecycle stage: Fabrication		
Recover	Improved waste collection and sorting	0.3 Mt (9%) 2 Mt CO_2-eq (2%)	All sectors when reaching End-of-Life	Yes, partially by the targets on recycling included in the Waste Framework Directive (WFD) (Directive EU 2018/851), Packaging and Packaging Waste Regulation (PPWR) (Regulation EU 2025/40) that also encompasses the establishment of mandatory Deposit Return System (DRS) and the use of matching labels for products and bins. Both the WFD and	Type: Admin/Econ; Mandatory Lifecycle stage: End-of-Life	Extension of EPR to further aluminium-containing products (e.g., windows).	Type: Admin/Econ; Mandatory Lifecycle stage: Manufacture, End-of-Life

				PPWR encompass the establishment of Extended Producer Responsibility (EPR) schemes.		Introduction of waste sorting labels into packaging and aluminium-based products. Financial incentives for the deployment of new and advanced sorting technologies. Horizon Europe can support research in the development of new sorting technologies.	Type: Inform; Mandatory Lifecycle stage: End-of-Life Type: Econ; Voluntary Lifecycle stage: End-of-Life Type: Econ; Voluntary Lifecycle stage: End-of-Life
	Improved waste collection and sorting, and scrap quality	0.3 Mt (9%) 3 Mt CO_2-eq (3%)	All sectors when reaching End-of-Life	Yes, partially by the targets on recycling included in the Waste Framework Directive (WFD) (Directive EU 2018/851), Packaging and Packaging Waste Regulation (PPWR) (Regulation EU 2025/40) that also encompasses the establishment of mandatory Deposit Return System (DRS) and the use of matching labels for products and bins. Both the WFD and PPWR encompass the establishment of Extended Producer Responsibility (EPR) schemes.	Type: Admin/Econ; Mandatory Lifecycle stage: End-of-Life	Implementation of eco-modulated fees linked to output quality via closed-loop recycling for packaging and building components.	Type: Econ; Mandatory Lifecycle stage: End-of-Life

						Financial incentives for the deployment of new and advanced sorting technologies. Subsidise the recycle industry to foster preservation of quality. Horizon Europe can support research in the development of new sorting technologies.	Type: Admin/Econ; Voluntary Lifecycle stage: End-of-Life Type: Econ; Voluntary Lifecycle stage: End-of-Life Type: Econ; Voluntary Lifecycle stage: End-of-Life
	Design for packaging recoverability and recycling	0.01 Mt (0.3%) 0.1 Mt CO_2-eq (0.1%)	Packaging when reaching End-of-Life	Yes, the Packaging and Packaging Waste Regulation (PPWR) (Regulation EU 2025/40) establishes that all packaging on the market shall be recyclable.	Type: Admin; Mandatory Lifecycle stage: Manufacture, End-of-Life	Implementation of eco-modulated fees into the EPR schemes to reduce the fees for easy to recycle packaging.	Type: Admin/Econ; Mandatory Lifecycle stage: Manufacture, End-of-Life
	Expansion of Deposit Return Systems	0.2 Mt (4%) 3 Mt CO_2-eq (4%)	Packaging when reaching End-of-Life	Yes, the Packaging and Packaging Waste Regulation (PPWR) (Regulation EU 2025/40) establishes the implementation of deposit return systems.	Type: Admin; Mandatory Lifecycle stage: End-of-Life	Mandate existing EPR schemes for packaging to implement DRS in all MS.	Type: Admin; Mandatory Lifecycle stage: End-of-Life
	Recovery from mixed waste	1 Mt (14%) 2 Mt CO_2-eq (2%)	Packaging when reaching End-of-Life	Yes, partially via the requirement of attaining municipal waste recycling targets established within the Waste Framework Directive (WFD) (Directive EU 2018/851), and attaining the targets on limiting landfilling of the Landfill Directive (Directive EU 2018/850).	Type: Admin; Mandatory Lifecycle stage: End-of-Life	EU-wide ban of mixed residual waste to be landfilled without a mandatory pre-sorting stage to recover aluminium that can be recycled.	Type: Admin; Mandatory Lifecycle stage: End-of-Life

Note: The reduction in primary material demand and GHG reduction are expressed relative to the baseline in year 2050, taken as the reference (i.e. values should be interpreted as the additional savings incurred by the levers relative to the baseline in 2050)

Source: JRC elaboration

7.3.1 Reduce

Background: The manufacturing of aluminium-containing products and, especially, the fabrication of aluminium semis are highly optimised processes. Based on discussions with the industry, limited improvements are expected in further optimisations of such processes to reduce losses.

Policy instrument in place: No specific instrument exists to optimise the fabrication and manufacturing processes as the industry already strives to fully exploit such a valuable material.

Policy instruments and/or research (further) suggested: Improvements in the fabrication and manufacture process can be achieved by supporting research and development (R&D) in the sector. This can be supported via, for example, the Horizon Europe programme.

Increased burdens for industry or consumers: None are suggested as this requires further investigation that is not herein performed.

7.3.2 Reuse

Background: The potential to extend the lifetime of aluminium contained in buildings and in the transport sector is debated due to possible trade-offs between lifetime extension and efficiency loss (e.g. performance of windows to ensure energy efficient buildings) and changes in the vehicle fleet (i.e. transition from combustion engines to electric vehicles). Further, based on discussions with the industry, repairing of vehicles represents a niche market as of today and it is not expected to expand in the future. Nevertheless, better design of products ensuring easier remanufacturing, disassembly, and replacement can reduce the demand of virgin aluminium and decrease environmental impacts, as supported by our analysis.

Policy instruments in place: For buildings, Green Public Procurement (GPP) already encompasses criteria on design for reusability for construction products. For vehicles, the End-of-Life Vehicles (ELV) Regulation proposal addresses the need to design vehicles that are easy to dismantle, reuse and recover. Further, transport and road vehicles are also addressed via GPP, although criteria addressing the extension of lifetime of vehicles are not included. Other transport sectors (aerospace, railway cars, etc.) are not specifically targeted by any legislation. Within the electrical sector, batteries are herein included and Ecodesign requirements addressing design for removability and replaceability exist. With respect to consumer durables and other, the Waste from Electrical and Electronic Equipment (WEEE) Directive is in place and supports the need for cooperation among producers and recyclers to facilitate reuse, dismantling and recovery of WEEE, its components and materials. Further, GPP addressing design for reusability and reparability exists for electronic equipment and ICT, and household appliances. Machinery and equipment are not targeted with a specific policy intervention. Overall, across all sectors, the Ecodesign for Sustainable Products Regulation (ESPR) is in place and is expected to deliver on requirements for products' reusability with respect to aluminium intermediate products that are fed into all analysed sectors.

Policy instruments and/or research (further) suggested: It is suggested to establish mandatory GPP requirements on design for reusability of aluminium-based products (e.g. windows). Further, additional requirements on design for reusability and reparability for aluminium in construction products could be implemented, for example, via the Construction Product Regulation (CPR). The CPR mainly targets cement, steel, and insulation materials while setting standards and introducing measure on Digital Product Passport, CE marking needs reflecting both technical performance and environmental impacts, and reporting on CO_2 emissions and energy use; yet its scope and requirements could be expanded to include aluminium based products. With respect to electrical, vehicles, consumer durables and others, the existing GPP and eco-design requirements should be made mandatory specifically addressing design for reusability and repairability.

Increased burdens for industry or consumers: Despite not being quantitatively assessed in our analysis, the implementation of ESPR might lead to additional administrative and compliance burdens for producers.

7.3.3 Recover

Background: despite being highly recycled, different alloys are frequently mixed together restricting their recycling into cast aluminium alloys only. Ensuring closed loop recycling, especially for wrought aluminium alloys, represents a challenge that requires better collection and more refined sorting technologies. Separate collection of, for example, aluminium-containing construction products could be now justified by emerging consistent flows that, ultimately, could be recycled more closed loop. Further, design of products targeting material identification, disassembly, and recycling also represent another challenge that needs to be addressed to increase recycling and its quality. Finally, missorted aluminium could be additionally recovered from sorting facilities prior final treatment.

Policy instruments in place: the Packaging and Packaging Waste Regulation (PPWR), the Waste Framework Directive (WFD), and the Landfill Directive are in place and set targets on recycling and on limits of municipal waste to be landfilled. None of these instruments targets improving quality of recycling.

Policy instruments and/or research (further) suggested: the Horizon Europe program could support R&D of new sorting technologies able to sort waste based on, for example, alloys to enhance the quantity of material recycled and its quality. The quality aspect could also be addressed via, for example, introducing financial incentives for the deployment of new sorting technologies or by subsidising the recycling industry to preserve quality. Extended Producer Responsibility (EPR) schemes introduced in the WFD could be extended to, for example, building components with the introduction of eco-modulated fees linked to output quality via closed-loop recycling. Within EPR schemes, eco-modulated fees could also be implemented to reduce the fees for easy to recycle packaging supporting design for recycling. Further, EPR schemes could also be used for implementing Deposit Return Systems (DRS) in all Member States. Finally, within existing policies, such as the WFD and the Landfill Directive, an EU-wide ban of mixed residual waste to be landfilled without a mandatory pre-sorting stage to recover aluminium to be recycled could also be mandated.

Increased burdens for industry or consumers: despite not being quantitatively assessed in our assessment, mandating DRS in countries where a separate collection system does exist may incur transition costs, especially for Producer Responsibility Organisations. Finally, centralised sorting plants would require financial support to become economically viable, which could have implications for consumers having to pay higher municipal waste management costs.

8 Conclusions

8.1 Key scientific findings

This study has investigated the potential of circular economy (CE) levers to mitigate climate change, reduce resource dependency, and promote socio-economic benefits in the EU aluminium sector. The results indicate that the implementation of CE levers can lead to significant reductions in GHG emissions, primary material demand, and waste generation. The study highlights the importance of a holistic approach to CE, considering the entire life cycle of aluminium and the interactions between different stakeholders and sectors.

The analysis suggests that the CE levers studied can achieve an additional impact reduction on Climate Change of between 12-14 Mt CO_2-eq. annually by 2050, on top of what would be achieved by decarbonisation of the energy system only. The results also show that CE can lead to a decrease in the EU demand for bauxite, which is the precursor of aluminium, as well as reduction in energy demand. Implementing the CE levers at once would also positively affect the EU's trade balance, which is estimated to increase by approx. EUR 3.6 billion annually while reducing imports from outside the EU. However, these changes also come with observed decreases in Gross Values Added, Gross Domestic Product, and employment. While these are expected because of the reduction in material demanded by the industry, it emphasizes the need for further research on the CE implications on the service (e.g. repair) sectors. In this study, a simplified but commonly used approach was followed, whereby the reductions in economic input demanded by a sector were diverted to repair/services and innovation, but this reallocation of resources may be very different and deserves further investigation.

The study emphasizes the importance of a consistent policy mix approach, combining different policy instruments to address the complex challenges of CE. The study suggests a range of policy instruments to activate the CE levers, including mandatory and voluntary instruments, such as administrative, economic, and informative instruments. The policy instruments suggested encompass measures to optimise production, extend lifetime, recover materials, and enhance recycling quality.

In conclusion, this study demonstrates the potential of CE to contribute to a more sustainable and resource-efficient aluminium sector in the EU. The implementation of CE levers can lead to significant environmental benefits, but it requires a holistic approach, careful policy design, and coordination among stakeholders. The study's findings and recommendations can inform policymaking and support the transition to a more circular and sustainable economy.

8.2 Key policy recommendations

The following policy recommendations are designed to support the implementation of the CE levers in the aluminium sector, with the goal of reducing primary aluminium production and use, promoting sustainable use of materials, and minimising waste.

- *Reduce* (reduce production of pre-consumer scrap optimising the fabrication and manufacturing process):
    - Provide financial instruments (via, e.g., Horizon Europe) to the industry to support research and development in the sector to optimise production processes by increasing the yield while minimising pre-consumer waste.

- *Reuse* (extending lifetime of products):
    - Implement mandatory Green Public Procurement criteria for (public) building to promote reusability of aluminium-containing construction products (e.g. windows).
    - Introduce regulatory requirements on reusability and reparability for aluminium-based construction products.
    - Introduce mandatory Ecodesign requirements on design for removability and replaceability for aluminium-based electrical products.
    - Implement Green Public Procurement criteria for transport to promote remanufacturing of vehicle parts.
- *Recover* (improving recycling rate and quality):
    - Extend the scope of Extended Producer Responsibility to additional aluminium-containing products (e.g. windows) and implement the use of ecomodulated fees to reduce the fees for easy to recycle packaging and building components.
    - Provide financial and administrative instruments to support advanced sorting technologies and ensure high-quality recycled scrap and subsidise the recycle industry to foster preservation of quality.
    - Introduce mandatory Deposit Return Systems and foster sorting, notably by deployment of centralised sorting plants for mixed waste to increase material recovery rates.
    - Ban of mixed residual waste to be transferred for incineration or landfilling without obligatory pre-sorting.

8.3 Future Research Directions

The following limitations and challenges of this study could be addressed by further research:

- Economic growth of service sector: this study takes simplified assumptions on the effects of CE levers on service sectors, such as repair or remanufacturing. We encourage to analyse the implications of CE levers on repair and similar service activities as well as research and innovation activities in detail. This may also be done by employing Input-Output analysis or dynamic macroeconomic models such as FIDELIO (or similar). However, the focus should specifically be on the socio-economic consequences in service sectors, in terms of trade, growth, and employment change, as a response to selected CE lever implementation.
- Strengthening integration of bottom-up and top-down methos: this study strengthens the link between bottom-up (MFA, LCA) and top-down (EEIOA, dynamic macroeconomic modelling) tools in several ways, notably by disaggregating the Eurostat compliant FIGAROE3 Input-Output tables in accordance with detailed sector-specific material flow analyses and life cycle datasets. However, while the life cycle inventories from the LCA were used as input for the EEIOA for steel, aluminium, cement/concrete sector (and to some extent, also for plastic), ideally, the assessment would integrate the four sectors into one dynamic macroeconomic model in FIDELO.

- Prospective assessment on demand-shocks: this study is the first that the authors are aware of to illustrate the trade effects of CE levers. However, in view of the ongoing geopolitical landscape characterised by tariffs and trade wars, we encourage research looking at extreme scenarios identified through foresight tools, e.g. in terms of drastic changes to trade relationships, 'buy EU' requirements, GDP growth, or energy scenarios (e.g. use FIDELIO to model the selective application of tariffs to distort current market prices, affecting trade partnerships and final consumer goods prices).
- Implementation of the levers via policy: this study focuses on the impacts of CE levers and does not focus on how to concretely implement them in policy or on the transition pathways required to achieve a full-fledge CE implementation. The former is a typical task of impact assessment supporting studies, including identifying appropriate policy measures (and options) to enable the levers, assessing administrative costs (on top of compliance ones, which are partially captured in this study), and distributional effects across affected income groups. Studying transitional pathways requires instead dedicated foresight analyses of exploratory nature.

