Environmental and socio-economic impacts of the circular economy transition in the EU steel sector: analysing steel material flows with life cycle-based and macroeconomic assessment models

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European Commission

Joint Research Centre

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

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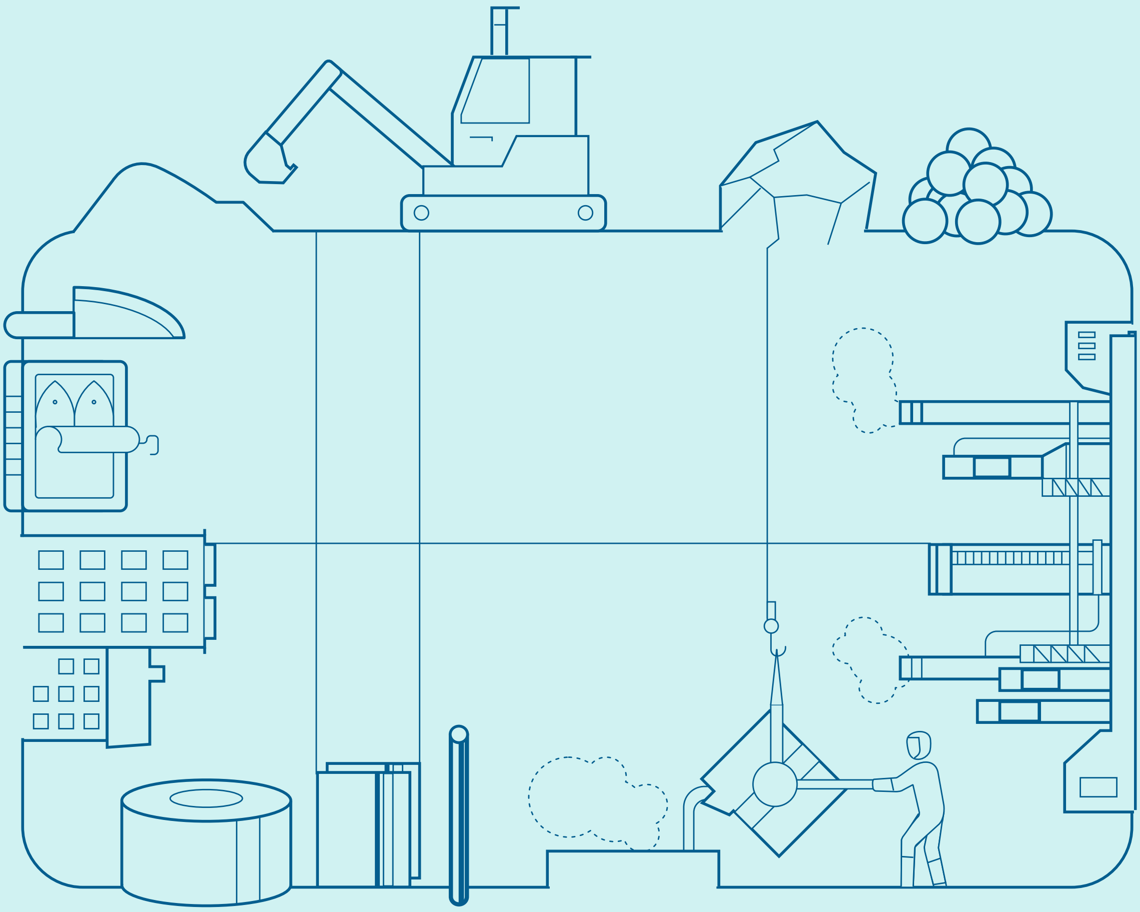

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Contents

Abstract

The EU steel sector can reduce greenhouse gas emissions by 64-81 Mt CO_2-eq. annually by 2050 through circular economy (CE) measures. CE can also significantly decrease EU demand for ores and energy products, leading to a EUR 7 billion annual increase in the EU trade balance with significant imports reduction from China, US, UK, and Russia. However, this may come with trade-offs such as reduced employment and gross value added, which need to be further studied. The study's findings are policy-relevant, highlighting the need for a holistic approach and policy mix to materialise CE potential and informing EU policymakers on strategies to support the steel sector's sustainable transition.

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Executive summary

Policy context

The EU steel and metal industry is facing several challenges in relation to its sustainable transition and the internal competition. In this difficult landscape, the recently launched EU metal action plan aims to ensure the industry's long-term sustainability, addressing challenges such as high energy costs and international competition. The plan focuses on clean energy, circularity, and quality industrial jobs, with measures to increase recycling by enhanced scrap management and demand for scrap. In this, Circular Economy (CE) plays a central role, and it is pivotal to fulfil the long-term decarbonization and sustainability goals of the sector and the EU.

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 steel sector can lead to significant environmental benefits, including reductions in GHG emissions, energy and resource consumption, and waste generation. This comes along with decreased EU dependency from import of fossil fuels and ores leading to a positive increase in the EU net trade balance with its global trade partners. The study also indicates that trade-offs can occur in terms of reduced employment and gross value added, although additional research is strongly encouraged to better understand the CE consequences in the service and R&D sectors, which were only limitedly addressed 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. increase usage intensity, reduce mass, extend lifetime, recover materials, and enhance recycling quality.

Main findings

The study's key scientific findings include:

- The implementation of CE levers in the EU steel sector can achieve an additional reduction of annual 64-81 Mt CO_2-eq. relative to a decarbonised baseline scenario, by 2050. These savings are related to CE levers that do not imply significant behavioural changes. Including these further increase the potential GHG savings to annual 81-99 Mt CO_2-eq., by 2050.
- CE can achieve a significant decrease in the EU demand for metal ores, up to 27% relative to a decarbonized baseline by 2050 (corresponding to ca. annual 40 Mt iron ore), and for

energy products. The overall decrease in fossil energy carrier requirements for the EU steel industries is quantified at ca. 28%. Specifically, this means 38% for coal, lignite and peat, 15% for crude oil, 22% for natural gas and 64% for other fossil fuel relative to the decarbonized baseline, by 2050. Most of these reductions affect imported products (ca. 94%). The reduction of electricity demand for the EU steel industries is also substantial, at 36% relative to the decarbonized baseline, by 2050.

- The decrease in resource and energy demand for the EU steel sector leads to a trade balance increase of ca. EUR 7 billion annually for the EU, relative to the decarbonized baseline by 2050. This is thanks to reduction in imports from US, Russia, China, and UK.
- The study also notes that, under the assumptions and limitations involved, CE implementation leads to decrease in Gross Value Added (thus 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 and R&D sectors.
- The study shows the potential of combining modelling tools that are too often used in isolation, notably material flow analyses, life cycle-based models, environmentally extended input-output, and dynamic economic models. Life cycle-based tools are not meant to capture market-triggered effects, price or investment dynamics, and macro-economic rebound effects. For these reasons, not only the economic and social effects of CE cannot be fully captured by these tools, but also market-driven environmental effects are overlooked. Accompanying process-based life cycle assessment and costing with environmentally extended input-output and dynamic economic modelling allows better capturing macroeconomic effects (e.g. rebound) and interdependencies between sectors and countries. Their combined use significantly improves the information obtained in relation to the effects on economic security aspects, e.g. trade balance with relevant global partners, import reliance, value added, GDP, and employment.

Related and future JRC work

This study complements parallel JRC work on steel, notably within Eco-Design for Sustainable Product Regulation (ongoing work; e.g. Blanco et al., 2024, 2025; Thibaut et al., 2025) and industrial emissions (notably, Koolen & Vidovic, 2022; Moya & Boulamanti, 2016; Somers, 2022). The novel angle of this study, relative to the abovementioned ones, is the strong focus on CE and the quantitative assessment of its global environmental and socio-economic impacts, as well as the suggestion of specific policy instruments to unlock CE potential. While the priorities of future work are summarised in the conclusions (section 10), our findings show that improving the understanding of scrap quality flows and markets as well as the socio-economic implications of CE on the EU service and research sectors is fundamental to grasp the economy-wide effects of CE.

1 The EU steel sector: Background information

1.1 Key figures on the sector

According to the latest publication from the industry covering year 2023 (Eurofer, 2024), the EU is the second-largest steel-producing region in the world, accounting in year 2023 for around 13.8% of global production. In 2023, the EU produced approximately 126 million tonnes of crude steel, with Germany, Italy, and Spain being the top three producers.

The EU steel industry in 2023 had a turnover of around EUR 191 billion and directly employing 303,000 (mostly considered highly skilled) people. The EU steel industry supports nearly 2.6 million jobs, with a multiplier effect of 6 for jobs and 4 for Gross Value Added (GVA) according to estimates from the industry association. Based on this, it can be estimated that the industry overall creates, directly and indirectly, around EUR 152 billion of GVA (Eurofer, 2024).

The EU steel market is supplied by both domestic production and imports from third countries. In 2023, the EU imported 25.6 million tonnes of finished steel products, with Asia being the largest supplier. The EU also exported about 16 million tonnes of finished steel products, with Turkey and the USA being the top two destinations. For the overall trade balance, the EU has a trade deficit of around 9.3 million tonnes of finished steel products in 2023, with imports exceeding exports by 9.3 million tonnes (Eurofer, 2024).

The industry currently consumes significant amounts of steel scrap, with a total consumption estimated to ca. 75 million tonnes in 2023 (Eurofer, 2024). The EU is a significant trader of scrap steel, with imports of 3.9 million tonnes and exports of 18.9 million tonnes in 2023. Recent scientific studies agree on that the scrap exported from EU is mainly low-quality scrap destined to applications in the construction sector (buildings and infrastructure) in third countries, such as Turkey, where demand is rapidly growing and higher relative to the demand in the EU market (notably, Dworak et al., 2022; Daehn et al., 2019).

1.2 Steel supply chain and environmental pressures

Iron and steel production is considered a hard-to-abate sector from a GHG emission reduction perspective due to the techno-economic challenges for replacing energy sources and technologies currently applied to iron reduction or for reducing emissions via capture systems. Together with other basic metal industries, the steel sector is accountable for ca. 13% of the total EU GHG emissions in 2020 and is also a large source of air pollutants[1]. More specifically, in this study we estimate for 2020 that the EU steel sector contributes with ca. 217 Mt CO_2-eq. via direct stack emissions (i.e. emissions occurring on site, in EU territory), corresponding to ca. 8% of EU territorial

[1] Obtained using EUROSTAT for broad industries in 2020. Basic metals (C24) contribute with 149 Mt CO_2-eq. via direct stack emissions, corresponding to ca. 20% of the GHG emissions directly emitted in the EU territory by industry activities (NACE - C), and 13% of all EU territorial emissions (i.e. including electricity, waste and agriculture also). Total industry emissions is 762 Mt CO_2-eq, and total EU territorial emissions is 3478 Mt CO_2-eq. Similar figures are reported in the EU metal action plan (European Commission, 2025).

emissions. The main GHG emission hotspots are the production of primary iron and steel via the so-called blast furnace and blast oxygen furnace (BF-BOF) route[2].

Iron ore is mainly imported to EU, with an overall EU-dependency on foreign sourcing estimated at about 88% today[3]. Iron ore in the BF-BOF route is first subject to a preparation step to produce iron pellets. This consists of crushing, grinding, and concentrating the ore so to increase iron content of the feedstock followed by addition of a binder (e.g. bentonite) to form pellets. This is then followed by sintering, i.e. hardening via heating process, to create a stronger and durable pellet. Coke[4], coal, natural gas and heavy fuel oils are typically applied for this first preparation step. The iron pellets are then fed into the blast furnace where they are reduced to pig iron. To this aim, coke and coal, with coke being the primary reductant, are used. Some blast furnaces may also use injectants such as pulverized coal or natural gas to supplement the coke and improve the efficiency of the process.

Pig iron is then fed to blast oxygen furnace (BOF) for steel production using oxygen. The resulting molten steel is then tapped and cast into slabs or blooms. In total, about 2.3 kg CO_2-eq. kg/kg steel are generated during these steps according to global figures from steelwatch (2025), of which most emissions occur during iron making (Figure 1). This GHG emission figure should be seen as purely indicative and may vary depending on the industrial fuel mix applied for chemical reduction of iron ore pellets, currently mostly based on coke, coal, and natural gas (another source of uncertainty is the GHG accounting methodology, which may also affect the figure). For example, a recent study by Lee et al. (2025) reports 1.61 kg CO_2-eq/kg steel. Downstream the metal supply chain, manufacture of steel containing products also contributes with GHG emissions mainly owing to electricity and heat used for metal working and assembly of product components, but to a much lesser extent compared with (iron and steel) production stage, when a product life cycle perspective is considered.

Recycling steel scrap into new steel (secondary route) reduces by ca. 80% the energy required to produce the same amount of steel relative to primary production (European Commision, 2015), thus significantly abating GHG emission relative to the primary BF-BOF route. The actual GHG emissions from recycling relate to consumption of electricity for remelting of the scrap via processing in electric arc furnace (EAF) and are further expected to decrease with the decarbonization of the EU electricity grid. For the purpose of comparison, various sources report GHG emissions from recycling of steel scrap into new crude steel around 0.37-0.41 kg CO_2-eq. kg/kg steel produced (Ecoinvent centre, 2021; ESTEP, 2021; Lee et al., 2025; among the others), which represents an abatement of 75-84% of the GHG emissions from BF-BOF route when relativized to the GHG figures reported just above.

[2] Throughout the report we will refer to this route as 'primary (production) route', as opposite to the secondary (production) route from scrap recycling. Additionally, any other route starting from ore (as opposite to starting from scrap), such as direct reduction of ore via hydrogen, will also be referred to as 'primary (production) route'.

[3] Own calculation, based on EEIOA (Figaro-E3). We calculate that 17 Mt iron ore is domestically extracted in EU versus an import of 125 Mt to fulfil EU industry demand of 142 Mt (dependency ~88%).

[4] Coke is a type of fuel that is produced by heating coal in the absence of air, and it plays a crucial role in the blast furnace process by providing the necessary carbon for iron reduction.

Figure 1. Overview of the main hotspots for GHG emissions in iron and steel making production via blast furnace and blast oxygen furnace route

Source: steelwatch, 2025

1.3 Sustainable transition and the EU metal action plan

The EU steel industry aims to achieve a transformation in its environmental impact, with the goal of reducing greenhouse gas (GHG) emissions by 80-95% by 2050 compared to 1990 levels (Eurofer, 2019). To achieve this, the industry plans to invest in new technological developments, such as hydrogen-based iron reduction and Carbon Capture and Storage or Use (CCS, CCU) technologies. The industry also aims to increase the use of scrap and improve recycling rates, as secondary steel production (i.e. from steel scrap via recycling) plays a crucial role in reducing GHG emissions as mentioned earlier.

The EU steel industry has identified six scenarios for its transformation, ranging from a business-as-usual approach to more ambitious pathways that involve the deployment of low-carbon technologies and the use of low-carbon energy sources. The industry asks for a supportive regulatory framework to ensure its competitiveness, as well as access to low-carbon energy sources, such as electricity and hydrogen, at commercially viable rates. The transformation of the steel sector is expected to require significant investment, with estimated costs ranging from EUR 52 billion to EUR 120 billion, depending on the scenario (Eurofer, 2019).

The EU metal action plan (European Commission, 2025) aims to ensure the long-term sustainability of the metal industry in Europe, both from an environmental and a socio-economic perspective. While metal industry is key for many (downstream) economic activities, notably construction and automotive, over the last decade the EU share of global steel production shrunk to 7-8% with the EU steel output steadily declining since 2017, from 160 million tonnes to 126 million tonnes in 2023. On the opposite, there has been a major expansion of metal production capacity in Asia and Middle East taking over a significant share of the global market. Draghi (2024) identifies high energy costs and exposure to an unlevel playing field in international competition as the main challenges for these EU industry sectors, followed by the need at EU domestic level to accelerate on decarbonization investment and regulatory burden decrease.

With these challenges in mind, the EU metal action plan is built around six main pillars: ensuring abundant and affordable clean energy; preventing carbon leakage; promoting and protecting EU industrial capacities; promoting circularity for metals; defending quality industrial jobs; and de-risking through lead markets and support to investments. To address competitiveness, the EU plan focuses on reducing energy costs and promoting clean energy, with actions such as developing a delegated act on low-carbon hydrogen and providing guidance on network tariffs to lower costs for energy-intensive industries.

The plan clearly emphasizes the importance of circular economy in supporting the sector in its long-term environmental and socio-economic sustainability, with measures to increase recycling and reuse of metals, such as stimulating demand for scrap in selected sectors while improving waste management to ensure scrap usability in high-quality applications such as automotive. The metal plan clearly states that such a shift towards high-quality recycling requires investments from sorters/recyclers and off-takers (the end-use sectors for the secondary material, such as automotive), as well as incentives at both the EU and national levels, alongside design requirements for relevant product groups, which are studied under the Eco-design for Sustainable Product Regulation (ESPR). In relation to these, a preparatory study on iron and steel ecodesign measures under ESPR is currently ongoing (Blanco et al., 2024). Last, to facilitate the uptake of secondary content in such sectors traditionally dependent on primary metals, the metal plan mentions that the EU Commission will consider the setting of targets for recycled steel in key products, likely under the umbrella of ESPR. Additionally, moving beyond scrap management but still connected to circular economy broadly, the metal plan emphasizes the role of standardisation, notably the promotion of high-strength steel, the reuse of structural steel and the update of scrap qualities classification.

1.4 Structure of the report

This study continues with a description of the research design (section 2). Afterwards, we screen and identify relevant CE levers (section 3) that are subsequently quantitatively assessed. To this aim, we apply a toolkit composed of material flow analysis (section 4, 5), life cycle assessment and costing (section 6), environmentally extended input-output analysis (section 7) and dynamic macroeconomic modelling (section 8). For each individual quantitative analysis, first we describe the methodology and then report the results. Section 9 synthetises and discusses the results from the different analyses altogether, based on which we suggest several policy interventions. The conclusion (section 10) condenses the study to a set of main messages.

2 Research design: CE scenarios and assessment

The research design of this study is composed of several components. First, the CE strategies are introduced to streamline different types of strategies for the analysis (section 2.1). In a second step, four scenarios are explored (section 2.2): one reflects the Status Quo (starting point, today); the second simulates a business-as-usual baseline in the absence of CE policies or additional strategies; a third reflects yet another baseline under the achievement of a selection of CE policy targets (belonging to the Circular Economy Action Plan 1-2 packages; CEAP1-2); and the last scenario reflects the implementation of ambitious CE levers to maximise material savings while reducing environmental impact. The scenarios are assessed applying a toolkit of methods summarised in section 2.3.

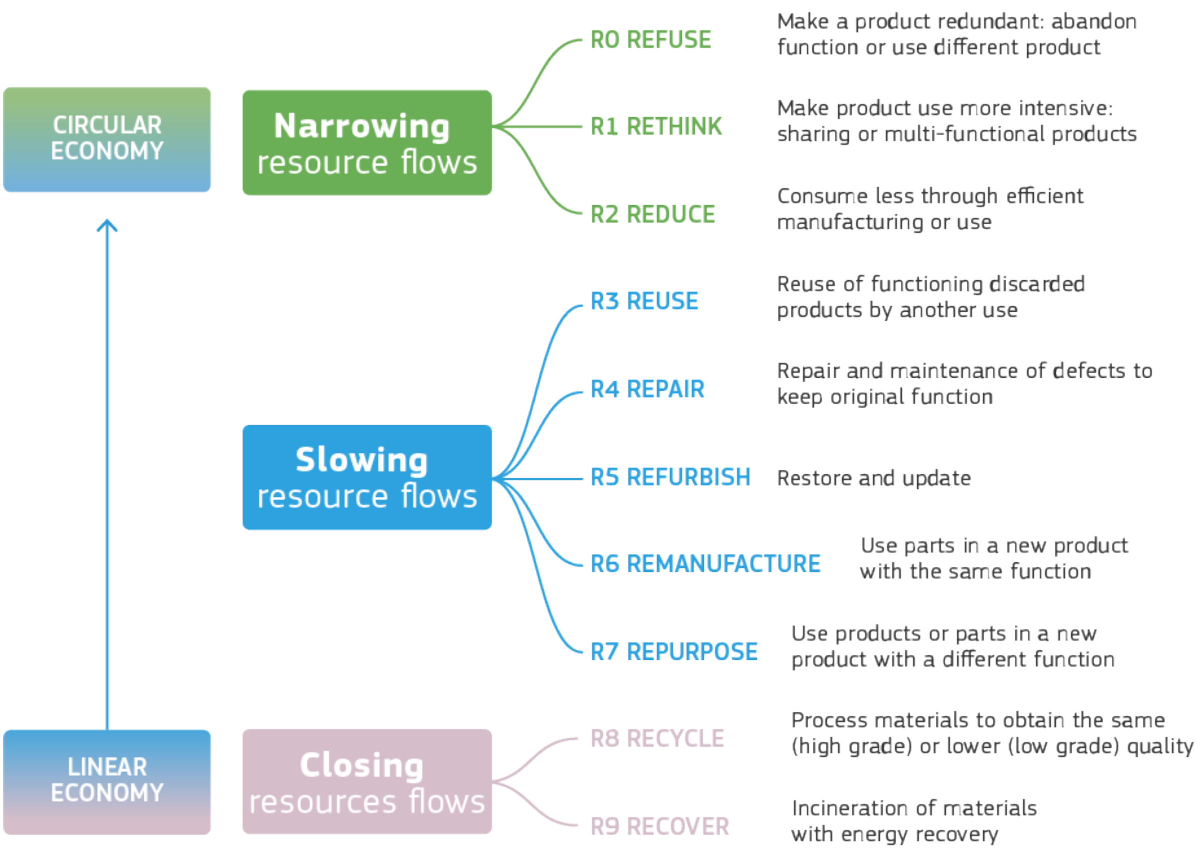
2.1 Circular Economy (CE) strategies

The concept of CE has proliferated over the last decade, and especially after the introduction of the first CEAP published by the EU Commission in 2015. Although there is no single definition for CE, it is generally understood as an economy where the value of materials is maximised and maintained for as long as possible. Moreover, the input of materials and their consumption is minimised, and the generation of waste is prevented and negative environmental impacts reduced throughout the life-cycle of materials (OECD, 2024).

The concept of a CE is multi-dimensional (Ghisellini et al., 2016) and relates to other concepts and principles, including but not limited to, the so-called R-framework that distinguishes different strategies to achieve the goals of CE, the concept of resource productivity or resource efficiency, and sustainable materials management. CE focuses on closing material flows and on the socioeconomic and environmental benefits that arise from it, with the objective of reducing natural resource extraction and decreasing environmental and social impacts without an associated reduction of economic output. The application of CE strategies enables the transition to a CE, but also contributes to increased competitiveness, job creation and re-industrialisation (OECD, 2024).

CE strategies take place at different levels, including different government levels (regional, national, and supra-national), different firm/sector levels and different geographical areas. The most common approach to identifying and defining CE strategies constitutes 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 as available from selected literature, separated into narrowing, slowing, and closing resource flows



Source: elaborated based on Potting et al. (2017)

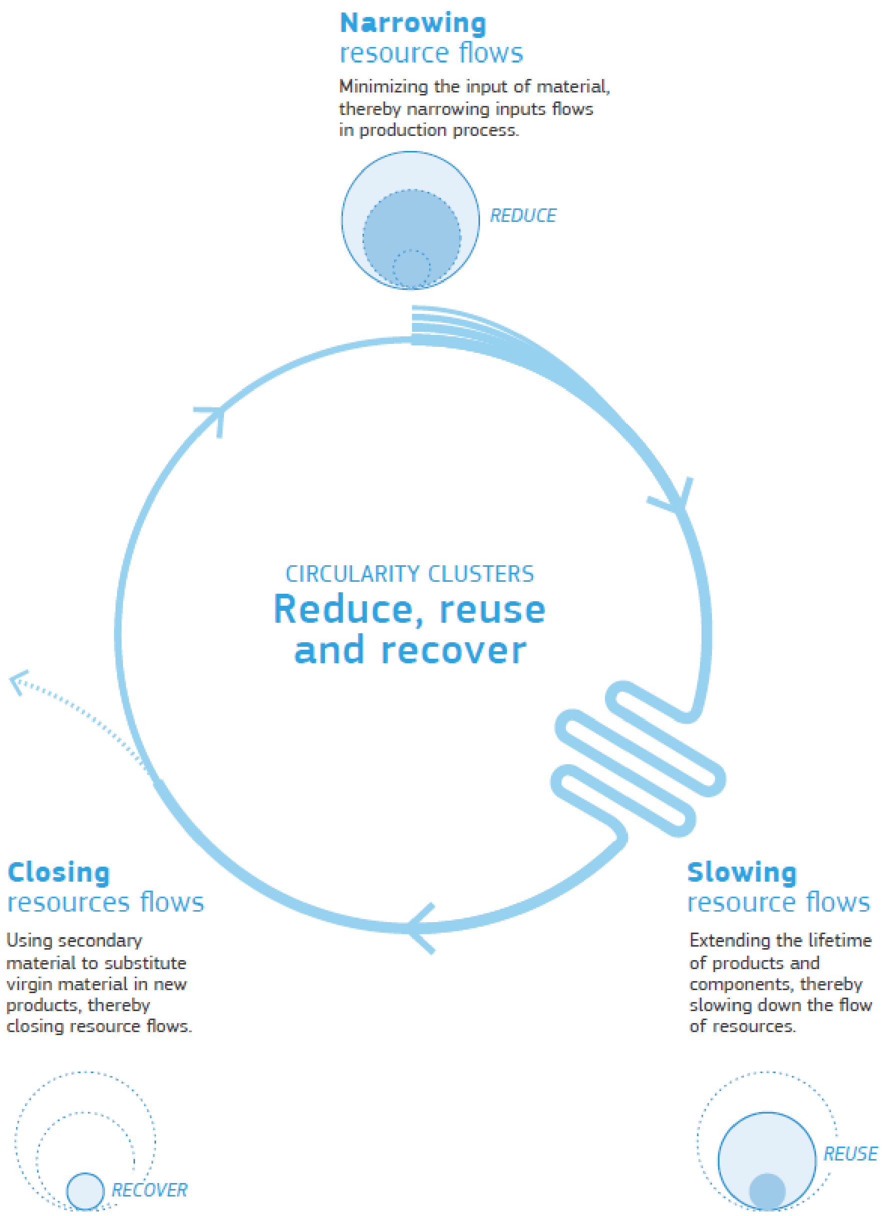
The R Framework is useful in presenting a whole array of CE strategies aiming at a certain material flow outcome, specified as (i) reduction of material input, (ii) extension of material useful life, and (iii) recirculation of materials at the end of life of products. The specific CE strategies exemplify the different ways possible 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 useful life of products; yet their outcome in relation to material use is the same. Therefore, the R Framework can be simplified into a resource outcome-oriented R framework that emphasizes on the broad categories of "Reduce", "Reuse", and "Recycle" as the primary components. Similarly, research on CE strategies has concluded on the usefulness and applicability of this approach, especially when taking on business and policy perspectives (OECD, 2024). For instance, Bocken et al. (2016) have introduced the 'closing', 'slowing', and 'narrowing' resource loops approach. According to this approach:

- 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 capacity, and using natural resources, materials, and products more efficiently.
- Slowing resource loops reduces the need for additional consumption and demand for primary raw materials by extending the life of existing goods. This can be achieved by building long-lasting products that are easy to repair and the ownership of which can change during their lifecycle.