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List of abbreviations and definitions

Abbreviations	Definitions
ACE50	Ambitious Circular Economy scenario (2050)
BAU	Business as Usual
BSL50	Baseline scenario (2050)
CAPEX	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CE	Circular Economy
CEAP	Circular Economy Action Plan
CFF	Circular Footprint Formula
CGE	Computable General Equilibrium
CMUR	Circular Material Use Rate
CPR	Construction Products Regulation
CRM	Critical Raw Material
CTC50	Compliance with selected Targets on Circular Economy scenario (2050)
DRS	Deposit Return System
EC	European Commission
ECO50	Eco-States scenario (2050)
EEIOA	Environmentally Extended Input-Output Analysis
EEMRIO	Environmentally Extended Multi Regional Input-Output
EF	Environmental Footprint

Abbreviations	Definitions
eLCC	Environmental Life Cycle Costing
EPR	Extended Producer Responsibility
ESPR	Ecodesign for Sustainable Products Regulation
ETS	Emissions Trading System
EU	European Union
feLCC	Full Environmental Life Cycle Costing
GBB50	Green Business Boom scenario (2050)
GDP	Gross Domestic Product
GECO	Global Energy and Climate Outlook
GEW50	Glocal Eco-World scenario (2050)
GHG	Greenhouse Gas
GPP	Green Public Procurement
GRO50	Growth-oriented baseline scenario (2050)
GTC50	Greening through Crisis scenario (2050)
GVA	Gross Value Added
IAM	Integrated Assessment Model
IOA	Input-Output Analysis
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
ME	Macroeconomic analysis
MFA	Material Flow Analysis
MREEIO	Multi Regional Environmentally Extended Input Output

Abbreviations	Definitions
Mt	Megatonne
NDC-LTS	Nationally Determined Contribution - Long-Term Strategies
OPEX	Operating costs
PJ	Petajoule
PPWR	Packaging and Packaging Waste Regulation
ROW/RoW	Rest of the World
SHR50	Shrink-oriented baseline scenario (2050)
SME	Small and medium-sized enterprises
STQ21	Status Quo scenario (2021)
SUT	Supply and Use Tables
WEEE	Waste from Electrical and Electronic Equipment
WFD	Waste Framework Directive

List of figures

List of tables

Annexes

Annex 1. Circularity levers

This section outlines the method employed to define circularity levers in the aluminium sector. The method consisted of four main steps: system boundaries definition, levers identification, levers validation, levers quantification.

Step 1: System boundary definition

The first step was to define the system boundaries for the analysis. These were set by considering all the stages of the material supply chain (from mining to waste management – see Figure 11) with a focus on the relevance for the European aluminium sector. To this end, the scope of the analysis was mainly focused to a set of key applications for EU industry, defined according to former scientific work in support of EU policy (Passarini et al., 2018) and a recent industry report on their circularity relevance (European Aluminium, 2020), in consultation with a team of experts from European Aluminium (association of 100+ members representing the industry in 30 countries). The circularity levers identified mainly focus on interventions on the transport, construction, and packaging sectors. Yet, whenever the information was available in the selected publications, the effect of the circularity lever was extended to the other sectors, namely electrical, mechanical equipment, consumer durables, and other.

Step 2: Levers identification

The second step was the identification of circularity levers relevant for the aluminium sector. To this end, three researchers collected data from both scientific and grey literature on the subject. Selected grey literature included relevant reports on aluminium and its circularity (mainly in the European context) developed over the past 6 years, provided by experts from the aluminium industry, consultancy firms, and policymaking. The inclusion of such grey literature was functional to capture up-to-date information and key industry and policy developments in the EU and, when relevant, globally. Scientific literature included peer reviewed journal articles, conference proceedings and academic dissertations. First, the supplementary information of the literature listed in the study performed by Creutzig et al. (2022) was analysed to identify any previously collected literature that could be reused. After this first rapid search, Google Scholar was used to search the combination of R9 strategies (according to the definition of Potting et al., 2017) with the keyword "Aluminium". The papers were then selected based on number of citations and availability of quantified results that could be reused within the modelling. A list with all the literature sources used for the identification of circularity levers for aluminium in the EU is provided in Table A 1

Table A 1. List of literature sources for the identification of circularity levers for aluminium in the EU

Author	Year	Title	Source
Agora Industrie & SYSTEMIQ	2023	Resilienter Klimaschutz durch eine zirjuläre Wirtschaft. Perspektiven und potenziale für energie-intensive Grundstoffindustrien	Industry report
Bertam et al.	2017	A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products	Scientific journal
Brough & Jouhara	2020	The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery	Scientific journal
Cooper & Allwood	2012	Reusing Steel and Aluminium Components at End of Product Life	Scientific journal

Cui & Roven	2010	Recycling of automotive aluminium	Scientific journal
Cullen & Allwood	2013	Mapping the Global Flow of Aluminium: From Liquid Aluminium to End-Use Goods	Scientific journal
Dev Srivyas & Charoo	2019	Application of Hybrid Aluminium Matrix Composite in Automotive Industry	Scientific conference
Ducker	2023	Aluminium Content in Passenger Vehicles (Europe). Assessment 2022 and Outlook 2026, 2030.	Industry report
Duflou et al.	2015	Environmental assessment of solid state recycling routes for aluminium alloys: Can solid state processes significantly reduce the environmental impact of aluminium recycling?	Scientific conference
Energy Transition Commission	2023	Material and Resource Requirements for the Energy Transition	Industry report
European Aluminium	2004	Collection of Aluminium from Buildings in Europe: A study by Delft University of Technology	Industry report
European Aluminium	2018	Environmental Profile Report: Life-Cycle inventory data for aluminium production and transformation processes in Europe	Industry report
European Aluminium	2020	Circular Aluminium Action Plan: A Strategy for Achieving Aluminium's Full Potential for Circular Economy by 2030	Industry report
European Aluminium	2022	Aluminium beverage can recycling rates 2020	Industry report
European Aluminium	2023	End-of-life of vehicles Directive revision: European aluminium top priorities	Industry report
European Commission	2020	Study on the EU's list of Critical Raw Materials (2020) – Final report	Policy report
Fam et al.	2006	Repair of damaged aluminium truss joints of highway overhead sign structures using FRP	Scientific journal
Farjana et al.	2019	Impacts of aluminium production: A cradle to gate investigation using life-cycle assessment	Scientific Journal
Fernström et al.	2022	Circularity of aluminium: Mapping difficulties in scrap circulation. A literature study and interviews with actors with focus on aluminium circulation in Sweden.	Academic dissertation
Han et al.	2017	Circular economy measures that boost the upgrade of an aluminium industrial park	Scientific Journal
Institut de Recherche Technologique	2023	Market development for secondary casting alloys beyond motor blocks - study on casting alloy market and recycling	Scientific report
International Energy Agency	2022	The Role of Critical Minerals in Clean Energy Transitions	Policy report
Labberton	2020	The ideal aluminium packaging sorting model	Industry report
Liesbet & van Acker	2022	Metals for Clean Energy: Pathways to solving Europe's raw materials challenge	Industry report
Løvik et al.	2014	Long-Term Strategies for Increased Recycling of Automotive Aluminium and Its Alloying Elements	Scientific journal
Lu et al.	2022	A solid-state electrolysis process for upcycling aluminium scrap	Scientific journal
Material Economics	2018	The circular economy—A powerful force for climate mitigation	Industry report
Material Economics	2019	Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry	Industry report
Milford et al.	2011	Assessing the potential of yield improvements, through process scrap reduction, for energy and CO_2 abatement in the steel and aluminium sectors	Scientific journal
Mission Possible Partnership	2023	Making net-zero aluminium possible. An industry-backed, 1.5°C-aligned transition strategy	Industry report
Passarini et al.	2013	Aluminium flows in vehicles: Enhancing the recovery at end-of-life	Scientific journal

Passarini et al.	2018	Material Flow Analysis of Aluminium, Copper, and Iron in the EU-28	Policy report
Pavel & Tzimas	2016	Raw materials in the European defence industry	Policy report
Pedneault et al.	2023	How much sorting is required for a circular low carbon aluminium economy?	Scientific journal
Rech et al.	2014	Different Cold Spray Deposition Strategies: Single- and Multi-layers to Repair Aluminium Alloy Components	Scientific journal
Sevigné-Itoiz et al.	2014	Environmental consequences of recycling aluminium old scrap in a global market	Scientific journal
Singhvi	2021	The incentives for and the problems faced in aluminium recycling: A case study of the process of singulation for aluminium scrap of 50-180 mm size range	Academic dissertation
Slingerland et al.	2015	Energy efficiency and GHG emissions – Prospective scenarios for the aluminium industry	Policy report
Spinger & Hasanbeigi	2016	Emerging energy efficiency and carbon dioxide emissions – Reduction technologies for industrial production of aluminium	Policy report
US Department. of Energy	2023	Critical materials assessment	Policy report
Warrings & Fellner	2018	Current status of circularity for aluminium from household waste in Austria	Scientific journal
Warrings & Fellner	2021	How to increase recycling rates. The case of aluminium packaging in Austria	Scientific journal
Widener et al.	2018	Structural repair using cold spray technology for enhanced sustainability of high value assets	Scientific conference
Wong et al.	2018	Recycling of end-of-life vehicles (ELVs) for building products: Concept of processing framework from automotive to construction industries in Malaysia	Scientific journal
World Bank	2022	Competitiveness of global aluminium supply chains under carbon pricing scenarios for solar PV	Scientific report
World Economic Forum	2021	The answer to the aluminium industry's emissions issue? Aluminium's infinite recyclability	Online article
Yang et al.	2015	The Impact of Automotive Product Remanufacturing on Environmental Performance	Scientific conference
Yılmaz et al.	2017	A Study of Lightweight Door Hinges of Commercial Vehicles Using Aluminium Instead of Steel for Sustainable Transportation	Scientific journal
Zibell et al.	2022	Impacts of Circular Economy on EU climate policies - mitigation and adaptation	Policy report

Source: JRC elaboration

The data from selected sources was analysed using a qualitative method based on a deductive coding procedure (Fereday & Muir-Cochrane, 2006). This method entails performing a thematic clustering of insights derived from diverse written sources, guided by pre-existing conceptual categories relevant for the analysis. Information on aluminium circularity from selected sources was merged and integrated into a list of levers structured according to the classification provided in Section 2.1. By doing so, the list that was obtained by including all references reported in Table A 1 was reduced to a preliminary list of 43 levers.

Step 3: Levers validation

The preliminary list of levers based solely on the analysis of literature was consequently validated with industry experts from European Aluminium as well as with academics and colleagues from the Joint Research Centre of the European Commission. Following a conversational interview approach (Patton, 2002), a video conference was organised with the abovementioned experts. In this consultation, various levers were discarded, enriched with new detail and/or merged in view of feasibility considerations within the industry context. This resulted in an updated list of 11 levers. This step also enabled to collect initial information on a possible quantification of the effects of the levers.

Step 4: Levers quantification

After validation, the fourth step entailed the quantification of the effect of the levers. This was done by retrieving quantitative data available from the original source documents and the supplementary material provided by a subset of documents from the full list of selected literature presented in Table A 1. In the process, the list of levers was again updated by adding, eliminating, or subtracting elements, depending on bottom-up and top-down modelling possibilities and constraints. The list was further refined and scaled down to 6 levers of the preliminary 11 ones. Two additional levers were then added after the online consultation based on additional literature that was not initially considered. This resulted in the final list of 8 levers, complemented with categorisation and quantification, as presented in the overview provided in Table 3. In the following section, each lever from Table 3 is explained in greater detail.

Description of circularity levers and implementation in the modelling

1. Pre-consumer scrap reduction

This lever addresses pre-consumer scrap reduction. Pre-consumer scrap includes both fabrication scrap from creating semi-finished products and scrap arose during manufacturing of finished products (Bertram et al., 2017). This is generated, for example, during aluminium bar extrusion or from cutting aluminium sheets into final shapes.

According to Material Economics (2018), in the processes of casting, fabrication and manufacturing large amounts of pre-consumer scrap are generated; indeed, it is estimated that about 35-41% of the material ends up as pre-consumer scrap rather than as products. Yet, scrap generation varies significantly across sectors. For example, some car manufacturers produce over 40% scrap, while best practice is closer to 25% (Material Economics, 2018). Most of the pre-consumer scrap enters recycling directly from the fabricators. Hence, the quality and alloys used are known and, usually, the pre-consumer scrap is uncoated. Prior to remelting in reverbatory furnaces, little preparation is needed to produce wrought alloys. Yet, when arising at manufacturing, the pre-consumer scrap may be coated with paints, plastics or ink. Hence, this needs to be de-coated, which is usually the only significant scrap pre-treatment needed prior to its remelting (European Aluminium, 2018)

This circularity lever focuses on reducing such losses, through process improvements and optimization, ultimately reducing the amount of virgin material needed. According to Milford et al. (2011), three possible strategies are applicable to reduce yield losses (i.e. pre-consumer scrap generation), namely: i) developing new manufacturing processes with intermediate products closer in geometry to final components; ii) operating existing processes more effectively to improve yield; or, iii) modifying component designs to enhance tessellation. Yet, Milford et al. (2011) argue that: i) developing new manufacturing processes is limited by lack of economies of scale; ii) operating existing processes more effectively is often limited by the boundaries of the site; and, iii) modifying component designs can lead to a reduction in the demand for molten aluminium only if the scrap would take the place of some of the original product mass.

According to Milford et al. (2011), the reduction potential corresponds to 20%. This was thoroughly discussed with experts in European Aluminium as production processes in the aluminium industry are known to be already well optimized and such a value was considered to be too optimistic. After consultations with the industry, it was decided to have a more conservative approach and assume that such improvements would only result in a 5% reduction, at most.

Further, the 5% reduction was first applied to the amount of manufacturing scrap. Having modified this, the amount of semi-finished products and corresponding fabrication scrap were re-calculated. Based on the 'new' amount of fabrication scrap, a further 5% reduction was applied. Table A 2 summarises the modelling implementation of the lever discussed.

Table A 2. Modelling implementation of the lever focused on pre-consumer scrap reduction

Year	2050
Value	-5%
Type	Supply side
Circular economy strategy	Reduce
Modelling interpretation (bottom-up assessment)	Demand reduction for virgin aluminium due to the improved mechanical processes at fabrication and manufacturing stages. The lever results in a reduction in virgin molten aluminium, but also in a reduction of generated pre-consumer scrap that results in less recycled aluminium. *Functional unit*: Meeting the demand of final products in EU in 2050
Assumptions on the elaboration of the data taken from literature	The value taken from literature (i.e. 20% reduction in 2030) is considered as not realistic after discussions with the industry. Therefore, a conservative approach is used instead and a reduction of 5% is assumed for both manufacturing and fabrication scrap.
Limits and improvements (bottom-up assessment)	- No specific strategy among the ones listed in Milford et al. (2011) are indicated as most probable to occur. Hence, the technical implementation of the lever is not clear. - According to our calculations, the mass of primary aluminium required is higher than in the Baseline scenario. This is counterintuitive as if less input is required to produce the same unit of product, then one would expect that the mass of primary aluminium would also decrease. However, from a mathematical point of view, this is correct – it is affected by the way the mass balance has been constructed.

Source: JRC elaboration

2. Design for reusability

This lever addresses design for reusability and modularity of final products. It focuses on extending product lifetimes to avoid recycling, which is more cost-effective and environmentally beneficial, as it requires less energy (Cooper & Allwood, 2012). Achieving this involves various interventions, at the product and component level (Material Economics, 2018).

At the product level, there are four concrete approaches (Ardente et al., 2018; Kirchherr et al., 2017): i) direct reuse, where a product can find a second life in the same application by another consumer; ii) repair, which involves fixing a defective product to continue its original function; iii) refurbishing, which updates and restores an old product; and, iv) remanufacturing, which incorporates parts of a discarded product into a new one serving the same function.

At the component level, life extension is influenced by two factors: performance and demand (Cooper & Allwood, 2012). When performance is high, and demand is high, end-of-life components can be directly relocated into a new product. When performance is low, and demand is low they can be repurposed either by cascading "as-is" or by reshaping their geometry to fit into a different product with less sophisticated needs. When performance is low, but demand is high, component remanufacturing takes place, which entails further disassembly, redrilling, and surface recovery techniques to restore properties and re-use in a fully functional new product. Challenges to consider entail disassembly time, labour cost, logistical issues, and lack of an established supply chains and economies of scale.