- 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 (i.e. from recycled pre-consumer or post-consumer waste), thus substituting demand for primary raw materials in production.

Furthermore, each of the CE strategies can be applied in isolation or in connection with another according to anticipated outcomes. There is a certain embeddedness of the CE strategies in relation to their application, with the 'Narrowing' strategy affecting also the outcomes of the remaining CE strategies. On the one hand, in a 'narrow' resource loop (flow) – at the beginning of a product's life-cycle – the volume of material is defined, only that amount can become available for the application of the remaining CE strategies (e.g. slowing or closing loops). On the other hand, closing resource loops and reclaiming secondary raw materials can also influence 'narrowing' the demand of primary raw materials (virgin), see Figure 3.

Figure 3. CE strategies key features and effects



Source: JRC elaboration based on OECD (2024) and Konietzko et al. (2020)

In conclusion, taking stock of the available knowledge on the definition of CE strategies that is commonly applied, in this study we consider the following CE strategies:

- *Reduce resource input* (corresponding to R0-R2 and the 'narrowing' resource loop strategies), referred to as *Reduce* in this study (Figure 3)**.**
- *Slow resource throughput* (corresponding to R3-R7 and the 'slowing' resource loop strategies), referred to as *Reuse* in this study (Figure 3)**.**
- *Enhance the recirculation of resources* (corresponding to R8 and the 'closing' resource loop strategies), referred to as *Recover* in this study (Figure 3)**.**

From the CE strategies framework applied in this study, the energy recovery from resources is explicitly excluded, since the focus is on material resource efficiency. 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 are therefore exiting the economy.

2.2 Scenarios definition

To quantify the environmental and socio-economic impacts related to different CE strategies, a Status Quo reflecting 2020 situation, and three future scenarios are defined as follows:

- Status Quo scenario (STQ20), reflecting 2020 conditions.
- 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.
- Ambitious Circular Economy scenario (ACE50), reflecting the implementation of ambitious CE levers on the BSL50, to maximise circularity.

2.2.1 Status Quo 2020 scenario (STQ20)

This scenario reflects the sector in its current conditions, which is represented by year 2020 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 energy transition towards a cleaner grid. The detailed description of the iron and steel flows in the Status Quo STQ20 may be consulted at section 4.

2.2.2 Baseline 2050 scenario (BSL50)

This scenario reflects the evolution of the sector during the time horizon investigated (2020-2050) 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 2020 are extrapolated (i.e. we assume CEAP 1-2 policies have not had an impact on the available waste/materials statistics up to 2020). 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 decarbonization efforts occurring in the energy production sector. In line with the Better Regulation toolbox, this scenario thus represents a benchmark against which the benefits generated by the EU CEAP1-2 policies can be estimated via the scenario CTC50 (Compliance with selected Circular economy Targets scenario). The background conditions considered include:

- Demand for the (functional unit of the) material streams as external factors. While the demand of e.g. recycled materials can also be an endogenous variable, the demand of the function delivered by the product (irrespective of whether it is primary or secondary material) is estimated based on literature.
- 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.
- Carbon price set by the EU Emission Trading System (ETS) as an external factor, which will come into force after the steel industry has benefited from free emission allowances to prevent carbon leakage. These free allowances are going to be phased out between 2026 and 2034 and instead complemented with the Carbon Border Adjustment Mechanism (CBAM).

The detailed description of the iron and steel flows in the Baseline BSL2050 can be consulted at section 4.1.2 (methodology) and 4.2.2 (results). As a general trend, the demand for crude steel is expected to develop as shown in the study by Fraunhofer ISI & European Commission (2023). As a saturation level for steel consumption has been reached until 2020, the underlying assumption for the future Baseline scenario is that the demand for steel stays mostly constant until 2050. For the modelling of the production routes of iron and steel, we rely on the projections of the GECO 2023 (Keramidas et al.; 2023), where the ratio between primary to secondary or alternative routes is about 23:77 by 2050. While other projections exist (e.g. Fleiter et al.; 2021), focusing on the possible alternative routes is beyond the scope of this study. The downstream production volumes (finished steel products) are expected to develop parallel to the crude steel production (same growth/reduction rate per year). The finished steel products are disaggregated into 15 intermediate product groups. Collection and recycling rates follow current levels.

2.2.3 Compliance with selected Targets on Circular economy 2050 scenario (CTC50)

This scenario reflects the evolution of the sector during the time horizon investigated (2020-2050), if the targets reported 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 the achievement of the CEAP1-2 targets as listed in Table 1. Remarkably, none of the targets that may be part of the Eco-Design for Sustainable Product Regulation (ESPR) could be included during this study.

Table 1. CE policy targets considered in the scenario CTC50. For WEEE, only the highest target was used (85%), since it is not possible to differentiate between the categories mentioned

Policy	**Target**	**Year**	**Value**	**Sectors affected**
Waste Framework Directive	Preparing for re-use and recycling of municipal waste	2035	65% by weight	All sectors generating municipal waste
Packaging and Packaging Waste Directive	Preparing for re-use and recycling of ferrous packaging waste	2050	80% by weight	Packaging sector
End-of-Life vehicles	Reuse and recycling	2015	85% by average weight per vehicle	Transport sector
Waste electric and electrical equipment (WEEE) Directive	Recovery, category 1 or 4	2018	85% by weight	All sectors generating WEEE
	Prepared for reuse and recycling, category 1 or 4	2018	80% by weight	All sectors generating WEEE
	Recovery, category 2	2018	80% by weight	All sectors generating WEEE
	Prepared for reuse and recycling, category 2	2018	70% by weight	All sectors generating WEEE
	Recovery, category 5 or 6	2018	75% by weight	All sectors generating WEEE
	Prepared for re-use and recycling, category 5 or 6	2018	55% by weight	All sectors generating WEEE
	Recycled, category 3	2018	80% by weight	All sectors generating WEEE

Source: JRC elaboration

2.2.4 Ambitious Circular Economy 2050 scenario (ACE50)

This scenario reflects a normative scenario, in which ambitious levers are implemented based on the selection of a portfolio of levers, as defined in section 3. The full potential of these levers is assumed to be achieved in the target year 2050 of the analysis; this assumption is then tested in a sensitivity analysis based on stakeholder's inputs. This ACE50 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 greenhouse gases (GHG) emissions by 2050. The CE strategies outlined in Section 3 are functional to capture a wide spectrum of possible CE measures, 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 concrete 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 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 levers is identified from literature, and the corresponding economic and environmental impacts on the material system subsequently assessed. The levers are clustered according to the respective CE strategies that were previously defined (reducing resource input or *Reduce*, slowing resource throughput or *Reuse*, enhancing the recirculation of resources or *Recover*). The CE levers only include measures related to material flows and do not endogenously take into consideration the deployment of decarbonization technologies, such as carbon capture and storage or electrification of production plants. These are already part of the background conditions of the analysis, i.e. the Business-as-Usual (BAU) Baseline (BSL50) considered for the assessment.

2.3 Toolkit used for the assessment

To quantitatively assess the impacts of the scenarios, we apply a toolkit composed of Material Flow Analysis, (bottom-up) Life Cycle Assessment and Costing, Environmentally Extended Input-Output Analysis, and Dynamic Macroeconomic Modelling. Whereas the individual methodologies are described in detail in section 4.1 (MFA), section 6.1 (LCA and LCC), section 7.1 (EEIOA) and section 8.1 (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. This was expanded by including recycling quality aspects, building upon previous work from Dworak et al. (2022); Dworak & Fellner (2021), forward-looking 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 macro-economic 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 macro-economic effects such as spillover effects, changes in prices, investments, and trades.
- EEIOA, based on FIGARO tables, 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 macro-economic indicators such as Gross Value-Added changes, GDP, employment, 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, using the FIDELIO 3 model, provides a framework for understanding the broader economic consequences of the CE transition. The FIDELIO 3 model is a dynamic, multi-regional input-output model with new-Keynesian features, suitable for analysing medium-term transitions. It is designed to capture spill-over and rebound effects, and quantify impacts on jobs, growth, energy savings, resource use, and trade balance. Additional to the EEIOA, it accounts for investments, price change effects, and change in trade patterns offering a better angle on the full macro-economic effects.

Table 2. Illustration of the scope, strength and limitations of the methods applied, and their complementarities

Assessment Method	**Scope**	**Granularity**	**Strengths**	**Limitations**
Life Cycle Assessment and Costing (LCA & LCC)	Limited to industry production and consumption in Europe, incl. waste management. Trade flows are simplified via net trade. The rest of the economy is truncated.	The system boundary represents detailed flows of iron and steel from production to waste management within EU.	Detailed flows and supply chain representation for the steel material system under assessment.	Relative to EEIOA and DMM: Truncation error (it does not take into account spillovers, investments, price change effects, and change in trade patterns).
Environmentally Extended Input-Output Analysis (EEIOA)	Global economy with disaggregated EU steel industry. The economy is not truncated.	The EU and Global economy is represented by 165 sectors (Figaro IO tables); the EU steel sector is further disaggregated (sector C24).	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 is represented by 64 sectors.	Investments, price change effects, and change in trade patterns.	Relative to LCA and EEIOA: Aggregation error.

Note: DMM: Dynamic Macroeconomic Modelling. EEIOA: Environmentally Extended Input-Output Analysis; LCA: Life Cycle Assessment; LCC: Life Cycle Costing

Source: JRC elaboration

3 Identification of circular economy (CE) levers

This section describes the methodology applied for the identification of the CE levers pertaining to the three overarching strategies (*Reduce, Reuse, Recover*). On this basis, the CE strategies are further subdivided into CE levers, the effects of which are described in the following subchapters. Once these effects are fed into the Material Flow Analysis (MFA), the resulting MFA scenarios provide the basis for the subsequent quantification of the impacts (bottom-up via LCA and LCC, top-down via EEIOA or DMM).

3.1 Methodology

This section presents the CE levers that have been developed for specific end-use products using steel, namely residential buildings, commercial buildings, road infrastructure, railway infrastructure, mechanical equipment, cars, trucks, locomotives and rail rolling stock, and food packaging. These end-use products were selected on the basis of their consumption of steel for their manufacturing, as presented in Table 3.

Table 3. Quantities of steel used in the manufacturing of end-use products in the EU based on Rostek et al. (2022)

Aggregated categories of end-use products	**Categories of end-use products, as per MFA**	**Quantities of steel used in the EU (kt) in 2021**	**Quantities of steel used in the EU in 2021 (% of total)**
Construction	Buildings	63,663	41.1%
	Infrastructure	35,048	22.6%
Industrial equipment	Mechanical equipment	19,197	12.4%
	Electrical equipment	4,955	3.2%
Vehicles	Cars	6,494	4.2%
	Trucks	2,860	1.8%
	Ships & others	3,346	2.2%
Metal goods	Food packaging	3,770	2.4%
	Appliances	266	0.2%
	All other metal goods	15,373	9.9%
Total		154,972	100%

Source: JRC elaboration

Table 3 presents the broader set of CE levers that have been identified for the EU steel sector. Table 4 shows the categories of CE levers, clustered according to the overarching CE strategies (*Reduce*, *Reuse*, *Recover*), the end-use products to which they apply, and the scenario in which they are considered. In addition, if a lever is a “Supporting lever”, the table indicates the “Final lever” that it supports. If the lever is “Final”, then it supports no further lever, which is indicated in the table as well. Cells in grey contain levers that require an important change in the behaviour of citizens, which political and societal acceptability is currently low.

Table 4. Summary of the entire set of CE levers applicable to end-products using steel and scenarios to which they would apply

High-level CE strategy	Category of Circular Economy lever	Circular Economy levers applicable to end-use products using steel	End-use products using steel to which levers apply	Final lever(s) that the lever supports	Scenario CTC50	Scenario ACE50
***Reduce* (Reduce the input of resource)**	**1.** Increase material efficiency in processes along the lifecycle	**1.a** Eco-design options, such as: • avoid cutting • use straight perpendicular cuts • make goods from long-products rather than flat-products • design sheet steel components to tessellate, by optimizing steel plate and roll cutting patterns • reduce the gripping border around drawn sheet parts • reduce machining by casting complex shapes close to their final shape (near-net-shape casting)	• All	*None (Final lever)*	✓	✓
	2. Reduce service level to reduce size and mass	**2.a** Quantitative limitation in the housing surface per person	• Residential buildings • Commercial buildings	*None (Final lever)*		✓
		2.b Reduce the size and / or power of individual cars	• Cars	*None (Final lever)*		✓
	3. Reduce the size of the stock					
	3.1. Increase usage intensity	**3.1.a** Sharing of building spaces (e.g. guest room, party room, laundry room in dwellings, shared office spaces)	• Residential buildings • Commercial buildings	*None (Final lever)*		✓
		3.1.b Increase road and rail usage capacity	• Road infrastructure • Railway infrastructure	*None (Final lever)*		✓
		3.1.c Stimulate the sharing of truck transport capacity	• Trucks	*None (Final lever)*		✓
		3.1.d Sharing of mechanical and electronic equipment and domestic goods through dedicated platforms	• Mechanical equipment	*None (Final lever)*		✓
	3.2. Reduce consumption to reduce the stock of infrastructure	**3.2.a** Stimulate car-pooling and ride-sharing in suburban and rural environments	• Cars	*None (Final lever)*		✓
		3.2.b Net-zero land take policies	• Residential buildings • Commercial buildings • Road infrastructure • Railway infrastructure	*None (Final lever)*		✓

	and productive assets	**3.2.c** Quantitative limitation in the total mass of goods purchased per year and per person	• Road infrastructure • Railway infrastructure • Trucks • Locomotives and rail rolling stocks	*None (Final lever)*		√
		3.2.d Quantitative limitation in the electric consumption per year and per person	• Road infrastructure • Railway infrastructure	*None (Final lever)*		√
		3.2.e Quantitative limitation in the water consumption per year and per person	• Road infrastructure • Railway infrastructure • Mechanical equipment	*None (Final lever)*		√
		3.2.f Quantitative limitation in the number of kilometres travelled by train or plane per year and per person	• Road infrastructure • Railway infrastructure • Locomotives and rail rolling stocks	*None (Final lever)*		√
		3.2.g Quantitative limitation in the data traffic on the Internet per year and per person	• Road infrastructure • Railway infrastructure	*None (Final lever)*		√
	4. Reduce the amount of materials used to perform a function at constant service level					
	4.1. Substitute a technical solution by a more material-efficient one	**4.1.a** Substitution of office spaces by teleworking	• Commercial buildings	*None (Final lever)*		√
		4.1.b Stimulate living in apartment buildings vs. individual houses	• Residential buildings • Commercial buildings	*None (Final lever)*		√
		4.1.d Substitute cars with a combination of bicycles + trains	• Cars	*None (Final lever)*		√
	4.2. Reduce mass	**4.2.a** Reduce over-specification in buildings and infrastructure – reduce the amounts of reinforced concrete (based on steel) that is used	• Residential buildings • Commercial buildings • Road infrastructure • Railway infrastructure	*None (Final lever)*		√
		4.2.b Implement high-strength steel or composites to reach the same strength with less weight	• All	*None (Final lever)*		√
	5. Reduce the share of non-renewable					

	primary metals, materials, or chemicals in each item					
	5.1. Increase share of biobased materials	**5.1.a** Substitute part of the structural elements, e.g. steel beams or reinforced concrete beams by wooden beams	• Residential buildings • Commercial buildings • Road infrastructure • Railway infrastructure	*None (Final lever)*		✓
		5.1.b Shift to wood-based construction, using innovative materials such as cross-laminated timber	• Residential buildings • Commercial buildings • Road infrastructure • Railway infrastructure	*None (Final lever)*		✓
	5.2. Increase share of secondary materials	**5.2.a** Minimum recycled content in new products[5]	• All	*None (Final lever) supported by levers: 7.a – 7.g*	✓	✓
***Reuse* (Slow resource throughput)**	**6.** Increase lifetime (of complete systems and of their modules, parts, and components	**6.a** Digital Product Passport for steel components, containing the data necessary for disassembly, test, diagnostics, maintenance, repair, and re-assembly	• All except Food packaging	6.f 6.g 6.h		✓
		6.b Design for longevity/durability, reversible dis-assembly, maintenance, repair, re-furbishing, re-use and recycling	• All	6.f 6.g 6.h 6.j		✓
		6.c Modular design separating the modules containing fast-changing technologies (specifically: electronics) from	• All except Food packaging	6.f 6.g		✓

[5] The main limiting factor why recycling is not performed enough is that there is no lucrative market for secondary materials, which must compete with low-priced primary materials. If the law sets a minimum share of secondary materials, then it creates a market that is specific to secondary materials, where the prices can differ, if needed significantly, from those for primary materials. It hence creates a much more lucrative and quantitatively stable market for secondary materials, and for the activity of recyclers, with a possibility to invest in high-performance technologies and to remunerate the providers of clean secondary materials (including consumers). If the target for minimum recycled content is set high enough, targets for the separate collection of waste may become less important, because economic operators and consumers alike will converge towards maximising that rate for economic reasons. However, being the market global, recycled material can also be provided by suppliers external to EU, thus inducing EU waste to be landfilled or incinerated if the cost of collection, sorting and recycling in EU are higher (see case of plastic). Therefore, levers (such as binding targets) on the EU secondary material supply-side (recycling value chain) may still make sense to support EU recyclers and avoid a downgraded management of the EU locally generated waste.

		those with technologies evolving more slowly (e.g. purely mechanical parts)		6.h		
		6.d Availability of spare parts over a long period of time	• All except Food packaging	6.f 6.g 6.h		✓
		6.e Re-use components or spare parts from discarded technical systems in new systems or for the maintenance or repair of existing systems	• All except Food packaging	6.f 6.g 6.h		✓
		6.f Use complete technical systems for a longer time in their existing function with their existing owner	• All except Food packaging	*None (Final lever) supported by: 6.a to 6.e*		✓
		6.g Re-use complete technical systems, e.g. via secondary markets of officially certified second-hand equipment = changing owner without changing function	• All except Food packaging	*None (Final lever) supported by: 6.a to 6.e*		✓
		6.h Refurbish and upgrade technical systems after some years of use to extend their lifetime, e.g. via clarification of liability of refurbishers = improving function with the same owner	• All except Food packaging	*None (Final lever) supported by: 6.a to 6.e*		✓
		6.i Set up backward collection logistics systems for metal packaging to enable their re-use	• Food packaging	6.j		✓
		6.j Re-use metal packaging over several cycles	• Food packaging	*None (Final lever) supported by: 6.b and 6.i*		✓
		6.k Quantitative limitation in the number of kilometres travelled by car per year and per person	• Road infrastructure • Railway infrastructure • Cars	*None (Final lever)*		✓
***Recover* (Enhance**	Enhance End-of-Life material recovery[6]	**7.a** Increase efficiency and selectivity of separate waste collection (including avoidance of leakage) and of sorting. Thereby supply high-quality and high-purity secondary	• All	5.2.g	✓	✓

[6] CE lever category 7 in isolation (without the CE lever 5.2.a) is only an enabler of environmental benefits, but brings none per se. If materials are collected and sorted at end of life and are not used, then there is no environmental benefit. The environmental benefits of the collection of materials at end of life only materialise when these secondary materials are used, because they substitute primary materials.

the cycling of resources)		material that effectively substitutes primary material on the EU or global market				
		7.b Ecodesign: use reversible assembly processes between pieces made of different qualities of steel and between pieces made of steel and pieces made of metal other than steel (specifically: copper) at the manufacturing stage to enable lossless and high-purity disassembly at end of life	• All	5.2.g		✓
		7.c Digital Product Passport containing the exact nature of the steel alloy used in each homogeneous component, and instructions for non-destructive dis-assembly, to facilitate high-purity, circular recycling	• All	5.2.g	✓	✓
		7.d Limit the number of different steel alloys used, enabling the management of separate high-purity waste streams for circular recycling	• All	5.2.g		✓
		7.e Increase quality of separate waste collection by enhanced sorting to supply high-quality secondary material and reduce low quality export	• All	5.2.g		✓
		7.f Implement industrial-scale dis-assembly of End-of-Life durable goods instead of their shredding	• All	5.2.g		✓
		7.g Execute demolition and transport of End-of-Life building components with care (in particular: remove debris of concrete attached to the steel reinforcement structure), to facilitate separate sorting and high-purity recycling	• Residential buildings • Commercial buildings • Road infrastructure • Railway infrastructure	5.2.g		✓

Source: JRC elaboration

3.1.1 Link between CE levers, quantitative indicators, and Material Flow Analysis

Table 5 links the categories of CE levers with their impacts on the quantitative indicators used to describe the current situation (Status Quo), and the path through which they modify the environmental and climate impacts of the production of steel and management of waste thereby generated. The current situation of steel use in the end-use products is presented in detail in the Supplementary Material named 'Circular Economy Levers and Scenarios' (available upon request).

Table 5 also provides the calendar of implementation and of propagation of the effects across the stock of existing end-use products. This calendar uses as a parameter a time constant common to several propagation effects that we call the Adaptation Period of Industry, which is the time needed for industry to adapt the design and the manufacturing of its end-use products to the new regulatory framework. For the sake of simplicity in the modelling, the implementation of the CE levers is assumed to be stepwise after that Adaptation Period of Industry, i.e. with no effect during that period, and then full effect. For the subsequent computations of effects of Circular Economy levers in the Material Flow Analysis, it is assumed that the Adaptation Period of Industry is equal to 5 years.

When on the opposite the implementation of the CE lever is progressive, that lever varies with a constant increase or decrease rate between the initial value and the target value (i.e. along an exponential curve), over the whole duration of the simulation.[7]

Once the change in the design and the manufacturing of the product has taken place, it propagates in the existing stock of end-use products as described in Text box 1.

[7] Constant rate of increase or decrease is considered a change that occurs with a constant multiplication factor between year N and year N+1, leading to an exponential curve of increase or of decrease. This multiplication factor often is expressed in % / year.

Table 5. Links between the categories of CE levers and their impacts on the quantitative indicators and on environmental and climate impacts of the production of steel

Category of Circular Economy levers in the classification	**Quantitative indicator(s) being impacted**	**Pathway to the reduction in the environmental and climate impacts of the production of steel**	**Calendar of implementation and of propagation of the effects across the stock of existing end-use products**
1. Increase material efficiency in processes along the lifecycle	Resource used per kg of steel (valid for all end-use products)	Direct	The increase in material efficiency is achieved at a constant rate over the **whole duration of the simulation**
2. Reduce service level to reduce size and mass	Intensity of use of end-use products in stock *or* Efficiency in the usage of steel	Reduced service per unit manufactured ⇨ Reduced consumption of steel per unit manufactured ⇨ Reduced production of steel ⇨ Reduced environmental and climate impacts	The new service level is implemented **in full** to all **newly manufactured** end-use products (not to those in stock) at the end of the **Adaptation Period of Industry**
3. Reduce the size of the stock			
3.1. Increase usage intensity	Intensity of use of end-use products in stock *or* Efficiency in the usage of steel	Reduced stock of end-use products ⇨ Reduced inflow of new end-use products + Reduced inflow of steel to maintain the stock ⇨ Reduced production of steel ⇨ Reduced environmental and climate impacts	At the end of the life of one end-use product, it is (on average) replaced by **less than one** end-use product, the **reduction factor R** evolving at a constant rate over the **whole duration of the simulation**
3.2 Reduce consumption to reduce the stock of infrastructure and productive assets	Size of the stock of end-use product or Quantity of steel in the stock of end-use products	Reduced stock of end-use products ⇨ Reduced inflow of new end-use products + Reduced inflow of steel to maintain the stock ⇨ Reduced production of steel ⇨ Reduced environmental and climate impacts	At the end of the life of one end-use product, it is (on average) replaced by **less than one** end-use product, the **reduction factor R** evolving at a constant rate over the **whole duration of the simulation**
4. Reduce the amount of materials used to perform a function at constant service level			
4.1 Substitute a technical solution by a more material-efficient one	Inflow of new end-use products	Reduced inflow of new end-use products ⇨ Reduced production of steel ⇨ Reduced environmental and climate impacts	At the end of the life of one end-use product, it is (on average) replaced by **less than one** end-use product, the **reduction factor R** evolving at a constant rate over the **whole duration of the simulation**

4.2 Reduce mass	Reduced consumption of materials per unit manufactured	Reduced consumption of steel per unit manufactured ⇨ Reduced production of steel ⇨ Reduced environmental and climate impacts	The new mass of steel per unit is implemented **in full** to all **newly manufactured** end-use products (not to those in stock) at the end of the **Adaptation Period of Industry**
5. Reduce the share of non-renewable primary metals, materials or chemicals in each item			
5.1 Increase share of sustainably-sourced biobased materials	Mass of steel per end-use product in stock	Reduced consumption of steel per unit manufactured ⇨ Reduced production of steel ⇨ Reduced environmental and climate impacts	The new mass of steel per unit is implemented **in full** to all **newly manufactured** end-use products (not to those in stock) at the end of the **Adaptation Period of Industry**
5.2 Increase share of secondary materials	Share of recycled steel	Reduced consumption of primary steel per unit manufactured Increased consumption of secondary steel per unit manufactured ⇨ Reduced environmental and climate impacts	The increase in the share of secondary steel in the inflow of steel used to manufacture the end-use product is achieved at a constant rate over the **whole duration of the simulation**
6. Increase lifetime	Lifetime of end-use products or Lifetime of steel in end-use products	End-use products remaining longer in stock ⇨ Reduced inflow of new end-use products ⇨ Reduced production of steel ⇨ Reduced environmental and climate impacts	The new lifetime is implemented **in full** to all **newly manufactured** end-use products (not to those in stock) at the end of the **Adaptation Period of Industry**
7. Enhance End-of-Life material recovery	None	Creates the enabling conditions for end-use products to be produced using higher share of recycled steel (lever 5.2). As such, the effect is reduction of primary material.	It is achieved at a constant rate over the time horizon investigated

Source: JRC elaboration

Text box 1. Propagation of the impacts of a Circular Economy lever across the stock of end-use products

For the sake of simplicity of the modelling, for each end-use product, only two types exist:

- The "linear" type of that end-use product, before implementation of the Circular Economy lever, identified with the index 1;
- The "circular" type of that end-use product, on and after implementation of the Circular Economy lever, identified with the index 2.

Each type of the end-use product is characterised by:

- a lifetime λi (i=1,2), which is longer for the "circular" type (i=2) than for the "linear" one (i=1);
- a mass of steel per functional unit μi (i=1,2), which is lower for the "circular" type (i=2) than for the "linear" one (i=1).

Circular Economy levers can lead to having one discarded functional unit of end-use products being replaced by less than one functional unit. The reduction factor in the number of functional units following the implementation of a Circular Economy lever is noted **R**.