According to Cooper & Allwood (2012), the following reductions could be achieved in 2012 by extending the lifetime of products: 40% in Transport, passenger car; 36% in Transport, aerospace; 10% in Transport, other; 50% in Construction, 50% in Electrical, cable; 10% in Electrical, other; 10% in Mechanical equipment; and, 50% in Consumer durables. Packaging is not affected by the lever as its products are characterised by a lifetime of 1 year. The values reported in the publication for Transport, passenger car, Construction, and Electrical, cable were thoroughly discussed with experts in European Aluminium. For passenger cars, it was discussed that the amount reported by Cooper & Allwood (2012) was not realistic due to the changes in the vehicle fleet expected in the next years (i.e. transition from combustion to electric engines), but also considering that the repairing of vehicles is a niche market. With respect to the construction sector, it was discussed that the amount reported by Cooper & Allwood (2012) was also not realistic. Indeed, aluminium is predominately used in windows. A possible repair of refurbishment of aluminium in a window would have negative impacts on the overall energy efficiency of a building. Finally, for cables, it was also discussed that the amount reported by Cooper & Allwood (2012) was not realistic as the aluminium used in cables is of very high quality and would be recycled while refurbishing might lead to losses of conductivity. Therefore, in the three mentioned applications it was decided to have a conservative approach. Hence, we departed from the reductions reported in the publication and assumed a 5% reduction for cables and the construction sector, and a 10% reduction for passenger cars. Finally, notice that values calculated for 2012 were assumed for 2050. Table A 3 summarises the modelling implementation of the lever discussed.

Table A 3. Modelling implementation of the lever focused on design for reusability

Year	2050
Value	Transport, passenger car -10%; Transport, aerospace -36%; Transport, other -10% Construction -5% Electrical, cable -5%; Electrical, other -10% Mechanical equipment -10% Consumer durables -50% Packaging, cans -0%; Packaging, foil -0% Other -10%
Type	Supply and demand side
Circular economy strategy	Reuse
Modelling interpretation (bottom-up assessment)	The reductions are applied to the final product demand resulting in a decrease in primary material needs and waste to be processed. *Functional unit*: Fulfilling the needs in terms of services in EU in 2050

Assumptions on the elaboration of the data taken from literature	- Design for reusability and modularity will affect all durable goods. - Data obtained from Cooper & Allwood (2012). - Intervention may affect both Business-to-Business but also Business-to-Consumers. - Potential as per year 2012.
Limits and improvements (bottom-up assessment)	- For "Construction" it is not yet standard practice for windows and other building components to extend their lifetime, but it will develop to some extent. It requires easier deconstruction and greater standardisation. - The value for "Other" is assumed as the lowest potential reported in Cooper & Allwood (2012). - As the model is not dynamic, it is assumed that the extension of lifetime has a pulse response in the year 2050, i.e. the reduction is 100% of its potential already in 2050. - In terms of environmental and economic impacts, remanufacturing is not accounted for.

Source: JRC elaboration

3. Remanufacturing of automotive components

This lever addresses remanufacturing of automotive components. When a vehicle reaches the end-of-life, dismantling specific aluminium parts for remanufacturing before shredding allows to increase resource efficiency. Most relevant parts in this sense include engines, heat exchangers, doors, bonnets, fenders, bumpers, and gearboxes (European Aluminium, 2020). This allows on the one hand segregating alloys to facilitate recycling and, on the other hand, it enables remanufacturing, which is preferable from an environmental perspective as discussed in Yang et al. (2015) where the authors estimated a reduction in energy inputs (between 68% to 83%) and lower CO_2 emissions (between 73% to 87%) compared to the corresponding virgin manufacturing process.

In automotive, remanufacturing is intended as the process restoring end-of-life components to a "new" condition, after disassembly, cleaning, inspection, reconditioning, replacement, and reassembly into a new vehicle, ultimately extending their lifetime. This process demands more labour but limited investment in machinery and energy compared to recycling. It is estimated that approximately 20% of a vehicle's weight could be affected by remanufacturing (Yang et al., 2015). The most promising aluminium components for remanufacturing are engine blocks, alternators, transformers, wheels, and transmission casing (Cooper & Allwood, 2012; Yang et al., 2015). Remanufacturing challenges include achieving "good as new" quality and dealing with poor-quality returned parts, technology constraints, and low recoverable value. To address these, challenges, product design is crucial, avoiding protruding structures to prevent damage during transportation, standardizing fasteners, and joints for easy disassembly, and adopting platform design or modularity to facilitate product upgrading (Yang et al., 2015). Table A 4 summarises the modelling implementation of the lever discussed.

Table A 4. Modelling implementation of the lever focused on remanufacturing of automotive components

Year	2050
Value	-10%
Type	Supply side

Circular economy strategy	Reuse
Modelling interpretation (bottom-up assessment)	The reductions are applied to the demand of the final product "Transport, passenger car" only resulting in a decrease in primary material needs and waste to be processed. *Functional unit*: Fulfilling the needs in terms of services in EU in 2050
Assumptions on the elaboration of the data taken from literature	Reference components for intervention is international combustion engine vehicles (Yang et al., 2015).
Limits and improvements (bottom-up assessment)	- As the model is not dynamic, it is assumed that the extension of lifetime has a pulse response in the year 2050, i.e. the reduction is 100% of its potential already in 2050. - In terms of environmental and economic impacts, remanufacturing is not accounted for.

Source: JRC elaboration

4. Improved waste sorting

Products are used and often mixed when discarded at their end-of-life, scattering post-consumer aluminium across various waste streams like beverage cans, food packaging, vehicle components, and building materials, where it is frequently mixed with other materials. Further, this negatively affects the recycling of wrought aluminium alloys (having an alloy concentration comprised between 1-10%) as opposed to cast aluminium alloys (having an alloy concentration of up to 20%) (European Aluminium, 2018). Indeed, wrought aluminium alloys that have been mixed together with cast aluminium alloys cannot be recycled back to pure aluminium hence determining substantial amounts of wrought aluminium alloys to be recycled in lower quality applications, especially in the automotive industry (European Aluminium, 2020; Liesbet & van Acker, 2022). Indeed, the automotive industry is a sink for cast aluminium alloys that are needed for the production of engine blocks in combustion engines (Institut de Recherche Technologique, 2022). However, as components evolve and traditional parts like engine blocks disappear with the transition to electric cars, the market may in the future not be able to absorb this lower-quality cast aluminium (European Aluminium, 2020; Material Economics, 2018a). Cooperation between industries is crucial to ensure continued recycling of automotive aluminium in a closed loop to prevent downcycling (Løvik et al., 2014). Further, advanced sorting equipment and pre-treatment methods like pyrolysis can effectively remove contaminants (European Aluminium, 2020), while newly developed techniques, like laser-induced breakdown spectroscopy and solid-state recycling show promise in aluminium refining (Cui & Roven, 2010).

This lever addresses an improvement in waste sorting and collection. Europe has a well-developed recycling infrastructure, which counted 220 recycling plants in 2015, mostly small and medium-sized enterprises (European Aluminium, 2018). However, out of 4.3 Mt of end-of-life aluminium old scrap generated, only about 2.9 Mt were collected for recycling, resulting in a 69% end-of-life recycling rate (Passarini et al., 2018). Table A 5 summarises the modelling implementation of the lever discussed.

Table A 5. Modelling implementation of the lever focused on improved waste sorting

Year	2050
Value	-5.2%

Type	Supply side
Circular economy strategy	Recover
Modelling interpretation (bottom-up assessment)	The collection rates are re-calculated to have additional material sorted and entering recycling. This is done only for post-consumer scrap. Further, the improvements in collection and sorting result in a higher share of post-consumer scrap directed to remelting as opposed to refining, hence ensuring a closed-loop recycling. Overall, the lever results in higher masses collected, sorted and recycled. *Functional unit*: Collection, sorting and treatment of the European aluminium post-consumer scrap in 2050.
Assumptions on the elaboration of the data taken from literature	- In this case, we model the consequences of improved sorting. - Quantification sourced from Cui & Roven (2010), Løvik et al. (2014), and Pedneault et al. (2023).
Limits and improvements (bottom-up assessment)	- Due to the high amount of post-consumer scrap exported, it is not possible to reach the reduction reported in the literature (i.e. 30% for 2050). Hence, it was not possible to apply the value taken from literature. The value used as reduction is calculated based on the material flow analysis considering the substantial amount of post-consumer scrap currently exported. - No specific technology is identified for achieving the improvements.

Source: JRC elaboration

5. Improved waste sorting and scrap quality

As mentioned in Section 1.3, reaching high-quality of post-consumer scrap via collection and improved sorting is identified as a possible avenue to increase closed-loop recycling, especially for wrought aluminium alloys. Building on the previous lever (i.e., 'Improved waste sorting'), we assume that alloy-to-alloy separation occurs and collected wrought aluminium is fully directed to remelting, instead of refining. No specific technology is identified for achieving the improvements. It is assumed that the electricity consumption of the sorting plant is doubled according to estimations based on Albizzati, Foster, et al. (2024) and Daehn et al. (2019). In terms of labour and investments, no adjustments are made on the inputs. Table A 6 summarises the modelling implementation of the lever discussed.

Table A 6. Modelling implementation of the lever focused on improved waste sorting and scrap quality

Year	2050
Value	-5.2% and 100% diversion of wrought aluminium alloys to remelting
Type	Supply side
Circular economy strategy	Recover
Modelling interpretation (bottom-up assessment)	The collection rates are re-calculated to have additional material sorted and entering recycling. This is done only for post-consumer scrap. Further, the improvements in collection and sorting result in the diversion of wrought aluminium alloys to remelting as opposed to refining, hence ensuring a closed-loop recycling. Overall, the lever results in higher masses collected, sorted and recycled. *Functional unit*: Collection, sorting and treatment of the European aluminium post-consumer scrap in 2050.

Assumptions on the elaboration of the data taken from literature	- In this case, we model the consequences of improved sorting. - Quantification sourced from Cui & Roven (2010), Løvik et al. (2014), and Pedneault et al. (2023).
Limits and improvements (bottom-up assessment)	- Due to the high amount of post-consumer scrap exported, it is not possible to reach the reduction reported in the literature (i.e. 30% for 2050). Hence, it was not possible to apply the value taken from literature. The value used as reduction is calculated based on the material flow analysis considering the substantial amount of post-consumer scrap currently exported. - No specific technology is identified for achieving the improvements. - The electricity consumption of the sorting plant is doubled according to estimations based on Albizzati, Foster, et al. (2024) and Daehn et al. (2019).

Source: JRC elaboration

6. Design for packaging recoverability and recycling

This lever addresses design for packaging recoverability and recycling. It concerns enhancing the design of new packaging products to facilitate aluminium recovery at the end of their lifecycle, thereby promoting recycling, and decreasing the amount ending up in incineration or landfilling (European Aluminium, 2020). For example, several are the challenges related to recycling of aluminium foils, where a portion still remains uncollected and ends up in incineration or landfill (European Aluminium, 2020). Design for recoverability results in 8-10% packaging diversion from incineration and landfilling according to Warrings & Fellner (2018). Changes in design are not accounted for *per se*, i.e. a possible increase/decrease in mass is not considered. The only effect modelled is a reduction in packaging waste disposed and a proportional increase in recycled aluminium packaging. Table A 7 summarises the modelling implementation of the lever discussed.

Table A 7. Modelling implementation of the lever focused on design for packaging recoverability and recycling

Year	2050
Value	-10%
Type	Supply side
Circular economy strategy	Recover
Modelling interpretation (bottom-up assessment)	The changes are applied only to ´Packaging, cans' and 'Packaging, foil'. The effect of the lever is intended as a reduction in packaging currently treated through incineration/landfilling and a proportional increase of recycled packaging aluminium. Finally, having a different design for packaging is assumed not to affect either collection rates or sorting rates. *Functional unit*: Management of aluminium packaging waste collected in 2050 in Europe.
Assumptions on the elaboration of the data taken from literature	- Lack of a packaging category so fabricated metal products are used as a reference. - Data obtained from Warrings & Fellner (2018).
Limits and improvements (bottom-up assessment)	- Changes in design are not modelled *per se*, i.e. a possible increase/decrease in mass is not taken into account. The only effect

	modelled is a reduction in packaging waste disposed and a proportional increase in recycled aluminium packaging.

Source: JRC elaboration

7. Expansion of deposit return systems

Regarding aluminium cans, recycling is progressing well. Unlike other packaging materials, aluminium beverage cans can be recycled to a product with similar quality as the original, with an average collection rate of 74.5% across the EU (European Aluminium, 2020). However, there remains a wide range of performance among EU countries, with some reaching recycling rates below 40% (e.g., Romania) and others nearing 98% (e.g., Finland) (European Aluminium, 2020). Recycling rates are affected by a country's collection and sorting schemes. An avenue to ensure high collection and recycling rates is the implementation of deposit return systems for, among other packaging items, aluminium cans. Croatia, Denmark, Estonia, Finland, Germany, Malta, Lithuania, the Netherlands, and Sweden have successfully implemented deposit return systems and in Europe the coverage of such a collection scheme reaches approx. 11% (estimated from International Aluminium Institute, n.d.). Moving forward, achieving a 100% recycling rate for every aluminium can across Europe is essential to ensure closed loop can-to-can recycling (European Aluminium, 2020).

This lever aims at quantifying the impacts of having a 100% coverage of deposit return systems on all packaging cans waste generated in the EU with a 100% collection rate to investigate the maximum potential of such practice. Table A 8 summarises the modelling implementation of the lever discussed.

Table A 8. Modelling implementation of the levers focused on expansion of deposit return systems

Year	2050
Value	100% coverage and collection rate
Type	Supply
Circular economy strategy	Recover
Modelling interpretation (bottom-up assessment)	The lever is applied to 'Packaging, cans' only. A 100% coverage and 100% collection rate are assumed to explore the maximum potential of deposit return systems.

Source: JRC elaboration

8. Recovery from mixed waste

Products are used and often mixed when discarded at their end-of-life, scattering aluminium household waste across various waste streams, frequently mainly being segregated together with mixed waste. Warrings & Fellner (2021) have identified advanced material recovery facilities for mixed waste as a promising avenue to reach the ambitious recycling rates targets for aluminium waste.

Based on Albizzati, Foster, et al. (2024), as of 2020 the coverage of material recovery facilities across EU countries was 41%, i.e. of the mixed waste, 41% is sorted in a material recovery facility to recover recyclable materials prior to incineration or landfilling. The lever aims at quantifying the maximum potential of having *advanced* material recovery facilities with a coverage of 100%, i.e. all mixed waste is first sorted in a material recovery facility to recover recyclable materials and reduce the amount of waste sent to incineration or landfilling. Having an *advanced* material recovery facility is intended as a technology with recovery rates increasing from 54% (based on Albizzati, Tonini, et al., 2024) to 93% (based on Labberton, 2020). Table A 9 summarises the modelling implementation of the lever discussed.

Table A 9. Modelling implementation of the lever focused on recovery from mixed waste

Year	2050
Value	100% coverage 93% recovery
Type	Supply
Circular economy strategy	Recover
Modelling interpretation (bottom-up assessment)	The lever is applied to 'Packaging, cans' and 'Packaging foil' only as these are the flows assumed to be found in household mixed waste. Departing from a coverage of 41% and 54% recovery of aluminium from mixed waste in the Baseline scenario, in the ACE50 scenario a 100% coverage and 93% recovery rate are assumed to explore the maximum potential of advanced material recovery facilities
Assumptions on the elaboration of the data taken from literature	The configuration of the advanced material recovery assumed involves two eddy current separators and one induction sorting system, based on Labberton (2020), followed by manual sorting.
Limits and improvements (bottom-up assessment)	- It should be investigated whether other sectors might end up in household mixed waste. - Additional energy consumption and/or the need for additional ancillary materials for the functioning of the advanced material recovery facility are disregarded.