The **stock** of end-use products is represented by the accumulation of end-use products, grouped per **year of production**. All end-use products manufactured the same year have the same age. We note $\mathbf{N_k}$ the number of functional units that were manufactured in the year k, and $\mathbf{M_k}$ their total mass, with $\mathbf{M_k} = \mathbf{N_k} \,.\, \boldsymbol{\mu_k}$, and $\boldsymbol{\mu_k}$ taking the value $\boldsymbol{\mu_1}$ or $\boldsymbol{\mu_2}$) depending on the date of production k.

At the start of the simulation, the stock is made of "linear" types of the end-use products only.: the end-use products of all previous years are all of the "linear" type.

As the simulation evolves, the stock is made of a mix of "linear" and "circular" types:

- only "linear" types for all years before the implementation of the Circular Economy levers;
- only "circular" types for all years on and after the implementation of the Circular Economy levers.

The model implemented in the Material Flow Analysis to represent the stock generates, for each year of production in the past, and based on:

- the lifetime of the end-use products that were manufactured that year, and on
- the time elapsed since then (the age of these end-use products),

The mass of steel in the end-use products that are discarded and hence disappear from the stock. That mass steel in the end-use products that were produced in year k and are discarded in year K is proportional to the mass of steel in the end-use products that had been produced in year k, and is equal to $\mathbf{M_k} \,.\mathbf{f}(K - k; \boldsymbol{\mu_k})$, with:

- **f** the function in the MFA that represents the discarding over time of old end-use products;
- K the current year in the simulation (i.e. the year for which the computation is made of the mass of discarded units);
- k the year when the end-use product was manufactured, so that **(K-k)** is the **age** of the end-use product;
- $\boldsymbol{\lambda_k}$ taking the value ($\boldsymbol{\lambda_1}$ or $\boldsymbol{\lambda_2}$) depending on the date of production k.

This mass of steel discarded in year K from the stock and produced in year k corresponds to a number of functional units equal to $(\mathbf{M_k} / \mu_k) \,.\, \mathbf{f}(K - k; \boldsymbol{\lambda_k})$, with $\boldsymbol{\mu_k}$ taking the value μ_1 or μ_2) depending on the date of production k.

These discarded functional units from the production year k are replaced in the stock in the year K by a number of "circular" functional units which is equal to:

R. $(\mathbf{M_k} / \boldsymbol{\mu_k})$ **.** $\mathbf{f}(K - k; \boldsymbol{\lambda_k})$,

in which the total mass of steel is equal to:

R. $(\boldsymbol{\mu_2} / \boldsymbol{\mu_k})$ **.** $\mathbf{M_k}$ **.** $\mathbf{f}(K - k; \boldsymbol{\lambda_k})$.

This computation is made on each year K of the simulation, for each year of production of end-use products still in the stock at date K.

3.2 Results

The first order effects of the implementation of the CE levers under scenarios CTC50 and ACE50 are given in the tables below. The "first-order effect" is understood as the changes, compared to the Baseline, in the quantitative indicators (as presented in Table 5 above) that describe the flows and stocks of end-use products using steel, and the service that they provide to society. These indicators (presented in **bold** in the overview tables below) aim at providing a unified and homogeneous quantification of the use of steel in the manufacturing of each category of end-use product. For a detailed description of these indicators, the reader is advised to consult the Supplementary Material named 'Circular Economy Levers and Scenarios' (available upon request).

Table 6 and Table 7 provide a summary of the CE levers finally assessed in this study for the CTC50 and ACE50 scenario, respectively. In grey we highlight the levers implying a substantial change in citizen's behaviour. Notice that the results for the ACE50 scenario obtained via LCA and EEIOA will be illustrated with and without these levers. A description of the levers summarised in Table 6 and Table 7, including the rational for the assumptions on the 'first order effects', is provided throughout sections 3.2.1, 3.2.2, and 3.2.3. More details may be found in Annex 1 and in the associated Supplementary Material document 'Circular Economy Levers and Scenarios' (available upon request).

Table 6. Overview and first-order effects of levers in the CTC50 scenario with the estimated changes in material flows

CE strategy	CE lever	Description	First order effects	Sector / End-use	Source
Recover	Enhance End-of-Life material recovery	Preparing for re-use and recycling of municipal waste (65% by weight). Leading to: increased availability in EU of scrap collected and sorted for recycling.	LCA: increased amount of scrap available in EU, increasing recycling at EoL, thus reducing primary production, either in EU or elsewhere via export (+2 Mt relative to Baseline in 2050; total of Recover). EEIOA: increased share of EU secondary steel production, reducing EU primary steel production share (+2 Mt relative to Baseline in 2050; total of Recover).	All sectors	Modelling interpretation (LCA and EEIOA) of the CE policy targets
		Reuse and recycling - 85% by average weight per vehicle. Leading to: increased availability in EU of scrap collected and sorted for recycling.	LCA: increased amount of scrap available in EU, increasing recycling at EoL, thus reducing primary production, either in EU or elsewhere via export (+2 Mt relative to Baseline in 2050; total of Recover). EEIOA: increased share of EU secondary steel production, reducing EU primary steel production share (+2 Mt relative to Baseline in 2050; total of Recover).	Vehicles	Modelling interpretation (LCA and EEIOA) of the CE policy targets
		Reuse and recycling - 85% by average weight per vehicle. Leading to: increased availability in EU of scrap collected and sorted for recycling.	LCA: increased amount of scrap available in EU, increasing recycling at EoL, thus reducing primary production, either in EU or elsewhere via export (+2 Mt relative to Baseline in 2050; total of Recover). EEIOA: increased share of EU secondary steel production, reducing EU primary steel production share (+2 Mt relative to Baseline in 2050).	Metal goods - Appliances	Modelling interpretation (LCA and EEIOA) of the CE policy targets
		Preparing for re-use and recycling of municipal waste (65% by weight).	LCA: increased amount of scrap available in EU, increasing recycling at EoL, thus reducing primary production, either in EU or elsewhere	Food packaging	Modelling interpretation (LCA and

		Leading to: increased availability in EU of scrap collected and sorted for recycling.	via export (+2 Mt relative to Baseline in 2050). EEIOA: increased share of EU secondary steel production, reducing EU primary steel production share (+2 Mt relative to Baseline in 2050).		EEIOA) of the CE policy targets

Note: for the scenario CTC50, only levers related to *Recover* are considered because of the nature of the policy targets included

Source: JRC elaboration

Table 7. Overview and first-order effects of levers in the ACE50 scenario

CE Strategy	CE Lever	Description	First order effects	Sector / End-use
Reduce	Reduce service level	Reduce the size of residential apartments	Reduced **annual inflow of steel** for residential building by 57%.	Construction
		Reduce the size of private cars	Reduced **annual inflows of steel** for the production of cars by 20.6%.	Vehicles
	Increase usage intensity	Increase usage intensity of road infrastructure	Reduced **annual inflow of steel** for the construction of road infrastructure by 25.4%.	Construction
		Increase usage intensity of railway infrastructure	Reduced **annual inflow of steel** for the construction of rail infrastructure by 28.6%.	Construction
		Increase usage intensity of trucks	Reduced **annual inflow of steel** for the production of trucks by 5.5%.	Vehicles
		Reduce office space demand via sharing	Reduced **annual inflows of steel** for commercial buildings by 13%.	Construction
		Reduce vehicle demand via sharing	Reduced **annual inflows of steel** used for the production of cars from by 24%.	Vehicles
	Reduce mass	Reduce the mass of steel in buildings addressing over specification	Reduced **annual inflow of steel** for the construction of residential buildings by 36%.	Construction
		Reduce the mass of steel in cars using advanced high strength steel	Reduced **annual inflow of steel** for the production of cars by 31.3%.	Vehicles
		Reduce the mass of steel used in packaging	Reduced **annual inflow of steel** for the production of packaging by 20%.	Metal goods
	Substitute a technical solution with a more efficient one	Substitute cars with soft modes of transport	Reduced **annual inflow of steel** for the production of cars by 46.9%.	Vehicles
Reuse	Extend lifetime	Extend lifetime of residential buildings	Reduced **annual inflow of steel** for the construction of residential buildings by 16.7%.	Construction
		Extend lifetime of commercial buildings	Reduced **annual inflow of steel** for the construction of commercial buildings by 16.7%.	Construction
		Extend lifetime of industrial equipment	Reduced **annual inflow of steel** for the production of mechanical equipment by 15%.	Industrial equipment

		Extend lifetime of vehicles	Reduced **annual inflow of steel** for the production of cars by 20%.	Vehicles
Recover	Increase secondary steel share	Increase quantity of material recovered	Increase **collection rate of waste steel** to ca. 92% assuming DRS for packaging and centralised sorting of residual waste.	All sectors
	Increase secondary steel share	Enhance quality of recycling	Increase **waste quality** via separation of steel scrap by sector and enhanced sorting.	All sectors

Note: In grey we highlight the levers that imply a substantial change in behaviour (notice that the results for the ACE50 scenario will be described and discussed excluding these levers; we will only report the total result including those as additional information). The indicators presented in bold are the quantitative indicators describing the flows and stocks of end-use products using steel, and the service that they provide to society

Source: JRC elaboration

3.2.1 Reduce

3.2.1.1 Reduce service level

Reduce the size of residential apartment

This CE lever targets the consumption of resources per unit of manufactured products in the construction sector. The lever specifically aims at the service level of housing (residential buildings). The minimum living space, as suggested by WHO and UN is around 9-to-15 m^2 per person. For the case of residential buildings, an increase in the usage intensity of dwellings and offices by reducing square meters per person is considered. For residential buildings, the average living space is reduced from 42.5 m^2 per person, which is an own estimate for the average today in the EU, to 20 m^2 per person, which is an estimate for sufficient sustainable home sizes by Cohen (2021). This reduces the steel material demand for residential buildings by 53%.

Notice that this figure is applied in the study only to estimate the potential of the ACE scenario when including behaviour-oriented CE levers. However, it is not included in the main results reported and discussed under section 6-7-8, which exclude *in toto* levers that imply a significant change in behaviour.

Reduce the size of private cars

This CE lever targets the consumption of resources per unit of manufactured products in the transport sector. The lever specifically aims at the service level of passenger cars, targeting sport utility vehicles (SUVs). SUVs sale currently represent 49% of the new car sales at EU level according to Acea (2024) and 30% at German level (Kraftfahrtbundesamt, 2024). Based on vehicle registration data from Germany a scenario is built, where the currently most popular vehicle in the SUVs category, i.e. VW Tiguan II of 1.9 t, is assumed to be replaced by the currently most popular car in the European B-segment, i.e. VW Polo VI of 1.1 t[8] (Kraftfahrtbundesamt, 2024). This enables a reduction of 42% weight per each SUV avoided and replaced with the less heavy car. Considering the new sales as an indication of the demand trend (as abovementioned, SUVs represent 49% of the new sales at EU level in the period 2011-2023, and ca. 30% at German level), the estimate for the potential reduction in car weight demanded at EU level would be equal to 20.6% (49%*42%), if SUVs were replaced by smaller cars. Therefore, a correspondent reduction of 20.6% in the steel demand for passenger cars is assumed in this study under the hypothesis that the demand for 1.9 t SUVs is replaced by demand for the smaller 1.1 t cars of the EU B-segment.

Notice that this figure is applied in the study only to estimate the potential of the ACE scenario when including behaviour-oriented CE levers. However, it is not included in the main results reported and discussed under section 6-7-8, which exclude *in toto* levers that imply a significant change in behaviour.

3.2.1.2 Increase usage intensity

Increase usage intensity of road and railway infrastructure

This CE lever targets the intensity of use of manufactured products in the construction sector, specifically infrastructure (road and rails). The usage intensity of infrastructure can be increased by i) large-scale implementation of intelligent transport systems on highways and by ii) installing European Rail Traffic Management System (ERTMS) and associated signalling systems in railway networks to replace the existing national systems known as Automatic Train Protection systems. As for the first, The MAVEN project on Intelligent Transport Systems reports an increase of road capacity of 34% when implementing Cooperative Intelligent Transport Systems[9] (MAVEN, 2019). This leads to a reduction in steel demand equal to 25.4%. As for the second, the ERTMS is a major industrial project developed by eight UNIFE members (Alstom Transport, AZD Praha, Bombardier Transportation, CAF, Hitachi Rail STS, Mermec, Siemens Mobility and Thales) in close cooperation with the EU Commission, railway stakeholders and the GSM-R industry to replace the existing national systems with the ERTMS (level 2). The capacity gains generated by the installation of ERTMS signalling systems in railway networks are claimed by industry to stand at 40% (UNIFE (the European railway industry), 2024). The related reduction in steel demand is estimated equal to 28.6%. Based on the relative share of steel demanded for railways and roads an overall reduction of 27.2% in steel demand for infrastructure is calculated and applied in the study.

Increase usage intensity of trucks

This CE lever targets the intensity of use of manufactured products in the transport sector, specifically trucks. The usage intensity of trucks is increased by decreasing the total road freight vehicle-kilometres that is carried out by empty vehicles. According to Eurostat about 22% of total road freight vehicle-kilometres in the EU were carried out by empty vehicles (see Eurostat dataset

[8] Weights are approximated based on grey literature available in the net.

[9] MAVEN: Managing Automated Vehicles Enhances Network (2019) WP7 Assessment and demonstration - Deliverable nº: D7.2 - Impact Assessment; Technical Report, https://cordis.europa.eu/project/id/690727/results (accessed 12.2024).

‘road_go_ta_tott’[10]). The study by T&E (2017) estimated that empty trucks trips can be reduced by a quarter by 2030 through improvements in logistics efficiency. On this basis, reducing the total road freight vehicle-kilometres that is carried out by empty vehicles (which is assumed equal to 22%, from above) by 25% results in a 5.5% (22%*25%=5.5%) decrease in empty road freight-vehicle kilometres, which translates into 5.5% increase in the usage intensity of trucks.

Reduce office space demand via sharing

This CE lever targets the intensity of use of manufactured products in the construction sector, specifically commercial buildings. Data from the WHC from 2022 show that about 13% of workers were working remotely and ca. 29% in a hybrid mode as of April 2022 (Barrero et al., 2020). Mckinsey consultancy (Mischke et al., 2023) assessed the effects of home working and related increase of desk/office sharing to 2030 focusing on a large samples of cities. Two scenarios are assessed: a moderate scenario and severe scenario. In the moderate scenario, office attendance is higher than it is now but still lower than it was before the pandemic, and partial recovery continues indefinitely. In a more severe scenario, attendance for all office workers in 2030 falls to the rate already seen in large firms in the ‘knowledge economy’. Factors such as population growth and migration are also considered in their study. Their results show that demand for office space is 13% lower in 2030 than it was in 2019 for a median city in their study. In the severe scenario, demand falls by 38% in the most heavily affected city (however, the median is not provided). These estimates are comparable to those suggested in research from Moody’s, which suggest a most likely reduction of demand for office space in the range 12-14% relative to pre-pandemic levels, depending on parameters such as the share of hybrid and full-remote mode, corresponding to a peak vacancy around 24%. The same study suggests that this reduction in demand could increase to 16-20% under some assumptions. Based on the findings of McKinsey and Moody’s, for commercial buildings a reduction of demand for office space is assumed, resulting in a 13% reduction in demand for commercial buildings. Based on the material distribution between residential and commercial buildings taken from the MFA by Rostek et al. (2022), an overall reduction of 13% in steel demand for buildings is calculated and applied in the study.

Notice that this figure is applied in the study only to estimate the potential of the ACE scenario when including behaviour-oriented CE levers. However, it is not included in the main results reported and discussed under section 6-7-8, which exclude *in toto* levers that imply a significant change in behaviour.

Reduce vehicle demand via sharing

This CE lever targets the intensity of use of manufactured products in the transport sector, specifically vehicles. Earlier literature studies performing modelling prediction on car sharing penetration and consequent effects on the overall demand for cars report optimistic results, with car ownership ratio reduced between 5% and 43% or replacement rate (number of cars replaced for each shared car added to the fleet) between 1 and 15[11]. In general, previous research findings

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[10] https://ec.europa.eu/eurostat/databrowser/view/ROAD_GO_TA_TOTT/default/table?lang=en (accessed 12.2024).

[11] These figures are reported in (Bucsky & Juhász, 2022), main paper at Table 1 (Table 1 provides a mini-review of the literature findings up to 2021).

suggest that a reduction of private car stock of between 1.2% and 1.8% should be expected for those regions where sharing scheme is available[12]. Comparable figures are also assumed in the study of Pauliuk et al. (2021). However, more recent studies have demonstrated that evidence collected throughout the EU does not support such trend so far. What appears from statistics is that the current penetration rate of car sharing is limited and lower than anticipated by models, and the car ownership ratio in many regions where sharing is available has increased instead of decreased (Bucsky & Juhász, 2022). In their study, Bucsky & Juhász (2022) conclude that, while previous research findings suggest that a reduction of private car stock (e.g. abovementioned 1.2-1.8%) should be expected for those regions where sharing scheme is available, the vehicle stocks grew on average by 1.6% in the same regions. The authors conclude that evidence now shows that car sharing has a marginal impact on car ownership ratio. The same conclusion is found by Kolleck, (2021) for a case study focusing on Germany. Another study by Chapman et al. (2020) focusing on Belgium suggests that the key driver in car-sharing being able to reduce car-use is its effect on car-ownership: users who reduce car ownership will reduce their car-use, while those for whom car-sharing has no effect on car ownership will increase their car-use. According to these results, only by assuming that car sharing has a large effect on car ownership car-sharing lead to a statistically significant reduction in car use, suggesting that policy intervention is required to ensure the full environmental benefits of car sharing are realised. The authors suggest that policies should focus on encouraging car sharing at the expense of car-ownership, e.g. by increasing the tax burden associated with car ownership, or by reducing the convenience of car-ownership through stricter parking regulations.

For this study, while acknowledging that evidence so far is lacking on the real effect of car sharing or that current evidence so far collected does not support a reduction in demand, we nevertheless assume a potential decrease in demand based on the figures available in part of the literature. From these, a range can be estimated between ca. 5% and 43%. Given such range, we assume that a reduction of 24% of the demand for car (and therefore associated steel demand) could be achieved via car sharing. This is in line with the assumption of 25% taken in the study of Chapman et al. (2024) and Pauliuk et al. (2021) and other rather optimistic predictions by consultancy studies (e.g. 29% by PWC[13]).

Notice that this figure is applied in the study only to estimate the potential of the ACE scenario when including behaviour-oriented CE levers. However, it is not included in the main results reported and discussed under section 6-7-8, which exclude *in toto* levers that imply a significant change in behaviour.

3.2.1.3 Mass reduction

Reduce the mass of steel in buildings addressing over specification

[12] It is derived by the authors in their section 'discussion'. Available at: https://www.sciencedirect.com/science/article/pii/S2213624X22001833

[13] PWC (2018) suggests a 29% decrease by 2030 in the EU; available at: https://www.pwc.com/sk/en/current-press-releases/by-2030-transport-sector-will-require-138-million-fewer-cars.html).

This circular economy lever targets the consumption of resources per unit of manufactured products in the construction sector, specifically residential and commercial buildings. The lever reduces the mass of residential buildings and offices by reducing the quantity of steel used per square meter. The reduction in buildings comes through smarter building design, e.g. reducing overspecification and weight of columns and beams, while fulfilling the same service level. We rely on the findings of Moynihan & Allwood (2014), according to which there is the potential of reducing the steel beam mass of buildings by up to 36% without compromising safety and fulfilling the same service level. We apply this figure in the study. For additional details, the reader is referred to the original study by Moynihan & Allwood (2014). Comparable figures are provided in the recently released UK guidance on best practices in construction, where specific examples for storey buildings and infrastructure may be consulted[14].

Reduce the mass of steel in cars using high-strength steel

This circular economy lever targets the consumption of resources per unit of manufactured products in the transport sector, specifically vehicles. The lever aims at introducing innovations to the passenger car sector, which allow to reduce the amount of steel needed per car, to fulfil the same service level. Bian et al. (2015) suggest that the use high performance steel can lead to material savings of up to 68% depending on the application and loading case. Based on the most conservative loading case from the abovementioned study (weight savings are between 22.5% and 40% according to Bian et al.; 2015), an average material saving of 31.3% is applied in this study. For additional details, the reader is referred to the original study by Bian et al. (2015).

Reduce the mass of steel used in packaging

This circular economy lever targets the consumption of resources per unit of manufactured products in the packaging sector. Light-weighting can reduce the material needed to fulfil the same function, i.e. packaging food. The reduction of weight in steel packaging has been steadily increasing from 1970 to today. For a steel beverage can of 33 cl body weight the weight has decreased from 39.9g in 1973 (32g in 1980) to 23.2g in 2004 (i.e. a decrease of 41% from 1973 and ca. 27% from 1980). For 1/2 can 425 ml pet food (easy opening ends, EOE) the weight has decreased from 59.9g in 1980 to 45.4g in 2004 (i.e. decrease of 24%). For 4/4 can 850 ml vegetables (EOE) the weight has decreased from 103.3g in 1980 to 87.5g in 2004 (i.e. decrease of 15%) (ArcelorMittal, 2024). Taking 1980 as starting year and 2004 as final year, a weighted average of the reduction for the two types above listed (assuming an average of 15% and 24%, i.e. 19.5% for pet food steel packaging) equals 20%[15]. Based on this, we apply 20% potential weight reduction for steel food packaging by 2050 in our study, assuming that further light-weighting will occur as suggested by industry stakeholders (ArcelorMittal, 2024).

[14] See particularly the guidance by the Steel Construction Institute namely 'High strength steel design and execution guide' at: file:///D:/JRC%2004.2025%20back%20up/REcalibrate/Recalibrate%20literature/SCI2020_2025_High-Strength-Steel-and-Execution-Guide-P432.pdf

[15] ArcelorMittal (2024) reports that the ratio of steel packaging for pet food to steel packaging for beverage is 78:22 (page 5 of their report shows that they represent 53% and 15% of the total packaging market, respectively; this means that their shares, recalculated over 100%, is 78:22). Similar figures are reported in the study of Dupriez (2017).

3.2.1.4 Substitute a technical solution with a more efficient one

In Copenhagen, the European leader in soft modes of transport, the ratio of number of cars owned to the population is 21.5% (140000 cars owned for 650000 inhabitants in 2022; Itera, 2022), whereas in the average European city this figure is usually in the range of 30-40% (T&E, 2024). This means, that, approximately, the car ownership ratio can be reduced by a factor of 2 provided the right policy and conditions are in place (e.g. complementary public transport). In an ambitious scenario, it can be argued that the car ownership ratios across Europe reach the level of the current front-runners such as Copenhagen. Knowing that the EU has an average cars to population ratio of 57.6%, compared to Copenhagen levels of 21.5% (T&E, 2024), a reduction of 62.7% could thus be possible in cities and towns. According to Eurostat 74.8% of EU population was living in cities (38.9%) or towns/suburbs (35.9%) in 2021[16]. Applying these values, a reduction of the demand for cars equal to 46.9% is estimated (62.7%*74.8%). No effect in an increased demand for steel for bikes and infrastructure is assumed.

Notice that this figure is applied in the study only to estimate the potential of the ACE scenario when including behaviour-oriented CE levers. However, it is not included in the main results reported and discussed under section 6-7-8, which exclude *in toto* levers that imply a significant change in behaviour.

3.2.2 Reuse

This circular economy lever targets the lifetime of steel material across different sectors: construction, industrial equipment, and transport.

3.2.2.1 Extend lifetime of residential and non-residential buildings

While buildings are currently built with a projected lifetime of 60-100 years, statistical data have shown that their actual lifetime can be considerably longer with adequate maintenance and renovation (Deetman, 2021; Material Economics, 2018). The demolition of buildings is thus not much owed to material deterioration, but more often to change of use of the area, energy use optimisation of new buildings, high costs of renovation or different preferences of house owners (Damgaard et al., 2022; Material Economics, 2018). Being conscious of the significant environmental benefits of extending the lifetime of buildings, by simply not demolishing them, or by retrofitting them, can thus reduce the demand for construction (Damgaard et al., 2022). The extension of lifetime has been applied as a lever in both material flow analyses and input output analyses (Donati et al., 2020; Pauliuk et al., 2021). In both cases, the demand of service provided by the material (in this case m^2 of steel in the EU) were identified and the required material inflow, stock and outflow determined to satisfy this demand, in relationship with the average age of buildings. Given the age of buildings is to be extended, the existing buildings can fulfil a higher level of the demanded service provided by the material. Therefore, the overall demand for construction decreases by the relative percentage change of the annual service level that comes with the different lifetimes, while keeping the overall service level demand of m^2 constant. For example, with a constant service level demand (including material inflows, stocks and outflows), a

[16] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Urban-rural_Europe_-_introduction.

longer lifetime will reduce the annual demand for material to satisfy the service level demand. As building types differ in material intensities per sqm, there is usually a differentiation between residential buildings, expected to constitute 62% of the demanded sqm in 2050 and non-residential buildings, accounting for the remaining 38% (Damgaard et al., 2022). In line with propositions by Damgaard et al. (2022), Deetman (2021) and Marinova et al. (2020), the age of residential buildings is extended by 20 years and the age of non-residential buildings by 10 years. These values stem from the upper bound of lifetime of buildings, with Eastern European buildings having the longest average lifetime (Damgaard et al. 2022). By assuming these, it is calculated that the reduction of the demand for finished steel products for residential and non-residential buildings equals 16.7% and 13.4%, respectively.

Since previous models mostly applied lifetime extension to new buildings only, this would not yield any effects to the end of life in the current analysis, because they would yield effects after 2050. However, it was considered important to apply the lifetime extension to the existing building stock as well, given the large potential of material savings and available policy instruments to increase renovation as suggested in previous studies (Damgaard et al., 2022; Material Economics, 2018; Thung et al., 2024). Specifically, recent studies show that for non-residential buildings there is significant room for extending lifetime (Circuit project, 2024; Wu et al., 2023). This is further supported by the recent analysis by Andersen & Negendahl (2023), which shows, via model predictions, that the lifetime of non-residential buildings in the EU have been decreasing over the last decades (down to 41-47y relative to 61y) suggesting a tendency towards worse construction practices.

To model the effects at the End of Life, the volume of demolition decreases to a higher extent (stock outflow from demolition decreases by 19.6%), thus less waste is generated. This is due to the fact that demolition is commonly modelled according to the Weibull distribution, which spreads the likelihood of demolition across several years, taking into account the age cohorts of the stock (Deetman, 2021; Lotz et al., 2024). It is essential to underline the large differences between material flow analyses in terms of predicting the stocks and flows. These depend on their type (stock or flow driven) and underlying assumptions with regards to population and GDP growth, m^2 per person, as well as the building lifetime model applied (Deetman, 2021; Deng et al., 2023). Whereas these studies show considerable differences in both concrete inflows and outflows, as well as the ratio between the two, when compared to the data used here (Damgaard et al., 2022), the current and projected size of concrete stock are in a similar range of magnitude.