Source: JRC elaboration

Combination of levers

As anticipated, the levers are applied individually. When combining the CE levers at cluster (i.e. either Reduce, Reuse or Recover) or at ACE50 scenario level trade-offs between the levers might occur, meaning that the maximum circularity at cluster or ACE50 scenario level is not the same as the sum or multiplication of the different levers.

When implementing both levers belonging to the 'Reuse' cluster, a multiplicative effect is considered for 'Transport, passenger car'. Lever 2 (i.e. Design for reusability in Table 3) is assumed to be implemented first as it prolongs the lifetime of the product, while lever 3 (i.e. Remanufacturing of automotive components in Table 3) is subsequently implemented as it is an extension of lifetime of products close to their end-of-life. Further, as the two levers act on the same product at the same stage, a multiplicative effect is assumed.

When implementing the levers belonging to the recover cluster, it is assumed that lever 4 (i.e. Improved waste sorting in Table 3) is overruled by lever 5 (i.e. Improved waste sorting and scrap quality in Table 3) where one needs also to take into account that lever 7 (i.e. Expansion of deposit return systems in Table 3) overrules on the changes related to the stream of aluminium waste 'Packaging, cans'. Subsequently, lever 8 is implemented (Recovery from mixed waste in Table 3) and, finally, lever 5 is applied (i.e. Design for packaging recoverability and recycling in Table 3) as in the modelling this lever translates into more recycling.

Finally, when implementing all levers at once in the ACE50 scenario, it is assumed that the Reuse levers would be implemented first having these an effect on the Reduce lever, as the Reduce lever is only an optimisation of the fabrication and manufacturing process, while the Reuse levers reduce the demand for aluminium. Finally, the Recover levers are implemented.

A visual representation of the interrelationships between the levers is displayed in Table A 10, where a ‘Combine’ effect is intended as a multiplicative effect, an ‘Exclusive’ effect is intended as one lever overruling the other, an ‘Additive’ effect is intended as the two levers boosting their effect, and, finally, ‘No effect’ indicates that mass flows are not affected.

Table A 10. Razor matrix with interrelationships of Circular Economy (CE) levers in the Ambitious Circular Economy (ACE50) scenario

CE lever	Pre-consumer scrap reduction - L(1)	Design for reusability – L(2)	Remanufacturing of automotive components – L(3)	Improved waste sorting – L(4)	Improved waste sorting and scrap quality – L(5)	Design for packaging recoverability and recycling – L(6)	Expansion of DRS – L(7)	Recovery from mixed waste – L(8)
Pre-consumer scrap reduction – L(1)		No effect	No effect	No effect	No effect	No effect	No effect	No effect
Design for reusability – L(2)	No effect		No effect	No effect	No effect	Combine	No effect	No effect
Remanufacturing of automotive components – L(3)	No effect	No effect		No effect	No effect	No effect	Exclusive	No effect
Improved waste sorting – L(4)	No effect	No effect	No effect		Additive	No effect	No effect	No effect
Improved waste sorting and scrap quality – L(5)	No effect	No effect	No effect	Additive		No effect	No effect	No effect
Design for packaging recoverability and recycling – L(6)	No effect	Combine	No effect	No effect	No effect		No effect	Additive
Expansion of DRS – L(7)	No effect	No effect	Exclusive	No effect	No effect	No effect		No effect
Recovery from mixed waste – L(8)	No effect	No effect	No effect	No effect	No effect	Additive	No effect	

Note: For example, from line two 'Design for reusability' has no effect on 'Pre-consumer scrap reduction' but has a combined effect I.e. multiplicative) with 'Design for recycling', meaning that the two levers have a combined effect on passenger cars. 'Improved waste sorting' has no effect on 'Pre-consumer scrap reduction' but should be seen as additive to the effect of 'Improved waste sorting and scrap quality'. Notice that DRS stands for deposit return systems

Source: JRC elaboration

Annex 2. Life cycle inventories

With respect to the life cycle inventories of the aluminium production and recycling processes, the modelling was entirely based on European Aluminium (2018, 2021) and complemented (when needed) with ecoinvent datasets (Wernet et al., 2016).

Table A 11 provides the cost data used in the life cycle costing. The data is not corrected by inflation; in the life cycle costing all costs are referred to EUR2022.

Table A 11. Cost data used in the life cycle costing. Notice that the values reported are not corrected by inflation.

Process	Cost	Amount	Unit	Year	Reference
Ingot cast production	CAPEX	47	EUR t^{-1}	2021	Elaborations based on Luthin et al. (2021)
	OPEX	52	EUR t^{-1}	2021	Elaborations based on Luthin et al. (2021)
	Labour cost	30	EUR t^{-1}	2021	Elaborations based on Luthin et al. (2021)
	Employment	1.9E-05	FTE t^{-1}	2021	Elaborations based on Luthin et al. (2021)
Fabrication of rolling	CAPEX	260	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	OPEX	1787	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	Labour cost	30	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	Employment	1.9E-05	FTE t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
Fabrication of foil	CAPEX	260	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	OPEX	668	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	Labour cost	30	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials

	Employment	1.9E-05	FTE t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
Fabrication of casting	CAPEX	260	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	OPEX	44	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	Labour cost	30	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	Employment	1.9E-05	FTE t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
Fabrication of other (assumed as casting)	CAPEX	260	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	OPEX	44	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	Labour cost	30	EUR t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
	Employment	1.9E-05	FTE t^{-1}	2022	JRC elaboration based on LCI and cost of raw materials
Manufacturing of aluminium into construction/transport/packaging/machinery/electrical/consumer durables/other uses finished products	Total cost	681	EUR t^{-1}	2021	Elaborations based on Luthin et al. (2021)
	CAPEX	179	EUR t^{-1}	2021	Elaborations based on Luthin et al. (2021)
	OPEX	503	EUR t^{-1}	2021	Elaborations based on Luthin et al. (2021)
	Labour cost	30	EUR t^{-1}	2021	Elaborations based on Luthin et al. (2021)
	Employment	5.7E-04	FTE t^{-1}	2021	Elaborations based on Luthin et al. (2021)
Sorting	CAPEX	18.3	EUR t^{-1}	2015	Albizzati, Tonini, et al. (2024)

	OPEX	50	EUR t^{-1}	2015	Albizzati, Tonini, et al. (2024)
	Labour cost	35	EUR t^{-1}	2022	Albizzati, Tonini, et al. (2024)
	Employment	6.7E-04	FTE t^{-1}	2022	Albizzati, Tonini, et al. (2024)
Remelting/Refining	Total cost	1040	EUR t^{-1}	2015	Zore (2024)
Incineration	CAPEX	50	EUR t^{-1}	2015	Albizzati, Tonini, et al. (2024)
	OPEX	75	EUR t^{-1}	2015	Albizzati, Tonini, et al. (2024)
	Labour cost	8.3	EUR t^{-1}	2015	Albizzati, Tonini, et al. (2024)
	Employment	1.6E-04	FTE t^{-1}	2015	Albizzati, Tonini, et al. (2024)
	Tax	21	EUR t^{-1}	2022	Albizzati, Tonini, et al. (2024)
Landfill	CAPEX	12	EUR t^{-1}	2015	Albizzati, Tonini, et al. (2024)
	OPEX	18	EUR t^{-1}	2015	Albizzati, Tonini, et al. (2024)
	Employment	7.5E-05	FTE t^{-1}	2022	Albizzati, Tonini, et al. (2024)
	Tax	48	EUR t^{-1}	2022	Albizzati, Foster, et al. (2024)
Wrought aluminium alloy	Price	1710	EUR t^{-1}	2022	Schrottpreise-aktuell (n.d.)
Cast aluminium alloy	Price	1001	EUR t^{-1}	2022	Schrottpreise-aktuell (n.d.)
Transport – truck	Total cost	0.140	EUR t^{-1} km^{-1}	2006	Schade et al. (2006)
Transport – ship	Total cost	0.0022	EUR t^{-1} km^{-1}	2019	Schade et al. (2006)
Transport - barge	Total cost	0.0011	EUR t^{-1} km^{-1}	2019	Bernacki (2021)

Source: JRC elaboration

As for the energy mixes assumed in the study, the mixes elaborated based on GECO for electricity, industrial heat, and space heat for EU and non-EU are reported in Table A 12 and Table A 13 for both 2021 and 2050, and for the NDC-LTS and Reference scenarios. Notice that for the non-EU (in Table A 12 and Table A 13 reported as 'RoW'), the following countries were considered with the respective shares: China (22%), Egypt (5%), India (5%), Rest of Persian Gulf (16%), Rest of Sub-Saharan Africa (9%), Russian Federation (16%), and United States (8%). For all other non-EU countries/regions (namely, Argentina, Australia, Brazil, Canada, Chile, UK, Indonesia, Iran, Japan, Korea (Republic), Mediterranean Middle-East, Mexico, Malaysia, Tunisia+Morocco+Western Sahara, Algeria+Libya, Rest of Balkans, Rest of CIS, Rest of Pacific, Rest of South America, Saudi Arabia, Thailand, Turkey, Ukraine, Vietnam, South Africa), the remaining 19% of is split evenly across (i.e. each country contributes with 0.80%).

The complete datasets for the energy mixes are available in the Supplementary Material.

Table A 12. Energy mixes considered in the assessment. The values reported represent the share of the different sources in the average mix for EU27

	Electricity mix –NDC-LTS scenario, EU27		Electricity mix –Reference scenario, EU27	
Technology	2021 [%]	2050 [%]	2021 [%]	2050 [%]
Biomass	7%	10%	7%	9%
Solid coal	7%	0%	7%	2%
Solid Lignite	7%	0%	7%	0%
Geothermal	0%	0%	0%	1%
Hydro, lakes	7%	5%	7%	5%
Hydro, river	6%	4%	6%	4%
Natural gas, conventional	3%	0%	3%	2%
Natural gas, combined	12%	0%	12%	1%
Nuclear	25%	3%	25%	4%
Oil	2%	0%	2%	0%
Solar panels	5%	28%	5%	26%
Solar plants	0%	0%	0%	0%
Wind onshore	13%	41%	13%	39%
Wind offshore	2%	6%	2%	5%
CHP	5%	3%	5%	3%
	Industrial heat mix –NDC-LTS scenario, EU27		Industrial heat mix – Reference scenario, EU27	
Technology	2021 [%]	2050 [%]	2021 [%]	2050 [%]
Natural gas	47%	16%	47%	32%
Oil	13%	3%	13%	13%
Coal	3%	1%	3%	3%
District heating	9%	18%	9%	19%
Biomass	27%	60%	27%	29%
Hydrogen	0%	2%	0%	4%
	District heating mix –NDC-LTS scenario, EU27		District heating mix – Reference scenario, EU27	
Technology	2021 [%]	2050 [%]	2021 [%]	2050 [%]
Biomass	42%	85%	42%	85%
Natural gas	38%	15%	38%	15%
Oil	0%	0%	0%	0%
Coal	20%	0%	20%	0%
	Space heating mix –NDC-LTS scenario, EU27		Space heating mix – Reference scenario, EU27	
Technology	2021 [%]	2050 [%]	2021 [%]	2050 [%]
Natural gas	41%	0%	41%	3%
Oil	16%	1%	16%	9%
Coal	4%	0%	4%	2%
Electricity	10%	48%	10%	37%
District heating	14%	31%	14%	28%
Biomass	16%	20%	16%	21%
Hydrogen	0%	0%	0%	0%
	Electricity mix –NDC-LTS scenario, RoW		Electricity mix –Reference scenario, RoW	
Technology	2021 [%]	2050 [%]	2021 [%]	2050 [%]

Biomass	2%	4%	2%	0%
Solid coal	49%	4%	49%	27%
Solid Lignite	1%	0%	1%	0%
Geothermal	0%	0%	0%	0%
Hydro, lakes	16%	11%	16%	9%
Hydro, river	1%	0%	1%	0%
Natural gas, conventional	7%	2%	7%	6%
Natural gas, combined	7%	5%	7%	7%
Nuclear	8%	10%	8%	4%
Oil	1%	0%	1%	0%
Solar panels	3%	25%	3%	26%
Solar plants	0%	0%	0%	0%
Wind onshore	5%	36%	5%	18%
Wind offshore	0%	3%	0%	1%
CHP	1%	1%	1%	1%
	Industrial heat mix –NDC-LTS scenario, RoW		Industrial heat mix – Reference scenario, RoW	
Technology	2021 [%]	2050 [%]	2021 [%]	2050 [%]
Natural gas	29%	28%	29%	28%
Oil	22%	18%	22%	18%
Coal	27%	30%	27%	30%
District heating	12%	17%	12%	17%
Biomass	10%	6%	10%	6%
Hydrogen	0%	2%	0%	2%

Source: JRC elaboration

Table A 13. Energy mixes considered in the assessment. The values reported represent the share of the different sources in the marginal mix for EU27

Electricity mix –NDC-LTS scenario, EU27	
Technology	2050-2021 [%]
Biomass	8%
Solid coal	0%
Solid Lignite	0%
Geothermal	0%
Hydro, lakes	1%
Hydro, river	0%
Natural gas, conventional	0%
Natural gas, combined	0%
Nuclear	0%
Oil	0%
Solar panels	36%
Solar plants	0%
Wind onshore	47%
Wind offshore	8%
CHP	0%
Industrial heat mix –NDC-LTS scenario, EU27	
Technology	2050-2021 [%]
Natural gas	0%

Oil	0%
Coal	0%
District heating	0%
Biomass	58%
Hydrogen	42%

District heating mix –NDC-LTS scenario, EU27

Technology	2050-2021 [%]
Biomass	0%
Natural gas	100%
Oil	0%
Coal	0%

Space heating mix –NDC-LTS scenario, EU27

Technology	2050-2021 [%]
Natural gas	0%
Oil	0%
Coal	0%
Electricity	97%
District heating	3%
Biomass	0%
Hydrogen	0%

Electricity mix –NDC-LTS scenario, RoW

Technology	2050-2021 [%]
Biomass	4%
Solid coal	1%
Solid Lignite	0%
Geothermal	1%
Hydro, lakes	5%
Hydro, river	0%
Natural gas, conventional	1%
Natural gas, combined	4%
Nuclear	6%
Oil	0%
Solar panels	33%
Solar plants	0%
Wind onshore	41%
Wind offshore	4%
CHP	0%

Industrial heat mix –NDC-LTS scenario, RoW

Technology	2050-2021 [%]
Natural gas	46%
Oil	11%
Coal	35%
District heating	0%
Biomass	1%
Hydrogen	8%

Source: JRC elaboration

Annex 3. Additional LCA results

The relative reduction to the Baseline scenario (BSL50) calculated via LCA for the Compliance with selected Targets on Circular Economy scenario (CTC50), the Ambitious Circular Economy scenario (ACE50), and the Reduce, Reuse, Recover clusters are reported in Table A 14.