3.2.2.2 Extend lifetime of Industrial equipment

Cooper & Allwood (2012) studied the potential lifetime extension by reuse of selected materials across products from different end-use sectors. For steel contained in industrial equipment (which, according to the same authors, consists of 68% mechanical machinery, 16% electrical machinery, 11% motors and transformers, and 5% 'other' such as pylons, cables, shearers) the authors estimate an overall reuse potential (lifetime extension potential) of 17%. Specifically, for mechanical machinery the authors estimate 10%, electrical machinery 48%, motors and transformers 80%, and 'other' 10%. We take the average 17% lifetime extension potential relative to the Baseline. Based on this, a reduction of steel mass demanded for mechanical and electrical equipment of 14.5% is calculated and applied in in this study.

3.2.2.3 Extend lifetime of vehicles

Given the expected change in type of fleet, notably to electric vehicles, it is difficult to assess potential extension of lifetime for cars in the next decades. An indication on the technical lifetime extension potential, based on current fleet, is given by the increased lifetime achieved by cars in the EU27 from 2011 to 2023 (from 10.9 to 12.3 years, i.e. an increase of 13%), as reported by EEA (EEA, 2024). While this represents an average increase, differences between regions in EU exist, notably between Western and Eastern EU as illustrated in a recent study by Held et al. (2021). The authors suggest that lifetime differences within EU member states are strongly dependent on behavioural or socio-economic conditions. They also show that lifetime varies with the calculation method applied. It is thus difficult to distinguish the contribution of technical improvements and socio-economic drivers to lifetime of vehicles, which goes beyond the scope of this study. Acknowledging such uncertainty, the intention of our study is to focus on average technically feasible lifetime increases related to design and technical optimization, regardless of the geographically specific socio-economic background conditions. Bearing this in mind, we apply the figures suggested by WTO in a recent report (World Economic Forum, 2020), which suggest that lifetime increase of about 25% at EU level is technically possible. This means an increase in the average lifetime of cars in the EU from current 12.3y to 15.4y, which is comparable to the global average lifetime of 15.8y estimated by Nakamoto et al. (2019). This translates into a reduction in the demand of finished steel products for cars of 20%.

Similarly to cars, due to the expected change in type of fleet, it is difficult to assess potential extension of lifetime for trucks, though one may argue that electrification for this application is slower than for passenger vehicles. In this study, the potential extension of lifetime is based on the case of a single company's commitment. Following their circular economy commitments, Renault offers a regeneration scheme for their trucks that increase their lifespan by 3 years (Renault Trucks, 2024). Using this case, it is assumed that there is a potential for truck lifespan to increase by 3 years (from 14.2y to 17.3y, i.e. an increase of 21%), which leads to a reduction of steel mass demanded to provide the same service equal to 17.4%. We apply this figure in the study.

3.2.3 Recover

3.2.3.1 Increase quantity of material recovered

Products are used and often mixed when discarded at their End of Life, scattering post-consumer steel across various waste streams like consumer goods, food packaging, vehicle components, and building materials, where it is frequently mixed with other materials. Thus, post-consumer steel is present in waste streams where it can only be partly recovered. For example, deposit refund schemes (DRS) for steel cans are not commonplace in the EU to date and thus, steel cans are partly found in the mixed solid waste (European Commission, 2023b). This lever addresses an improvement in waste collection and sorting, by assuming:

- An EU-wide implementation of DRS based collection for all steel packaging waste generated in the EU to investigate the maximum potential of such practice. Since countries with DRS, such as Germany and Norway, achieve collection rates of ~95% for PET bottles and aluminium cans, this lever assumes a DRS-based separate collection rate of 95% as suggested for frontrunners in (Albizzati et al., 2023). This means that all packaging is collected with 95% success rate.

- An EU-wide implementation of centralized sorting facilities of the residual mixed waste (i.e. the fraction of the waste that is generated but not captured via separate collection). This means that the steel waste generated but not separately collected as part of municipal waste (MW) (including packaging not collected via DRS), waste electrical and electronic equipment (WEEE), end of life vehicle (ELV), industrial electronic waste (IEW), and industrial non-electronic waste (INEW) is assumed to undergo a centralized sorting (e.g. via mechanical biological treatment – MBT - plants or similar centralised recovery plants on mixed waste) with a ferrous metal material-specific recovery efficiency of 92% in line with typical efficiencies of magnet separators in these installations[17]. Since the separation efficiency of construction and demolition waste (CDW) is already at a level of 95% in the Baseline, it is kept to the level of 95%. It should be kept in mind that this lever does not assume any improvement in the quality of the separated material.

3.2.3.2 Enhance quality of recycling

Enhancing quality of recycling is regarded to avoid export of scrap and supply domestic industry with high quality feedstock. According to recent studies (notably, Dworak and Fellner, 2021; Dworak et al.; 2022) one of the main reasons for scrap export from EU to third countries is the low quality of the material, which does not find an absorbing market in the EU. Principally, low purity scrap (quality Q3 and Q4 as categorized in Dworak and Fellner, 2021; Dworak et al.; 2022) is exported as the end-use demand for these quality in the EU is lower than the amount of scrap of this quality collected and available for recycling in the EU.

With this in mind, this lever addresses the quality degradation of steel due to tramp element accumulation in steel scrap. The main issue causing quality degradation is the insufficient sorting of steel scrap. This is related to two main causes. First, the scrap arising from different finished products and industry sectors is not separated. This results in steel of different qualities being mixed and thus, a degradation of the high-quality share of the collected scrap (a type of "cross-contamination") (Dworak and Fellner, 2021; Dworak et al.; 2022). Second, tramp elements present on the surface of the steel scrap are typically not removed during mechanical sorting and are therefore transferred into the steel melt during recycling (Daehn et al.; 2019).

The lever addresses the quality issue through an improved shredding and magnetic separation of scrap, which more effectively separates materials. The process is described in Daehn et al. (2019). The improved separation leads to steel scrap which does not carry substantial quantities of other materials into the melt. As an additional part of this process, we assume steel scrap originating from different end-use sectors is collected and then recycled separately, to reduce the "cross-contamination" (e.g. avoiding mixing steel from building sector with that from automotive).

The first assumes that a more rigorous separate collection and sorting is implemented based on categories of finished steel products, which leads to maintain steel waste flows separated based on the type of semis. The second is a chemical treatment of the steel melt integrated into the recycling process itself, which is able to remove tramp elements. This pathway has the benefit of being able to remove tramp elements that are already part of the steel melt. However, due to its

[17] From Table S.24 supporting information in Albizzati, P. et al. "A model to assess the environmental and economic impacts of municipal waste management in Europe." Waste Management 174 (2024): 605-617.

energy inefficiency and unknown technological feasibility, is only assessed and shown as sensitivity analysis.

3.2.4 Synthesis of results to feed the MFA

Based on the results presented in the "First order effects" column in Table 7, the main mathematical parameters that feed into the MFA were estimated. These parameters are shown in Table 8 and include:

- The target value for the share of secondary (recycled) steel;
- The lifetime of the end-use product after application of the Circular Economy lever: parameter λ2;
- The mass of steel per functional unit of the end-use product after application of all Circular Economy levers (the "circular" type), relative to the mass of steel of the end-use product before the application of these levers (the "linear" type): parameter (μ2 / μ1).
- The reduction factor in the number of functional units following the implementation of all Circular Economy levers: parameter **R**.

Table 8. Summary of results for inclusion in the MFA for the ACE50 scenario

End-use product	**Share of recycled steel** (Target at the end of simulation)	**Size of the stock of end-use product** (Reduction factor ***R*** of functional units at the end of life)	**Lifetime of end-use product** (of "circular" type)	**Mass of steel per end-use product in the stock** (of "circular" type)
Residential buildings	Baseline: 100% 100% (no change) 100% (no change)	**R** = no change **R** = 0.43	λ_1 = 100y λ_2 = 120y λ_2 = 120y	(μ_2/μ_1) = 0.64 (μ_2/μ_1) = 0.64
Commercial buildings	Baseline: 100% 100% (no change) 100% (no change)	**R** = no change **R** = 0.87	λ_1 = 65y λ_2 = 75y λ_2 = 75y	(μ_2/μ_1) = 0.64 (μ_2/μ_1) = 0.64
Road infrastructure	Baseline: 100% 100% (no change) 100% (no change)	**R** = no change R = no change	λ_1 = 50y λ_2 = 50y λ_2 = 50y	(μ_2/μ_1) = 0.746 (μ_2/μ_1) = 0.746
Railway infrastructure	Baseline: 100% 100% (no change) 100% (no change)	**R** = no change R = no change	λ_1 = 50y λ_2 = 50y λ_2 = 50y	(μ_2/μ_1) = 0.714 (μ_2/μ_1) = 0.714
Mechanical equipment	Baseline: 25% 50% 50%	**R** = no change R = no change	λ_1 = 21.3y λ_2 = 24.9y λ_2 = 24.9y	(μ_2/μ_1) = 1 (μ_2/μ_1) = 1
Vehicles – cars	Baseline: 25% 50% 50%	**R** = 0.76 R = 0.406	λ_1 = 12y λ_2 = 15y λ_2 = 15y	(μ_2/μ_1) = 0.545 (μ_2/μ_1) = 0.545
Vehicles - trucks	Baseline: 25% 50% 50%	**R** = 0.945 **R** = 0.945	λ_1 = 14.2y λ_2 = 17.2y λ_2 = 17.2y	(μ_2/μ_1) = 1 (μ_2/μ_1) = 1

Locomotives and rail rolling stock	Baseline: 25% 50% 50%	**R** = no change **R** = no change	$\boldsymbol{\lambda_1}$ = 25-30y $\boldsymbol{\lambda_2}$ = 25-30y $\boldsymbol{\lambda_2}$ = 25-30y	($\boldsymbol{\mu_2/\mu_1}$) = no change ($\boldsymbol{\mu_2/\mu_1}$) = no change
Food packaging	Baseline: 25% 100% 100%	**R** = no change **R** = no change	$\boldsymbol{\lambda_1}$ = 0y $\boldsymbol{\lambda_2}$ = 0y $\boldsymbol{\lambda_2}$ = 0y	($\boldsymbol{\mu_2/\mu_1}$) = 0.8 ($\boldsymbol{\mu_2/\mu_1}$) = 0.8

Note: In black the results without including the levers implying a behavioral change are reported. In grey are reported the results when all levers are included, i.e. also those implying behavioral changes are included in the assessment

Source: JRC elaboration

4 Material Flow Analysis (MFA)

4.1 Methodology

Material Flow Analysis (MFA) allows for quantifying flows and stocks of a specific material (or substance) in a system. Specifically, the MFA of steel is grounded in the data published by Rostek et al. (2022). The spatial boundary of the MFA is EU27. The MFA covers iron mining to steel scrap collection and processing, which includes the return of scrap to steel production. The import and exports at different stages of the supply chain for EU are also considered. The industry sectors included in the MFA are construction, transport, metal goods, and industrial equipment with their respective subsectors. In addition to the MFA, we apply quality data from Dworak & Fellner (2021) to assess the quality of the recycled material flows (see section 5).

4.1.1 MFA of the Status Quo 2020 scenario (STQ20)

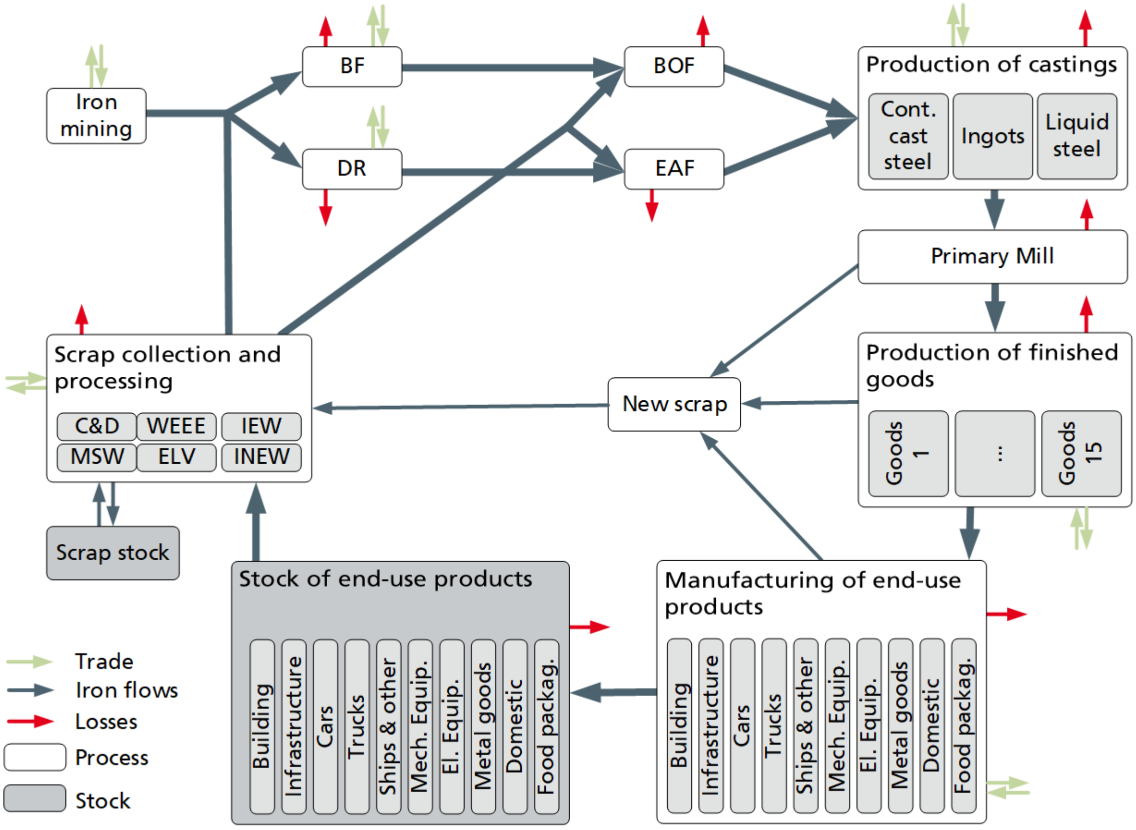
The Status Quo 2020 is based on Rostek et al. (2022). While the original publication covered the former EU28, Great Britain was subtracted to gain results for EU27. Figure 4 shows the structure of the MFA model covering the EU steel cycle from mining to recycling. While the following gives a brief overview of the methodology, a detailed description of the model, data and assumptions is provided in Rostek et al. (2022).