Table A 14. Savings relative to the Baseline scenario (BSL50) calculated via LCA

Impact category	CTC50	ACE50	Reduce	Reuse	Recover
Climate change	-3.0%	-14%	-1.0%	-11%	-6.0%
Ozone depletion	-2.0%	-13%	-1.0%	-10%	-4.0%
Human toxicity, cancer effects	-6.0%	-14%	-0.38%	-10%	-9.0%
Human toxicity, non-cancer effects	-5.0%	-13%	-1.0%	-10%	-7.0%
Particulate matter	-5.0%	-14%	-1.0%	-11%	-7.0%
Ionising radiation	-1.0%	-11%	-1.0%	-10%	-1.0%
Photochemical ozone formation	-3.0%	-13%	-1.0%	-11%	-5.0%
Acidification, terrestrial	-4.0%	-14%	-1.0%	-11%	-6.0%
Eutrophication, terrestrial	-2.0%	-13%	-1.0%	-11%	-3.0%
Eutrophication, freshwater	-2.0%	-14%	-1.0%	-11%	-4.0%
Eutrophication, marine	-2.0%	-13%	-1.0%	-11%	-4.0%
Ecotoxicity, freshwater	-3.0%	-15%	-1.0%	-11%	-5.0%
Land use	1.0%	-10%	-2.0%	-10%	0.17%
Water use	-1.0%	-11%	-1.0%	-10%	-2.0%
Resource use, minerals and metals	-0.14%	-10%	-1.0%	-10%	0.01%
Resource use, energy	-2.0%	-13%	-1.0%	-10%	-4.0%

Note: CTC50: Compliance with selected Targets on Circular Economy Targets, ACE50: Ambitious Circular Economy scenario

Source: JRC elaboration

The relative reductions to the Baseline scenario (BSL50) for the levers considered in the study are reported in Table A 15. Notice that L(1) corresponds to the 'Pre-consumer scrap reduction lever', L(2) to 'Design for reusability', L(3) to 'Remanufacturing of automotive components', L(4) to 'Improved waste sorting', L(5) 'Improved waste sorting and scrap quality', L(6) to 'Design for packaging recoverability and recycling', L(7) to "Expansion of deposit return systems', and L(8) to 'Recovery of mixed waste'.

Table A 15. Savings relative to the Baseline scenario (BSL50) calculated via LCA

Impact category	L(1)	L(2)	L(3)	L(4)	L(5)	L(6)	L(7)	L(8)
Climate change	-1.0%	-11%	-1.5%	-2.3%	-2.8%	-0.13%	-3.6%	-2.0%
Ozone depletion	-1.0%	-10%	-1.1%	-1.5%	-2.7%	-0.09%	-2.8%	-1.5%
Human toxicity, cancer effects	-0.38%	-11%	-2.5%	-3.2%	-2.8%	-0.15%	-5.4%	-3.1%
Human toxicity, non-cancer effects	-1.0%	-11%	-2.0%	-2.9%	-2.9%	-0.13%	-4.2%	-2.6%
Particulate matter	-1.0%	-11%	-2.0%	-2.7%	-3.0%	-0.15%	-4.3%	-2.6%
Ionising radiation	-1.0%	-10%	-0.40%	-0.14%	-2.4%	-0.05%	-1.1%	-0.51%
Photochemical ozone formation	-1.0%	-11%	-1.1%	-1.7%	-2.8%	-0.11%	-2.9%	-1.5%
Acidification, terrestrial	-1.0%	-11%	-1.8%	-2.4%	-2.9%	-0.14%	-3.8%	-2.3%
Eutrophication, terrestrial	-1.0%	-11%	-0.80%	-1.3%	-2.8%	-0.10%	-2.3%	-1.1%
Eutrophication, freshwater	-1.0%	-11%	-0.95%	-1.4%	-2.8%	-0.11%	-2.1%	-1.3%
Eutrophication, marine	-1.0%	-11%	-0.84%	-1.35%	-2.8%	-0.10%	-2.3%	-1.1%
Ecotoxicity, freshwater	-1.0%	-11%	-1.2%	-2.3%	-2.9%	-0.20%	-3.1%	-1.6%
Land use	-2.0%	-9.8%	0.31%	0.24%	-2.6%	-0.06%	-0.56%	0.40%
Water use	-1.0%	-10%	-0.50%	0.40%	-2.7%	-0.07%	-1.4%	-0.70%
Resource use, minerals and metals	-1.0%	-10%	-0.08%	0.40%	-2.7%	-0.05%	-0.60%	-0.12%
Resource use, energy	-1.0%	-10%	-0.9%	-1.7%	-2.7%	-0.13%	-2.7%	-1.2%

Note: CTC50: L(1) corresponds to the ‘Pre-consumer scrap reduction lever’, L(2) to ‘Design for reusability’, L(3) to ‘Remanufacturing of automotive components’, L(4) to ‘Improved waste sorting’, L(5) ‘Improved waste sorting and scrap quality’, L(6) to ‘Design for packaging recoverability and recycling’, L(7) to “Expansion of deposit return systems’, and L(8) to ‘Recovery of mixed waste’

Source: JRC elaboration

Annex 4. Values for epistemic uncertainty sensitivity analysis

The workshop determined the effectiveness of the lever in the alternative future through stress-testing the assumptions around the impact of CE clusters on material flows. For the analysis, the average of the low, medium and high range of effectiveness were taken, as reported Table A 16. Table A 16 also contains the expected change in material flow due to the macroeconomic changes, as proposed by the experts in the sense-making session, in line with the narrative of the scenarios. The magnitude of the change is in line with the one proposed by Schandl et al. (2020), where the reference is the difference between the scenario in line with the historical trajectory (SSP2) and the other four scenarios that either exhibit growing or contracting economies.

Table A 16. Values for epistemic uncertainty sensitivity analysis of prospective LCA

	Material flow change	Reduction	Reuse	Recirculation
Glocal Eco-World (Collectivist / not supportive)	-20%	Medium 67%	High 82%	Medium 67%
Ecostates (Collectivist / supportive)	20%	High 82%	High 82%	High 82%
Green Business Boom (Individualist / supportive)	20%	Low 52%	Low 52%	High 82%
Greening through Crisis (Individualist / not supportive)	-20%	Low 52%	Medium 67%	Medium 67%

Source: JRC elaboration

Annex 5. Criteria for Input-Output model selection

To fit the purpose of this study, the Input-Output (IO) model should be regularly updatable and verifiable by EU Commission services. The scope of the IO model should cover the global economy but should at least allow to separate impacts inside and outside the EU27. A higher sector disaggregation is preferred, especially a disaggregation of sectors linked to the selected case studies is considered an added value. The development of a disaggregation methodology is part of the methodology which allows to overcome the issue of too aggregated sector classifications. Also, either the use of product-by-product tables or the use of industry-by-industry tables is considered. Finally, it should be kept in mind that the selected model will be expanded to include dynamic analysis. The pre-existence of such a link (e.g. between FIGARO and FIDELIO) is a plus.

We prefer to first decide on the selection of the most appropriate monetary IO-model without considering the availability of environmental and other extensions. In case the selected model does not include sufficient coverage of environmental and other extensions, an additional step is needed to add the missing data via alternative sources (e.g. using LCI-data from ecoinvent). The reason to focus in a first step only on the monetary tables, is that it will allow to select the most appropriate, updatable, and high-quality IO model available fitting the purpose of this study and future work within the JRC. A minimum requirement for the IOA is to use tables that are widely available and known to the scientific community. The options would be too limited if the availability of environmental and other extensions is considered already in this decision step.

The following models are considered:

- FIGARO (the 2024 FIGARO edition)[30]: The EU inter-country supply, use and input-output tables (developed by Eurostat and the JRC) are part of official EU statistics (2000-2021 data). The FIGARO tables are benchmarked against the most recent macroeconomic aggregates and respect the same quality standards as official statistics and are released annually by Eurostat (T-2). The tables present the relationship between the EU27 and 18 non-EU countries plus a rest of world region, covering 64 industries (NACE rev.2 classification).

  Extension data in FIGARO: Air emissions accounts are collected under Regulation (EU) No 691/2011 on European Environmental Economic Accounts. Air emission accounts are compiled according to the system of environmental economic accounting and can therefore be readily combined with input-output tables for further analysis (assuming the use of industry-by-industry tables). The data on employment for each EU Member State at the level of 64 industries (based on NACE Rev. 2) are expressed in numbers of persons employed. These data are collected via the European system of accounts (ESA 2010) transmission programme and are available on Eurostat's website [nama_10_a64_e].

  Note: These data sources are restricted to EU27 data (and in addition UK-data), but do not cover data for non-EU countries.

30 https://ec.europa.eu/eurostat/web/esa-supply-use-input-tables/information-data#figaro

- FIGAROe3[31] is a comprehensive inter-country supply, use, and input-output database for 2015, featuring labour and environmental extensions that are in line with official statistics. The database encompasses data for 213 products and 176 industries across 45 geographical areas (country disaggregation is equal to FIGARO), as well as one aggregated rest of the world region. Labour accounts detail total employment and employment broken down by gender and skill level. Energy accounts include primary energy supply and net energy use, while air emission accounts cover four types of greenhouse gases - CO_2, CH_4, N_2O, and fluorinated gases - for both combustion and non-combustion processes.

- EXIOBASE[32]: v3.8.2/v4 includes a timeseries of supply, use and input-output tables covering 1995-2022. The 163 sectors and 200 products disaggregation provide highly detailed sector/product relations between the EU27 MS, 17 non-EU countries and 5 rest of world regions. The wide coverage of environmental extensions allows to (partly) cover 14 out of the 16 environmental impact categories[33] as well as employment. Hybrid versions and country extended versions of EXIOBASE (EXIOBASE3rx[34]) exist as well.

- OECD harmonised national Input-Output Tables (OECD IOT tables)[35]: Inter-industrial flows of goods and services for 76 countries (all OECD countries and several non-member economies (including all G20 countries)) and 45 sectors, covering the time-period 1995-2020 are available. Extension tables only cover CO_2-emissions from fuel combustion.

Based on the above listed characteristics, the use of either FIGARO or FIGAROe3 are both considered as the most suitable models in this project. FIGARO has the drawback of the limited sector disaggregation, while FIGAROe3 is currently only available for the year 2015. The project **team's preference** goes to the use of FIGAROe3 model, as it is best the one best in line with its needs. Still, the methodology will be developed in such a way that it will be applicable to the more common IO-tables. The following issues were considered in making this choice:

- Up-to-date multiregional input-output model covering at least the EU27 region and other major economies in the world: Both the FIGARO and the OECD IOT tables are regularly updated as both are institutionalised in Eurostat and OECD, respectively. The FIGAROe3 has currently only data for one year, namely 2015. The development of a time-series version of this experimental dataset is being planned. EXIOBASE is the culmination of work in the FP7 DESIRE project and builds upon earlier work on EXIOBASE 2 in the FP7 CREEA project and EXIOBASE 1 of the FP6 EXIOPOL project. Future updates are infrequent and uncertain. The latest data year for FIGARO is 2021; for FIGAROe3 is 2015; for EXIOBASE is 2022 (based on nowcasting); and for OECD IOT tables is 2020.
- The model should be verifiable by EU Commission services: The FIGARO tables are benchmarked against the most recent macroeconomic aggregates and respect the same

[31] https://data.jrc.ec.europa.eu/collection/id-00403

[32] Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., ... Tukker, A. (2021). EXIOBASE 3 (3.8.2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.5589597

[33] Correspondence tables are found here and here.

[34] Bjelle, Stadler, & Wood. (2019). EXIOBASE 3rx (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.2654460

[35] https://www.oecd.org/sti/ind/input-outputtables.htm

quality standards as official statistics and are released annually by Eurostat. Also, FIGAROe3 is line with official European statistics. This quality is not guaranteed in the use of EXIOBASE or the OECD IOT tables.

- The scope of the IO model should cover the global economy but should at least allow to separate impacts inside and outside the EU27: All models (FIGARO, FIGAROe3, EXIOBASE and OECD IOT tables) include the EU27 Member States and the rest of the world, although the country aggregation differs between the models.
- A higher sector disaggregation is preferred, especially a disaggregation of sectors linked to the selected case studies is considered an added value: The highest sector disaggregation is available in the FIGAROe3 model covering 176 sectors (and 213 product groups). Also, EXIOBASE uses a higher sector disaggregation level, detailing 163 sectors (and 200 product groups). Both the FIGARO and the OECD IOT tables use a more aggregated sectors classification, detailing only 64 and 45 sector groups, respectively. This project case studies focus on steel, aluminium, plastic, and cement. A first analysis focusing on mining, manufacturing and end-of-life treatment of each case study shows a difference in the relevance of sector disaggregation between the different IO models.
    - The limited sector detail in FIGARO and the OECD IOT tables does not allow to directly link the model to the case studies. The mining step is aggregated into mining and quarrying (in FIGARO) or into non-energy producing products (in OECD IOT). In manufacturing, only for the case of textiles one separate manufacturing step is available. Waste management is aggregated into the sector group 'Water supply, sewerage, waste management and remediation activities'.
    - Both FIGAROe3 and EXIOBASE have a much higher detail in their sector classification allowing to make a distinction between mining sectors (e.g. the mining of iron ores and aluminium ores are covered by separated sectors) and in manufacturing already some level of detail is available per case study (e.g. a distinction between textile production and production of wearing apparel is made). Also, for most cast studies a first distinction between primary and secondary production is available. Multiple steps in the waste management system are available.
- The use of product-by-product tables or the use of industry-by-industry tables is considered: The OECD IOT tables are only available following the industry-by-industry approach. FIGARO, FIGAROe3 and EXIOBASE are all available in both the industry-by-industry approach and the product-by-product approach.
- The availability of environmental and social extension tables is a plus: None of the IO models already include all the necessary environmental and social extension tables. EXIOBASE is the model with the most expanded set of mainly environmental extensions. In contrast, FIGARO does not include extension data, but its structure easily allows linkages to existing (official) EU datasets. FIGAROe3 covers extension data on employment, energy, and air emissions. The extension tables of the OECD IOT tables only cover CO_2-emissions from fuel combustion.

- The selected model will be expanded to include dynamic analysis. The pre-existence of such a link is a plus: There is a link between FIGARO (and FIGAROe3) and the dynamic econometric IO model FIDELIO. No link with a dynamic model is available for EXIOBASE or the OECD IOT tables.

Annex 6. FIGAROe3

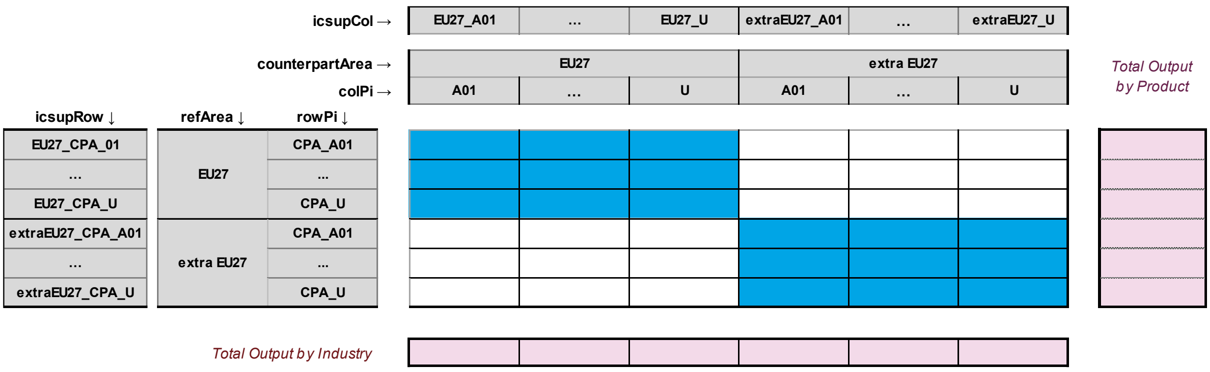
The monetary supply and use tables from the FIGAROe3 model cover 45 geographical areas plus one rest-of-the-world (FIGW1) region. Per region the model details 213 products and 176 industries. Labour accounts detail total employment and employment broken down by gender and skill level. Energy accounts include primary energy supply and net energy use, while air emission accounts cover four types of greenhouse gases - CO_2, CH_4, N_2O, and fluorinated gases - for both combustion and non-combustion processes.

The geographical areas covered by FIGAROe3 are the EU27 Member States and the individual countries Argentina, Australia, Brazil, Canada, Switzerland, China, Indonesia, India, Japan, South Korea, Mexico, Norway, Russia, Saudi Arabia, Turkey, United Kingdom, United States, and South Africa. In addition, one aggregated rest of the world region (FIGW1) is added to cover the full world economy.

The products classification in the FIGAROe3 model is linked to the CPA 2.1 nomenclature. The sector classification is linked to the NACE 2.1 nomenclature. The CPA product categories are related to the economic activities of the statistical classification of economic activities (NACE).

An inter-country supply table (matrix representation shown in Figure A 1) shows the supply of goods and services by type of product of an economy for a given period. Each column shows the output per sector (in NACE classification) disaggregated into different products (in CPA classification). As each sector can supply multiple products, the supply table is heterogeneous. The column headings show an area code (counterpartArea) and a sector classification code (colPi). The row headings show an area code (refArea) and a product classification code (rowPi). The column totals show the total output per sector; the row totals show the total output per product. Only the cells highlighted in blue will show observed values.

Figure A 1. Schematic presentation of an inter-country supply table, detailing two geographical areas (EU27 and non-EU27)



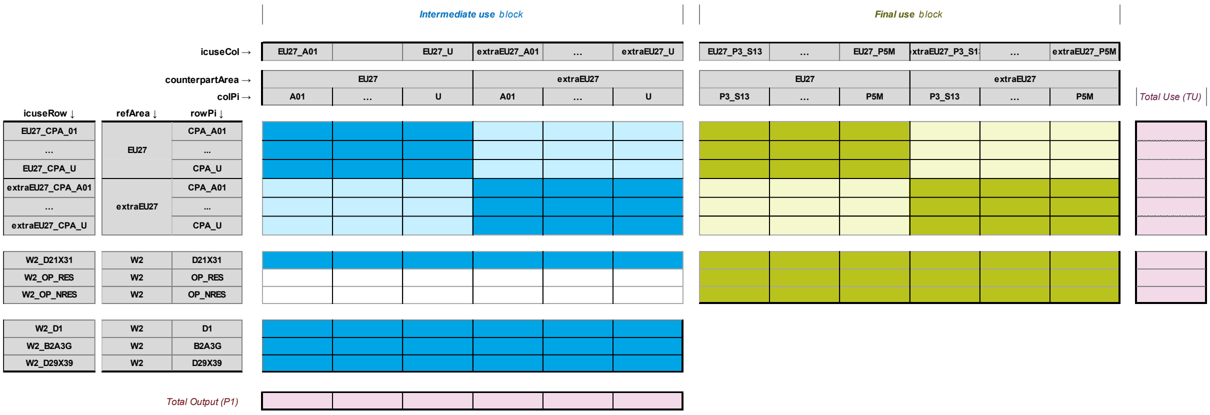
Source: JRC elaboration based on FIGARO description tables

An inter-country use table (matrix representation shown in Figure A 2) shows the use of goods and services by type of product (in CPA classification) per sector (in NACE classification) of an economy for a given period. The use of domestically produced goods and services is shown in the dark coloured areas on main diagonal, separately for intermediate use (blue) and for final use (green). The light areas represent, vertically, the intermediate (blue) and final use (green) use of goods and services produced abroad (imports). In contrast, when presented horizontally they represent exports broken down by user and by trading partner.

The use table is supplemented with data on tax less subsidies (AB21x31), direct purchases abroad by residents (OP_RES), and non-resident purchases in the territory (OP_NRES). The components of value added are compensation of employees (D1), other taxes less subsidies on production (AB29x39), and gross operating surplus and mixed income (B2A3G).

The final demand is disaggregated into final demand categories: government consumption (P3_S13), consumption of households (P3_S14), consumption of non-profit institutions serving households (NPISH; P3_S15), gross fixed capital formation (P51G), and changes in valuables and inventories (P5M).

Figure A 2. Schematic presentation of an inter-country use table, detailing two geographical areas (EU27 and non-EU27)



Source: JRC elaboration based on FIGARO description tables

The monetary values in the supply and use tables show basic prices (in million euros, current prices). A full description of the inter-country supply and use tables is given in the FIGARO manual[36] (2019-edition).

The FIGAROe3 database is downloaded from the Joint Research Centre Data Catalogue[37]. This includes the download of the inter-country supply and use matrices (Table A 17).

Table A 17. FIGAROe3 data download

Name	Data provider	Type	Last update	Unit
Inter-Country Supply Matrix	FIGAROe3 by JRC	CSV-file	27/02/2024	Basic prices, in million euros
Inter-Country Use Matrix	FIGAROe3 by JRC	CSV-file	27/02/2024	Basic prices, in million euros

[36] European Commission, Eurostat, Rémond-Tiedrez, I., Rueda-Cantuche, J., EU inter-country supply, use and input-output tables – Full international and global accounts for research in input-output analysis (FIGARO) – 2019 edition, Rémond-Tiedrez, I.(editor), Rueda-Cantuche, J.(editor), Publications Office, 2019, https://data.europa.eu/doi/10.2785/385561

[37] https://data.jrc.ec.europa.eu/collection/id-00403#details

Note: please make sure the values are correctly read by the software of choice (Excel, R …). Commas are used to separate values; decimal points indicate decimal numbers

Source: JRC elaboration

The FIGAROe3 inter-country supply and use tables (in matrix format) can be directly imported in R using the read.csv()-function. The tables have one row with column headers and one column with row labels, commas are used to separate values, and decimal points are used to indicate decimal numbers.

If the column headers are read in as variable names, the FIGAROe3 supply table has 9 798 rows (213 product categories * 46 regions) and 8 097 columns (1 row labels column + 176 industries * 46 regions). Similarly, the FIGAROe3 use table has 9 809 rows (213 product categories * 46 regions + 11 domestic rows) and 8 327 columns (1 row labels column + 176 industries * 46 regions + 5 final use categories * 46 regions).

The inter-country input-output tables of FIGARO are compiled using the standard assumptions for all countries. From inter-country supply and use tables, two inter-country input-output tables are created following the analytical transformation processes for deriving the input-output tables[38]: inter-country product-by-product input-output tables and inter-country industry-by-industry input-output tables.

- Model B (industry technology assumption) is applied to derive the industry technology product-by-product input-output tables.
- Model D (fixed product sales structure assumption) is applied to derive the fixed product sales structure industry-by-industry input-output tables.

The inter-country input-output tables are not downloaded but are directly created in the R-software. During the modelling of the scenarios, changes will be applied to the inter-country supply and/or use tables (and/or to the extension tables). After these changes are applied, a new inter-country input-output table is generated via the same analytical transformation process as the original inter-country input-output table.

A quality check is done to compare the self-created inter-country input-output table starting from the downloaded inter-country supply and use tables and the inter-country input-output table from the JRC data catalogue. Only minor deviations due to rounding differences are found (absolute value of deviations typically below 0.001).

[38] Eurostat (2008), Eurostat Manual of Supply, Use and Input-Output Tables, Publications Office of the European Union, Luxembourg

Annex 7. Input-Output analysis

The global distribution of pressures and effects related to final consumption of households have been calculated using an extended multiregional input-output models. For this purpose, environmentally extended industry-by-industry tables were used. The calculation started from the following identities:

$x = A \cdot x + y$ (Equation A1)

where x is the total output vector, A the matrix of direct input coefficients (or matrix of technological coefficients), and y is the final demand vector. Solving the model for output gives:

$x = (I - A)^{-1} \cdot y = L \cdot y$ (Equation A2)

with identity matrix I, and matrix L the Leontief inverse also known as the multiplier matrix or matrix of direct and indirect output requirements per unit produced for final demand. The Leontief model implies the following assumptions: prices are fixed in the short term, input coefficients are constant regardless of output or final demand level changes, structure of the economy is taken to be constant, at least in the reported period.

The direct environmental effects of national production are the result of the sum of the direct effects associated with each unit produced in each industry:

$E^T = \sum_1^n E_t = \sum_1^n e_t^{int} = \langle e^{int} \rangle \cdot x$ (Equation A3)

where E^T is the total environmental or socio-economic effect associated with the corresponding amounts of the final output x and e^{int} is the environmental or socio-economic effect intensity vector. Each element of e^{int} represents the amount of the effect directly caused by the production of a product group. By multiplying the environmental pressure per output unit (measured in physical units per euro worth of output) by the total output of each industry (measured in million euro), defined by equation (2), an environmentally extended input-output model is created:

$E^T = \langle e^{int} \rangle \cdot x = \langle e^{int} \rangle \cdot (I - A)^{-1} \cdot y$ (Equation A4)

in which E^T is the vector of total environmental pressures associated with the corresponding amounts of the products groups finally used (vector y) and e^{int} the environmental pressure intensity vector. Each element of e^{int}represents the amount of the environmental pressure directly caused by the production of a product group. Each element of e^{int} is allocated to a sector-region combination, which, for example, allows to derive the EU27 shares in the total footprint.

The global distribution of pressures and effects related to the final EU27 consumption have been calculated using an extended multiregional input-output model based on FIGAROe3 (industry-by-industry tables). The calculation is based on the following formula:

$$E_{ind}^T + E_{dir}^T = \langle e^{int} \rangle . x + E_{dir}^T = \langle e^{int} \rangle . (I - A)^{-1} . y + E_{dir}^T \quad \text{(Equation A5)}$$

with:

- E_{ind}^T: environmental footprint (indirect impacts)
- E_{dir}^T: environmental footprint (direct impacts generated by final demand)
- $\langle e^{int} \rangle$: environmental effect intensity vector, the amount of the effect directly caused by the production of a product group
- x: sectoral (monetary) output

- $(I - A)^{-1}$: Leontief inverse, representing the economic structure of the supply chain network
- y: final demand, EU27

The scope includes both indirect and direct impacts/resource use. The indirect impacts/resource use covers impacts upstream the global production network. It covers impacts from all kinds of activities, for example, manufacturing, agriculture, and transport. The direct impacts/resource uses cover impacts directly generated by households. For example, the burning of fuels for heating houses or driving a car.

Applying the formula gives individual results for each environmental extension available from the FIGAROe3-dataset.

Applying the formula results in a single value output. It is the total impacts (direct and indirect) related to EU27 final demand. To increase the details of the results, one needs to diagonalise either the environmental coefficient vectors, or the final demand vector, both result in a column and row vector respectively. Diagonalising the coefficient vector results in a column vector detailing by which region (geographically) and by which sector the impact is generated. Diagonalising the final demand vector results in a row vector detailing by which consumption (per region and per sector output) the impact is triggered. Diagonalising both the coefficient vector and the final demand vector results in an output matrix detailing both the origin of impacts and their triggers. Due to the large resolution of this matrix, this latter output is not preferred.

Annex 8. Implementation of the MFA and LCI for the IO analysis

As first step, a matching between the aluminium-related material flows and stocks and the product and sector classification of FIGAROe3 is performed. Table A 18 reports the similarities between the MFA and the products and sector classification from FIGAROe3.

Table A 18. Matching of MFA flows and FIGAROe3 categories

Production phase (based on MFA)	Product/sector classification (based on FIGAROe3)	Code (based on FIGAROe3)
Bauxite	Aluminium ores and concentrate	CPA_B07_E
Aluminium fluoride	Aluminium ores and concentrate	CPA_B07_E
Anodes, prebake	Petroleum coke	CPA_C192_Q
Anodes, Söderberg	Petroleum coke	CPA_C192_Q
Finished products, other uses	Manufacture of fabricated metal products, except machinery and equipment	CPA_C_25
Finished products, electric cables & electric others & consumer durables	Manufacture of electrical machinery and apparatus n.e.c.	CPA_C_27
Finished products, Machinery and equipment	Manufacture of machinery and equipment n.e.c.	CPA_C_28
Finished products, Transport (cars and light trucks)	Manufacture of motor vehicles, trailers and semi-trailers	CPA_C_29
Finished products, Transport (Aerospace) & Transport (Other)	Manufacture of other transport equipment	CPA_C_30
Finished products, Building	Construction	CPA_F_A
Finished products, Packaging (Cans) & Packaging (Foil)	Cultivation of paddy rice	CPA_A01_A
	Cultivation of wheat	CPA_A01_B
	Cultivation of cereal grains n.e.c.	CPA_A01_C
	Cultivation of vegetables, fruit, nuts	CPA_A01_D
	Cultivation of oil seeds	
	Cultivation of sugar cane, sugar beet	CPA_A01_E
	Cultivation of plant-based fibers	CPA_A01_F
	Cultivation of crops n.e.c.	
	Cattle farming	CPA_A01_G
	Pigs farming	CPA_A01_H
	Poultry farming	CPA_A01_I
	Meat animals n.e.c.	CPA_A01_J
	Animal products n.e.c.	CPA_A01_K
	Raw milk	CPA_A01_L
	Wool, silk-worm cocoons	CPA_A01_M
	Manure treatment (conventional), storage	CPA_A01_O CPA_A01_P
	Manure treatment (biogas), storage and land application	CPA_A01_P
	Fishing, operating of fish hatcheries and fish farms, service activities incidental to fishing	CPA_A01_Q
	Processing of meat cattle	CPA_A03
	Processing of meat pigs	
	Processing of meat poultry	

	Production of meat products n.e.c.	
	Manufacture of fish products	CPA_C10_A
	Processing vegetable oils and fats	CPA_C10_B
	Processing of dairy products	CPA_C10_C
	Processed rice	CPA_C10_D
	Sugar refining	
	Processing of food products n.e.c.	CPA_C10_E
	Manufacture of beverages	CPA_C10_F
		CPA_C10_G
		CPA_C10_H
		CPA_C10_I
		CPA_C10_J
		CPA_C11

Source: JRC elaboration

A disaggregation of the sector related to aluminium is required to allow for a better linkage between the results from the MFA and modelling of changes in the supply and use tables. The sector disaggregation includes, first, to make the sum of the existing sectors 'Aluminium production (C24_E) and 'Reprocessing of secondary aluminium into new aluminium' (C24_F), and second to disaggregate these sectors into 9 subsectors, depicted in Table A 19.

Table A 19. Disaggregated sectors with respective market prices

Adapted NACE code	Production sector	Estimated market price [EUR2020 kg^{-1}]	Price reference
C24_EF1	Bauxite refining, smelting, and ingot cast production	1.7	Eurostat trade data; 2020; CN7601; import; extraEU-trade by EU-27
C24_EF2	Production of semis – rolling	2.8	Eurostat trade data; 2020; CN7606; import; extraEU-trade by EU-27
C24_EF3	Production of semis – extrusion	2.0	Eurostat trade data; 2020; CN7605; import; extraEU-trade by EU-27
C24_EF4	Production of semis – casting	4.1	Eurostat trade data; 2020; CN7604; import; extraEU-trade by EU-27
C24_EF5	Production of semis – other	4.1	Eurostat trade data; 2020; CN7604-7616; import; extraEU-trade by EU-27
C24_EF6	Manufacturing	4.2	Eurostat trade data; 2020; CN7610; import; extraEU-trade by EU-27
C24_EF7	Collection and sorting	1.0	Eurostat trade data; 2020; CN7602; import; extraEU-trade by EU-27
C24_EF8	Recycling (remelting and refining)	1.3	Average of C24_EF1 and C24_EF7
C24_EF9	Others	-	-

Source: JRC elaboration

Notice that the sector 'Others' (C24_EF9) is added to entail the (minor) supply of other non-aluminium products as mentioned by the original aluminium sector (C24E + C24F) sector in FIGAROe3. Via this sector, the original balance of the FIGAROe3 model is maintained.

The newly added sectors have other (non-aluminium related) inputs which need to be included in the use table to complete the 'production recipe'. The input structure for sectors C24_EF1 to

C24_EF8 is based on data based on life cycle inventories of the LCA. Notice that C24_EF1 includes bauxite refining into alumina, alumina smelting into aluminium, and ingot casting.

First, the inputs of resources, materials, fuels, electricity, and heat is scaled to the sector size and converted into monetary units. Each input is linked to one or multiple CPA-codes of the FIGAROe3 classification.

After converting all the inputs from the LCI-data into the FIGAROe3 CPA-nomenclature, still many inputs (e.g. input of services) remain unspecified. For these inputs, the original values from the FIGAROe3 sector C24_E and C24_F are used and spread across the disaggregated sectors based on the monetary output shares. The CPA-codes related to aluminium flows are left untouched, as these are already based on data from the material flow analysis or from the life cycle inventories of the LCA.

The result is transferred into the use table. To do this, the data needs to be split across domestic (i.e. EU27) consumption and imports. This split is based on the original data from FIGAROe3. Afterwards, the RAS method is applied to balance the tables. Finally, at this point, the disaggregated supply and use table (both product and sector level detail) is increased to increase the granularity of the model specifically for the case-related sectors/products. Next, the model is regionally disaggregated again to return to the initial geographical detail of FIGAROe3.

Annex 9. Extension tables

9.1 Environmental Footprint

The Environmental Footprint (EF) method includes 16 impact categories of the environmental footprint method. The environmental categories included in the EF-method are:

- CC, Climate Change: Global impact due to changes induced to the climate, including increased average global temperatures and sudden regional climatic changes, as a consequence of the emissions to the atmosphere of the so-called greenhouse gases, such as CO_2, CH_4, and N_2O.
- ODP, Ozone Depletion: Global impact related to the broken-down of stratospheric O_3, including increased skin cancer cases in humans and damage to plants, as a consequence of man-made emissions of halocarbons (as CFCs and HCFCs), halons, and other long-lived gases containing chloride and bromine.
- HTOX_nc, Human Toxicity, non-cancer: Local and regional impact to humans due to the exposure (i.e. due to inhalation of air, drinking water, etc.) to toxic substances emitted in the environment and responsible for diseases (e.g. respiratory disease) other than cancer.
- HTOX_c, Human Toxicity, cancer: Local and regional impact to humans due to the exposure to toxic substances emitted in the environmental and responsible for cancer effects.
- PM, Particulate Matter: Impact on human health due to the increased ambient concentrations of particulate matter (PM) due to the emissions of primary and secondary particulates (i.e. precursors, NO_x, SO_2).
- IR, Ionising Radiation: Impact to human health due to the exposure to ionising radiation (radioactivity) under normal operating conditions (i.e. excluding accidents in nuclear plants)
- POF, Photochemical Ozone Formation: Local and regional impact to the environment and human health related to the formation of tropospheric ozone resulting from the oxidation of solvents and other volatile organic compounds (VOCs) released to the atmosphere that affects organic compounds in animals and plants and can increase the frequency of respiratory problems.
- AC, Acidification: Regional impact to the environment regarding the modification of acidity of soils, as consequences of emission and deposition of acids (and compounds that can be converted to acids) into the environment.
- TEU, Eutrophication, terrestrial: Local and regional impact on the terrestrial ecosystems due to substances containing nitrogen (N) or phosphorus (P) which leads to the disappearance of ecosystems that are poor in nutrients.
- FEU, Eutrophication, freshwater: Local and regional impact on the freshwater ecosystems due to substances containing phosphorus (P) which leads to the reduced oxygen availability consequent from increased algal growth.
- MEU, Eutrophication, marine: Local and regional impact on the marine ecosystems due to substances containing nitrogen (N) which leads to reduced oxygen availability consequent from increased algal growth.
- LU, Land Use: Impacts due to the effects of occupation and transformation of land in terms of reduction of soil qualities (e.g. modification in the organic matter content of soil, or loss of the soil itself (erosion))
- ECOTOX, Ecotoxicity freshwater: Local and regional impact to freshwater ecosystem due to the release of toxic substances that can accumulate and affect individual species as well as the functioning of the entire ecosystem.
- WU, Water Use: Impact related to the consumption of freshwater (lakes, rivers, or groundwater)
- FRD, Resource Use, fossils: Global impact related to the decreased availability and the potential scarcity for future generations of the total reserve of fossil resources.

- MRD, Resource Use, minerals and metals: Global impact related to the decreased availability and the potential scarcity for future generations of the total reserve of mineral and metal resources.

A detailed description of each impact category can be found in Annex 1 of Mengual et al., 2023. Those impacts might ultimately lead to impairment of human health, biodiversity and natural resource loss, climate change, land use, water use, etc. These 16 impact categories can be normalised and weighted into a single weighted score[39] (see Table A 20). Normalisation means that all impact indicators are multiplied by normalisation factors that represent the overall impact of a reference unit (e.g. a whole country or an average citizen). Normalised results based on the Environmental Footprint method express the relative shares of the impacts of EU consumption by citizens compared to global impacts (per person). Weighting means that all impact indicators are given a weight factor that expresses the 'importance' of the impact compared to the others. This allows the aggregation (summing up) of all impact indicators in one single value.

Table A 20. Normalisation and weighting factors of the Environmental Footprint method version 3.1

EF Impact Category	Unit	Normalization factor (EF-method 3.1)	Weighting factor
Climate Change	kg CO_2 eq	7 553.0832	0.2106
Ozone Depletion	kg CFC11 eq	0.0523484	0.0631
Ionising Radiation	kBq U-235 eq	4 220.1634	0.0501
Photochemical Ozone Formation	kg NMVOC eq	40.859198	0.0478
Particulate Matter	disease inc.	0.0005954	0.0896
Human Toxicity, non-cancer	CTU_h	0.0001287	0.0184
Human Toxicity, cancer	CTU_h	1.725E-05	0.0213
Acidification	mol H^+ eq	55.569541	0.062
Eutrophication, freshwater	kg P eq	1.6068521	0.028
Eutrophication, marine	kg N eq	19.545182	0.0296
Eutrophication, terrestrial	mol N eq	176.755	0.0371
Ecotoxicity, freshwater	CTU_e	56 716.586	0.0192
Land Use	Pt	819 498.18	0.0794
Water Use	m^3 depriv.	11 468.709	0.0851
Resource Use, fossils	MJ	65 004.26	0.0832

[39] In this study we apply the EF 3.1 normalisation and weighting factors, see https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html

Resource Use, minerals, and metals	kg Sb eq	0.0636226	0.0755

Source: JRC elaboration

The elementary flows need to be converted into environmental impacts using a matrix of characterisation factors. Ionising Radiation and Ozone Depletion are excluded because emissions related to these impact categories are missing. A matrix of characterization factors reports the impact intensity per unit of resource extracted or substance emitted in the environment. Beylot et al. (2019)[40] make use of 78 elementary flows to estimate 14 out of the 16 environmental impact categories. VITO created a matrix of characterisation factors in the ETC/CE project of the Consumption Footprint indicator commissioned by the EEA, translating the 528 unique environmental extension lines from EXIOBASE v3.8.2 into 14 out of the 16 impact categories of the EF-method (Mengual et al., 2023[41]).

The FIGAROe3 extension table includes emission data on carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases). This table contains data on air emissions by industries and direct emissions by households for 2015 in Gg. We opted for using the data in Gg instead of in Gg CO_2-equivalents, to allow the data to be usable as well for the non-Climate Change impact categories if relevant (e.g. for CH_4-emissions as part of the Photochemical Ozone Formation impact category). The extension data shows the total volume of emissions (in Gg) per sector per geographical area and per household per geographical area.

A wide coverage of environmental extensions is available from the EXIOBASE (currently v3.8.2) dataset. The wide coverage allows to calculate 14 out of the requested 16 impact categories in the EF-method. Ionising Radiation and Ozone Depletion are excluded because emissions related to these impact categories are missing. Whereas the EF-method also recommends assessing the impacts in terms of Ionising Radiation and Ozone Depletion, these two impact categories are excluded from this study. Indeed, in EXIOBASE coefficients relative to ionising radiations are missing while ozone-depleting substances very often lack a value as well (Beylot et al., 2019).

A remark here is that the EF-method defines characterization factors for more emissions and resources extracted than available in EXIOBASE. For some environmental impacts, like Climate Change, the coverage of EXIOBASE is quite complete. For other impacts however, like toxicity, EXIOBASE includes only a very limited selection of emissions. No information, and, thus, no extension lines are available in EXIOBASE to estimate the impact categories Ozone Depletion and Ionising Radiation.

Characterization factors for an Environmental Footprint estimate via Input-Output Analyses (based on Beylot et al., 2019[40]):

Firstly, when it was not possible to match one EXIOBASE extension to a flow in EF2017, a proxy characterisation factor (CF) was introduced. The selection of the proxy was based on the same pollutants group (e.g. Persistent Organic Pollutants and Persistent Bioaccumulative and Toxic) or

[40] Beylot, A., Secchi, M., Cerutti, A., Merciai, S., Schmidt, J., Sala, S., 2019. Assessing the environmental impacts of EU consumption at macro-scale. J. Clean. Prod. 216, 382–393. https://doi.org/10.1016/j.jclepro.2019.01.134

[41] Sanye Mengual, E. and Sala, S., Consumption Footprint and Domestic Footprint: Assessing the environmental impacts of EU consumption and production, EUR 31390 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-76-61754-9, doi:10.2760/218540, JRC128571

on the same chemical group (e.g. dioxins). Secondly, the oxidation state of chromium and arsenic emissions to air is missing in EXIOBASE, whereas it very often influences the fate and the effect of the chemical and, subsequently, the impact quantification (regarding human toxicity and ecotoxicity). The “unspecified” CF was therefore assigned to chromium, as available in EF2017, whereas the highest CF was selected regarding arsenic (no “unspecified” CF in that case, but CFs relative to arsenic III and arsenic V). Finally, all the aggregated flows from EXIOBASE needed the calculation of a CF encompassing all the substances included in the aggregation. Each of these CFs was estimated either i) as a weighted average considering the number of emissions or resource produced at EU27 or at global level, as the preferred solution when feasible, or ii) as an arithmetic average of the CFs available in EF2017 for the flows included in the group.

Overall, considering each impact category, a limited number of elementary flows is considered for the impact assessment step compared to the total number of flows for which a CF is available in the EF-method. In particular, toxicity and ecotoxicity impacts are calculated considering 11 to 15 substances, compared to 1 321 to 7 566 substances characterized in the EF-method. Substances in EXIOBASE assigned with a CF considering Human Toxicity (cancer and non-cancer) and Ecotoxicity freshwater are almost entirely emissions to air, whereas emissions to soil and water represent a share comparable to emissions to air in EF-method. Similarly, non-toxic impacts are calculated with considering from 2 to 5 elementary flows, compared to 7 to 212 substances differentiated in the EF-method. Finally, similar observations can be made regarding resource use (e.g. 13 resource flows assigned with a CF in EXIOBASE with respect to minerals and metals resource use, compared to 48 for which a CF is available in EF-method). This lower number of substances characterized (and therefore contributing to impacts in the assessment) using EXIOBASE compared to the full set of substances available in EF-method is essentially due to the absence of the corresponding substances in the EXIOBASE environmental extensions. The aggregation of some elementary flows in EXIOBASE (e.g. “other industrial minerals”) also additionally contributes to this discrepancy in the number of substances characterized. On the contrary, six elementary flows calculated from EXIOBASE have been unmapped (that is, these substances have been excluded from the impact characterization) in the absence of the corresponding flows (or proxy flows) in the EF-method.

A shortcoming of EXIOBASE is that the end years of the real data in the extension tables vary and are therefore not completely up to date. It means that the extension tables are based on real data till a certain year and then the extension coefficients (i.e. the environmental impact per monetary unit of sectoral output) are kept constant. This means that, after the data series based on real data end, the footprint calculations only capture changes in environmental impacts due to changes in output volumes. Changes in environmental efficiency per unit of output are not captured. The end years of the extension tables are: 2015 for energy, 2019 all greenhouse gases (nonfuel, non-carbon dioxide are nowcasted from 2018), 2013 for material use, and 2011 for most others, land, and water.

The Eurostat Air Emissions Accounts (AEA) by NACE Rev. 2 activity include air pollutants and greenhouse gases per sector per geographical area from 1995 till, currently (last update 20/12/2023), 2022. The database contains carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), nitrogen trifluoride and sulphur hexafluoride (NF_3 and SF_6), carbon dioxide from biomass used as fuel, sulphur oxides (SO_X), ammonia (NH_3), nitrogen oxides (NO_X), carbon monoxide (CO), particulates (both PM2.5 and PM10), and non-methane volatile organic compounds (NMVOC). In addition, this database provides aggregated air emissions like greenhouse gases[42], acidifying gases[43], and ozone precursors[44].

The data is disaggregated into the NACE Rev. 2 sector classification using 64 branches of activities (A64) and some aggregated values plus direct impacts by activities of households (disaggregated into heating/cooling activities, transport activities, and other activities by households). The disaggregation in geographical areas is available for the individual 27 EU Member States and Iceland, Norway, Switzerland, Serbia, and Turkey. Note, that the dataset is incomplete due to missing data and unavailable data for non-EU countries. For this reason, only the air pollutants for which the AEA data can be supplemented with the EXIOBASE data are retained (total CO_2, CH_4, N_2O, HFC, PFC, NH_3, NO_X, CO, PM2.5, PM10, and NMVOC). This results in the addition of new extension lines for these air pollutants, where EXIOBASE data is used to fill in missing values in the AEA data (AEA-adjusted extension lines).

As a result of the not-updated data in EXIOBASE and the incomplete data (missing values and no complete coverage of all geographical areas) in the Eurostat Air Emissions Accounts, we apply checks and corrections based on external data.

For Climate Change related air emissions, the corrections are based on the PRIMAP-hist national historical emission time series (1750-2022) v2.5.1 dataset[45]. It is a comprehensive set of greenhouse gas emission pathways for every country and Kyoto gas covering the years from 1750 to 2022, and all UNFCCC (United Nations Framework Convention on Climate Change) member states, as well as most non-UNFCCC territories.

The material extraction data can be overwritten to match, at country level, with the UNEP Global Material Flows Database[46] (including 13 material categories). This domestic extraction used in EXIOBASE can be overwritten to match with the total domestic extraction per material category, per year and per country from the UNEP-database. Per material category the sectoral distribution at country level available from EXIOBASE remains unchanged. This means that per material category and per country the totals are overwritten, but the allocation to the sectors of extraction remains unchanged, i.e. based on EXIOBASE.

Table A 21. Data downloaded for environmental extensions.

Name	Data provider	Type	Last update	Unit
Air Emissions Accounts Matrix (Gg)	FIGAROe3 by JRC	CSV-file	27/02/2024	Gg

[42] Greenhouse gas emissions include CO_2, N_2O, CH_4, HFC, PFDC, SF_6 and NF_3, all in CO_2-equivalents.

[43] Acidifying gases include SO_X, NO_X and NH_3, all in SO_2-equivalents.

[44] Ozone precursors include NMVOC, NOX, CO and CH4, all in NMVOC-equivalents.

[45] Gütschow, Johannes ; Pflüger, Mika ; Busch, Daniel (2024): The PRIMAP-hist national historical emissions time series (1750-2022) v2.5.1. Zenodo. https://doi.org/10.5281/zenodo.10705513

[46] Global Material Flows Database | Resource Panel (https://www.resourcepanel.org/global-material-flows-database)

F and Fhh from the file IOT_2015_ixi.zip\ satellite	EXIOBASE v3.8.2 by Stadler et al. (2021)[47]	txt-file	21/10/2021	See IOT_2015_ixi.zip\ satellite\unit.txt
Air emissions accounts by NACE Rev. 2 activity	Eurostat [env_ac_ainah_r2],	CSV-file	20/12/2023	tonne (note that some indicators are provided in equivalents)
PRIMAP-hist database v2.5.1 no rounding	Guetschow et al. (2024)	CSV-file	27/02/2024	Gg

Source: JRC elaboration

9.2 Financial costs

The extension tables of FIGAROe3 show the generation of value added per sector, disaggregated into 9 categories as reported in Figure A 3.

Figure A 3. Details on the value added extension table

Taxes less subsidies on products purchased: Total	M.EUR
Other net taxes on production	M.EUR
Compensation of employees; wages, salaries, & employers' social contributions: Low-skilled	M.EUR
Compensation of employees; wages, salaries, & employers' social contributions: Medium-skilled	M.EUR
Compensation of employees; wages, salaries, & employers' social contributions: High-skilled	M.EUR
Operating surplus: Consumption of fixed capital	M.EUR
Operating surplus: Rents on land	M.EUR
Operating surplus: Royalties on resources	M.EUR
Operating surplus: Remaining net operating surplus	M.EUR

Source: FIGAROe3

9.3 Employment

The extension tables of FIGAROe3 show two methods for skills, namely i) based on education, and ii) based on occupation. For each method, the data is disaggregated across male and female and across low-medium-high skilled. The unit is in 1 000 persons (Figure A 4).

[47] Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., ... Tukker, A. (2021). EXIOBASE 3 (3.8.2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.5589597

Figure A 4. Details on the employment extension table

FIGe3 - EMPLS_M_EDU	1000 p
FIGe3 - EMPLS_F_EDU	1000 p
FIGe3 - EMPMS_M_EDU	1000 p
FIGe3 - EMPMS_F_EDU	1000 p
FIGe3 - EMPHS_M_EDU	1000 p
FIGe3 - EMPHS_F_EDU	1000 p
FIGe3 - EMPLS_M_OCC	1000 p
FIGe3 - EMPLS_F_OCC	1000 p
FIGe3 - EMPMS_M_OCC	1000 p
FIGe3 - EMPMS_F_OCC	1000 p
FIGe3 - EMPHS_M_OCC	1000 p
FIGe3 - EMPHS_F_OCC	1000 p

Source: FIGAROe3

9.4 EU strategic autonomy

Global demand triggers production chains that rely on access to resources. Extension data on the use of metal ores is disaggregated into 12 categories, as shown in Figure A 5. These extension data is available from the EXIOBASE extension tables.

Figure A 5. Details on the strategic autonomy extension table

Domestic Extraction Used - Metal Ores - Bauxite and aluminium ores	kt
Domestic Extraction Used - Metal Ores - Copper ores	kt
Domestic Extraction Used - Metal Ores - Gold ores	kt
Domestic Extraction Used - Metal Ores - Iron ores	kt
Domestic Extraction Used - Metal Ores - Lead ores	kt
Domestic Extraction Used - Metal Ores - Nickel ores	kt
Domestic Extraction Used - Metal Ores - Other non-ferrous metal ores	kt
Domestic Extraction Used - Metal Ores - PGM ores	kt
Domestic Extraction Used - Metal Ores - Silver ores	kt
Domestic Extraction Used - Metal Ores - Tin ores	kt
Domestic Extraction Used - Metal Ores - Uranium and thorium ores	kt
Domestic Extraction Used - Metal Ores - Zinc ores	kt

Source: EXIOBASE

The extension lines show the amount of (global) metal ores extraction. All the lines available from the EXIOBASE model are included, but indeed not all of them are labelled as strategic. Gold, iron, lead, silver, tin, uranium, and zinc are identified as non-critical and non-strategic in the 2023 CRM-list. So, the focus for strategic autonomy should be on the demand for bauxite/aluminium, **copper, nickel, PGM's and other non**-ferrous. Unfortunately, no data is available for all individual strategic materials.

Annex 10. Implementation of GECO in prospective tables

Including the NDC-LTS scenario in the disaggregated supply and use tables

From the GECO-database only the Multi-Regional Input-Output tables for the GECO Reference scenario are available. To align with the NDC-LTS scenario multiple datapoint from GECO are used to adapt the FIGe3 supply and use tables to reflect future changes following the GECO NDC-LTS scenario.

First, the IO tables from GECO (using the reference scenario) are used to project the change (compared to 2015) in growth of value added and final demand across the 31 sectors and final demand categories in GECO. Next, the value added for each sector is aligned with specific data on the value added for the NDC-LTS scenario. This data is available from the main macroeconomic indicators reported in the original publication.

In addition, the changing energy production mix and energy use of the GECO NDC-LTS scenario is implemented into the disaggregated supply and use tables of FIGe3. The production and use of energy in the disaggregated supply and use tables are aligned with the projections in the GECO NDC-LTS scenario. The integration is based upon an intermediate step creating balanced tables (in ktoe) on the supply and use of energy. This balance is building upon the GECO Reference scenario and including the specific data on the GECO NDC-LTS scenario on the production and demand for energy by sector. A similar procedure is followed for the CO_2 combustion and non-combustion emissions and the other air pollutants (CH_4, NH_3, NO_X, $PM_{2.5}$, SO_2, and F-gases).

This alignment is limited to the aggregated EU27 and RoW changes derived from the GECO-results. No country specific results were used.

From these GECO-projections at 31 sector level and final demand, relative changes are derived between the base year (2015) and a future year (e.g., 2050). Relative changes are derived for value added generation, energy use, electricity production, final demand consumption, and emission intensities. All relative changes are derived separately for the EU-27 and the RoW. A cross-table shows the links between the sectors from GECO and the 176 sectors from FIGe3. Both a prospective use and supply table are estimated using these sectoral level relative changes. For example, a growth in the sector of 'crops' from GECO between 2015 and 2050 of 24% in EU-27 and 107% in the RoW is used for the FIGe3 cultivation sectors A01_A-A01_H. The input structure is maintained (so growing a similar pace), but the input energy mix is changing according to the relative changes in the energy mix. For example, for the same crop sector the input of coal and oil is reduced by 73% and 43% and substituted by gas in the EU-27.

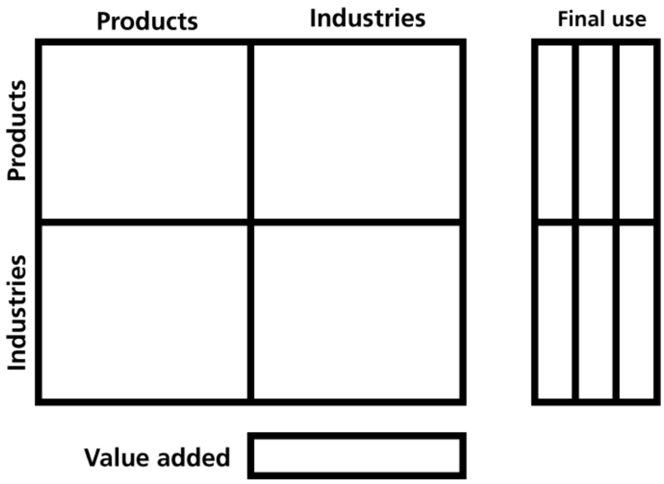
To balance the prospective supply table with the updated use table, a RAS-method is applied to the supply table.

The change in the extension tables is based on the relative change in the emission intensity. The emission intensity is calculated by dividing the emissions by the value added generated by the sector. The change ratio, often a reduction between 2015 and 2050, is applied to the original emission intensities (for CO_2, CH_4, NH_3, NO_X, $PM_{2.5}$, SO_2, and F-gases). All indicators keep the original intensities in the prospective tables.

Annex 11. Description of FIDELIO 4 modules and implementation of the CE levers in FIDELIO

Static supply-use model: The first module is a static supply-use model. It allows an assessment of intersectoral spillovers along global supply chains, following a standard Leontief approach that links the demand side of the model with the production side. The outline of the SUT structure is shown in Figure A 6.

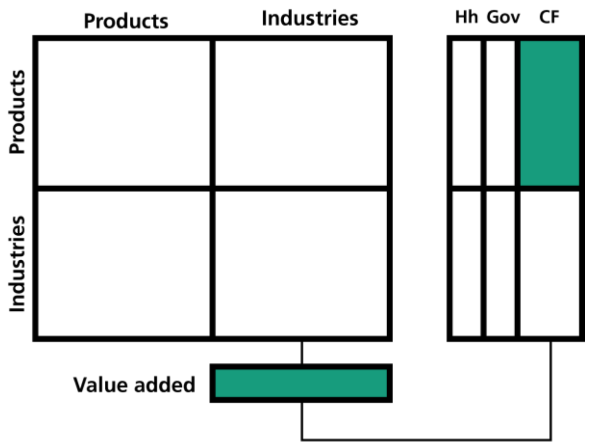
Figure A 6. First module of FIDELO: Static Supply-module



Source: JRC elaboration

Investment dynamics: The second module captures investment dynamics by expanding the gross fixed capital formation column (GFCF) into an investment matrix by industry and product. Investment dynamics are added, linking, for example, total output and gross operating surplus in the value-added section of the SUT to the investment decisions of an industry. Capital accumulation is implemented by adding investment and subtracting depreciation over time. Comparing the results of the investment module with those of the supply-use module makes it possible to assess the spill-over effects of investment in other sectors, such as R&D. The extension of the investment matrix and the dynamics are shown in the stylized version of an investment extended SUT structure in Figure A 7.

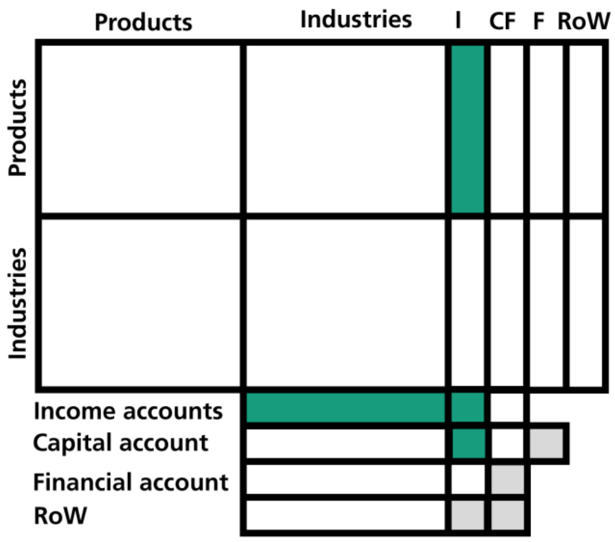
Figure A 7. Second module of FIDELIO: Investment dynamics



Note: CF: Capital account; Gov: Government; Hh: Household
Source: JRC elaboration

Consumption dynamics: The third module adds consumption dynamics. For this purpose, the table is restructured into a national accounting matrix (NAM), a format of IO data mainly used for computable general equilibrium models for a representation of the circular flow of income. Household consumption is divided into quintiles, allowing the impact on different parts of the income spectrum to be assessed. Changes in household disposable income led to changes in household expenditure based on an econometrically derived Almost Ideal Demand System (AIDS). Using the NAM structure, dynamics such as the link between wages and household disposable income or taxes and government spending are added. The module allows for an assessment of income effects highlighting the income distribution as well as CE rebounds due to re-spending (Figure A 8).

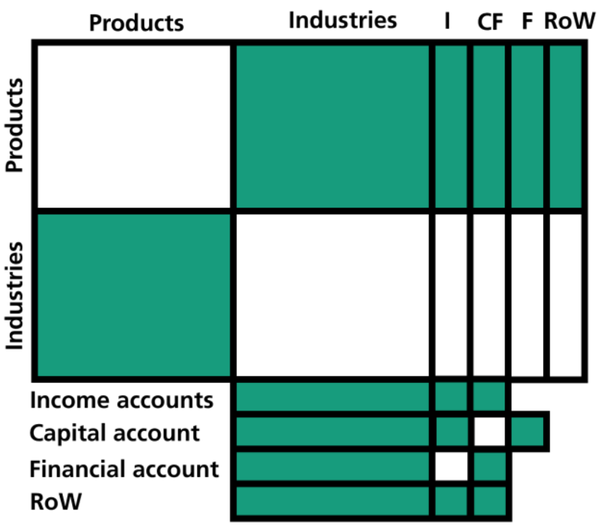
Figure A 8. Third module of FIDELIO: Consumption dynamics



Note: CF: Capital account; F: Financial account; I: Income account; RoW: Rest of the World
Source: JRC elaboration

Full model: In the full model, consumer and producer prices, wages and interest rates are activated. A nested constant elasticity of substitution function is now active on the supply side of the model using a standard CGE approach. While in the other modules the production recipes were kept static, in the fourth module changes in production inputs are possible when their prices change relative to each other. The demand for imports is decided based on an Armington elasticity, which considers price differences between countries. In the model, exports mirror changes in the demand for imports. Changes in consumer prices can lead to changes in consumption and vice versa. Thereby, a fall in demand can lead to a fall in prices, resulting in a partial increase in demand. This is a price rebound and can be investigated using the full model as opposed to the third module. To enhance realism, FIDELIO incorporates price rigidities, acknowledging that industries and consumers require time to adjust to optimal production and consumption levels. Economic equilibrium is achieved only in the long run, reflecting a neo-Keynesian approach that is more realistic than assuming an immediate adjustment to optimal decisions. The price dynamics will influence all matrices of the model as displayed in Figure A 9.

Figure A 9. Fourth module of FIDELIO: Full model with price dynamics



Note: CF: Capital account; F: Financial account; I: Income account; RoW: Rest of the World

Source: JRC elaboration

Herein the detailed implementation of the CE levers (i.e. the shocks) other than the ‘Recover’ ones is presented. The shocks are first implemented in Excel and then transposed into FIDELIO.

1. Implementation of lever 1 “Pre-consumer scrap reduction”

The information provided by the MFA is considered for the STQ21, BSL50, and ACE50 scenarios to calculate the relative reduction. The lever looks at both pre-consumer scrap produced at the fabrication and the manufacturing stage.

As for the changes to be applied for a reduction of the pre-consumer scrap arising at manufacturing, the shocks are implemented to the C24 industry (more specifically, C24_E and C24_F in FIGAROe3), while the commodity to which changes are applied is CPA_E37T39.

As for the changes to be applied for a reduction of the pre-consumer scrap arising at fabrication, the shocks are implemented to the C24 industry (more specifically, C24_E and C24_F), while the commodity to which changes are applied is CPA_B and, more specifically, CPA_B07_E in FIGAROe3.

2. Implementation of lever 2 & 3 "Design for reusability***" and "Remanufacturing of automotive components"***

The information provided by the MFA is considered for the STQ21, BSL50, and ACE50 scenarios to calculate the relative reduction. The lever looks at both pre-consumer scrap produced at the fabrication and the manufacturing stage.

As for the changes to be applied for the lifetime extension of "Transport, passenger car", the industry C29 and commodity CPA_C25 are targeted. Further, to represent the changes in aluminium production due to the lifetime extension, the industry C29 and commodities CPA_C24_E and CPA_C24_F are targeted.

As for the changes to be applied for the lifetime extension of "Transport, aerospace" and "Transport, other", the industry C30 and commodity CPA_C30 are targeted. Further, to represent the changes in aluminium production due to the lifetime extension, the industry C29 and commodities CPA_C24_E and CPA_C24_F are targeted.

As for the changes to be applied for the lifetime extension of "Buildings", the industry F_A and the commodity CPA_F are targeted. Further, to represent the changes in aluminium production due to the lifetime extension, the industry C29 and commodities CPA_C24_E and CPA_C24_F are targeted.

As for the changes to be applied for the lifetime extension of "Electrical, cables" and "Electrical, other", the industry C27 and the commodity CPA_C27 are targeted. Further, to represent the changes in aluminium production due to the lifetime extension, the industry C29 and commodities CPA_C24_E and CPA_C24_F are targeted.

As for the changes to be applied for the lifetime extension of "Machinery and Equipment", the industry C28_A and C28_B, and the commodity CPA_C28_A and CPA_C28_B are targeted. Further, to represent the changes in aluminium production due to the lifetime extension, the industry C29 and commodities CPA_C24_E and CPA_C24_F are targeted.

As for the change to be applied for the lifetime extension of "Other", the industry C32 and the commodity CPA_C31_32 are targeted. Further, to represent the changes in aluminium production due to the lifetime extension, the industry C29 and commodities CPA_C24_E and CPA_C24_F are targeted.

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