Two different routes for primary iron production are distinguished: the production of pig iron via the blast furnace (BF) and the production of direct reduced iron (DRI). Furthermore, two production routes of steel are quantified. The basic oxygen furnace (BOF) uses mostly pig iron and in smaller proportions steel scrap to produce crude steel. The electric arc furnace (EAF) uses steel scrap and DRI for steel production. The crude steel is used to produce a set of finished steel products, which are intermediate goods. The covered intermediates are based on the existing model by Rostek et al. (2022) disaggregated into 15 intermediate product groups, for which production data can be found in worldsteel's Steel Statistical Yearbook. A concordance of these finished steel products to the product categories defined within the draft of the ESPR preparatory study on iron and steel can be found in Annex 2. As the levers implemented in the MFA rely on the end use products and recycling, the intermediates are not further discussed in the following. The intermediates are distributed to the end use sectors buildings, infrastructure, cars, trucks, ships and other transportation, mechanical equipment, electrical equipment, metal goods, domestic appliances and food packaging. Allocation factors by Dworak & Fellner (2021) were applied to distribute the finished steel products towards the end use sectors. For each of the end use sectors, lifetime distributions are defined as shown by Rostek et al. (2022), which define the end of life (EoL) of specific products at a specific age. Collection and separation losses reduce the total EoL products which are finally available for recycling or export. Besides EoL scrap, new scrap[18] is generated in production and manufacturing processes and available for recycling. The volumes of generated new scrap depend on process efficiencies as defined by Rostek et al. (2022). At each stage of the life cycle, imports are added and exports subtracted from production volumes to calculate the consumption volumes. The main data source for production and trade is the Steel Statistical Yearbook by worldsteel. For additional

[18] 'New scrap' is here used as a synonym for 'pre-consumer scrap', as opposite to 'old scrap', which is also known as 'End-of-Life scrap' or 'post-consumer scrap'.

data sources used for the Status Quo scenario, the Baseline scenario (most of which apply as well to CTC50 and ACE50 scenarios) the reader is referred to Rostek et al (2022).

Figure 4. Structure of the EU steel cycle



Source: Rostek et al. (2022)

4.1.2 MFA of the Baseline 2050 scenario (BSL50)

The MFA used to quantify future steel flows consists of two parts, one covering the retrospective flows and stocks until 2020 and the other covering prospective flows and stocks until 2050. The retrospective model is described in the preceding section and is based on the work published by Rostek et al. (2022). The retrospective quantification until 2020 defines the Status Quo used for quantifying the changes in mass flows incurred by the studied levers, shown in Table 7-Table 8.

The Baseline scenario BSL50 is calculated by implementing an exogenous scenario for crude steel production into the MFA model described in the preceding section. The demand for crude steel is expected to develop as shown in the study by Fraunhofer ISI & European Commission (2023). As a saturation level for steel consumption has been reached until 2020, the underlying assumption for the future Baseline scenario is that the demand for steel stays mostly constant until 2050. The historical development of steel flows and stocks calculated following the methodology described in the preceding section fits well with the MFA shown by Dworak & Fellner (2021). However, (Dworak & Fellner, 2021) developed a future scenario, where the demand and stock of steel is still increasing, and a steady state is only reached around 2050. Consequently, this results in higher future scrap generation flows than calculated within this study. For the modelling of the production routes of iron and steel, we rely on the projections of the GECO 2023 (Keramidas et al.; 2023) to achieve consistency with the assumptions followed for the energy system. While other projections exist (e.g. Fleiter et al.; 2021), focusing on the possible alternatives energy transition paths is beyond the scope of this study.

The downstream production volumes (finished steel products) are expected to develop parallel to the crude steel production (same growth/reduction rate per year). The finished steel products are disaggregated into 15 intermediate product groups, which are already used in the existing model by Rostek et al. (2022). The ratio between domestic production and trade is assumed to be constant. The finished steel products are distributed to ten end use sectors according to an allocation matrix by Dworak et al. (2021). For each of these steps, yields are defined which give the volumes of new scrap. These yields are assumed to remain at current level. The stock of steel in use is calculated based on the stock inflow (production plus net imports) and the stock outflow, resulting from lifetime distributions. The stock outflow gives the old scrap which is potentially available for recycling. Constant collection rates (on average 75%) are used to calculate the actual available old scrap for recycling entering the market. A recycling input rate[19] (as defined in Eurofer and Eurometaux, 2012) of 60% is used to calculate the total recycled steel in Europe. The surplus scrap is assumed to be exported from EU.

4.1.3 MFA of the compliance and ambitious CE 2050 scenario (CTC50, ACE50)

The scenarios CTC50 and ACE50 are implemented differently compared to the BSL50, as these include the effect from the Circular Economy levers as described in Table 6 (for CTC50), Table 7-Table 8 (for ACE50).

For the CTC scenario, it is assumed that the additional steel available via increased collection and sorting to fulfil policy targets (Table 6) is recycled in the EU industry, thus increasing the share of secondary steel production over the total, while reducing primary. As the CE targets studied under the CTC only affects the scrap waste management (i.e. they can be considered as 'supply measures' only), it is assumed that the secondary production is increased proportionally in all the end-use sectors, according to their weight on the total EU production. The export of steel scrap from EU (generated steel scrap minus recycled steel scrap) is maintained as in the Baseline[20].

At the end use level, there is a differentiation between old linear product types and new circular product types. For the end use sectors for which no levers are defined in Table 6 (CTC50), Table 7 and Table 8 (ACE50), the demand equals the demand from the Baseline scenario. For sectors for which CE levers were defined, new product types are introduced. These new products are defined by three CE effective indicators: The reduction of mass of steel per functional unit (μ2 / μ k), the reduction factor for functional units (R) and the elongation of the products lifetime (λ2- λ1) (see Text box 1 for definitions and equations and Table 8 for values). This new circular product types are substituting the old linear product types from 2030 on, as it is assumed that there is a transition period of 5 years for the industry for product development. The reduction of steel intensity per

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[19] The recycling input rate is defined as $\frac{Secondary\ metal\ input\ (End\ of\ Life + new\ scrap\ recycled)}{Primary + secondary\ metal\ input}$

[20] One may also assume that the increased scrap available is exported. Notice that the effect of this would be similar when performing LCA (as the EoL formula applied, i.e. the CFF in this case, like any other does credit the EoL recycling regardless of where this would occur, under the condition that a market exists). However, in the EEIOA, it is not straightforward to credit scrap exported and recycled outside the EU. Therefore, the choice here is to assume that an increase in scrap collected and sorted for recycling in EU brings to an increase of secondary production (at the expenses of primary) in the EU.

functional unit and the elongation of lifetimes are affected completely after the 5y transition period onwards. By contrast, there is a longer transition phase for the reduction of functional units (sharing buildings and vehicles), as this requires changes in consumer behaviour and business models. Therefore, it is assumed that the defined total reduction of functional units will be reached in 2050, while the reduction factor from 2030 on is interpolated with an exponential function.

The quantification of the demand for steel contained in end uses is implemented according to the description in Section 3.1.1. The trade of end use goods, intermediates and crude steel is calculated by assuming a constant import rate. For each of the end use sectors, the share of finished steel products used to produce an end use is analysed for 2020. These shares are used to calculate the required volumes of finished steel products under consideration of new scrap generation and foreign trade. By doing so, the required production of finished steel products and subsequently for crude steel are derived for all years after 2020.

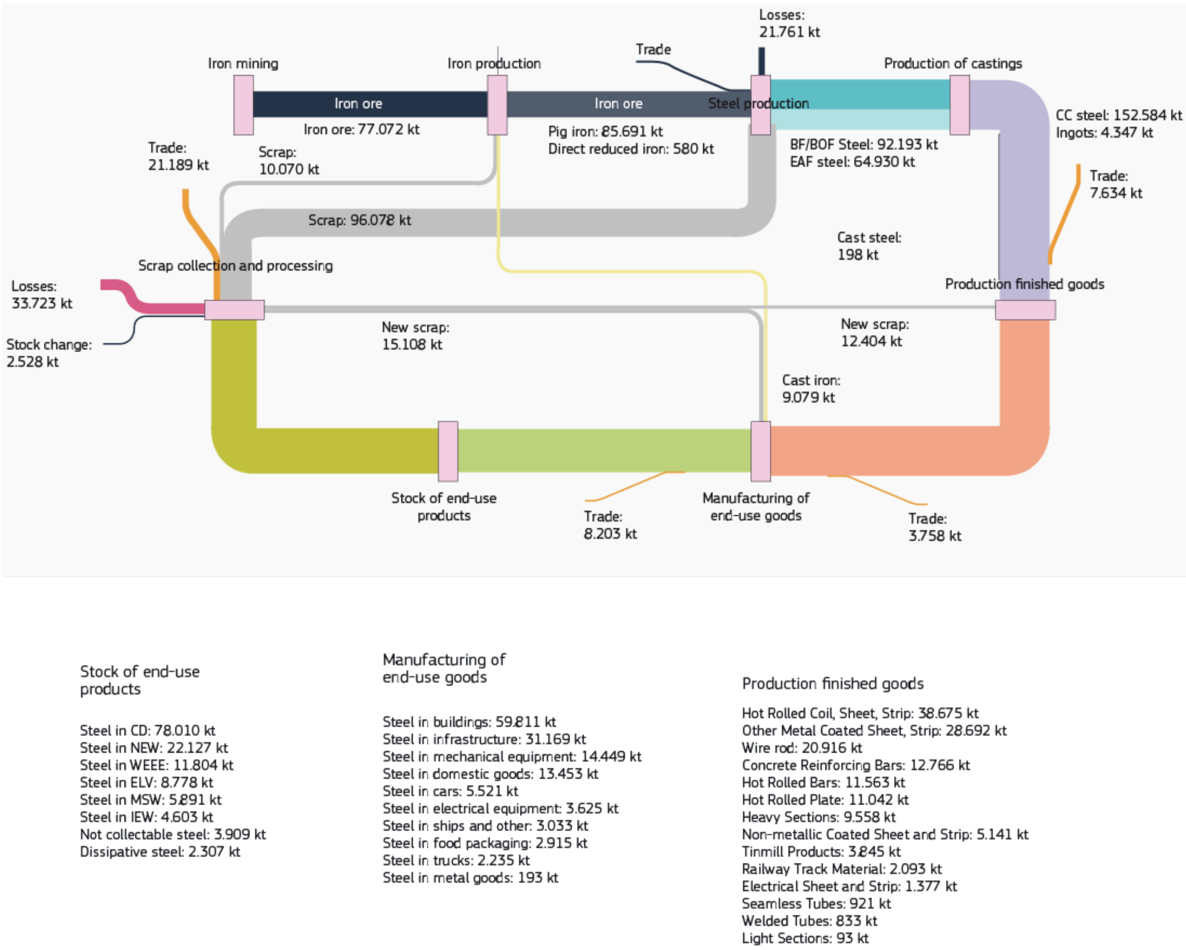
For the modelling of steel scrap, the generation and consumption are calculated differently. Analogous to the Baseline scenario, the total steel scrap generation is based on the 'new scrap' calculated through production volumes and process yields as well as 'old scrap' calculated through the lifetime model. The lower production volumes due to CE levers lead directly to lower generation of 'new scrap' and with a time delay (depending on lifetime of products) also to lower volumes of 'old scrap'. While CTC50 uses a constant end of life collection rate of 70%, in ACE50 it is assumed that the End-of-life collection rate constantly increases to 90% in 2050 to reflect the full-fledged effect of the studied recycling levers. The sum of collected 'old scrap' and 'new scrap' gives the total scrap available for recycling either in the EU or outside via export. The share of scrap exported from EU is kept constant as in the Baseline (i.e. ca. 18% of the total scrap made available via collection and sorting in EU).

4.2 Results

4.2.1 MFA of Status Quo 2020 scenario (STQ20)

A Sankey-based overview of the Status Quo 2020 scenario (STQ20) reflecting steel cycle in EU27 is provided in Figure 5. The flows are based on the work detailed in Rostek et al. (2022). Total EU steel production equals about 132 Mt, fulfilling a demand of finished steel products by EU industry quantified at ca. 134 Mt. The final demand of the EU economic sectors (buildings, infrastructure, cars, trucks, ships and other, mechanical equipment, metal goods, domestic goods and food packaging) demanding finished steel products to produce finished products is quantified at 111 Mt. The ‘new scrap’ (pre-consumer) and ‘old scrap’ (post-consumer) collected, sorted and sent for recycling in the EU equal ca. 84 Mt and 23.8 Mt, respectively. The net export of scrap is quantified at 24 Mt, i.e. about 18% of the total collected and sorted scrap within the EU.

Figure 5. Sankey diagram of iron and steel flows in the EU27 in 2020



Source: From Rostek et al. (2022), excluding UK

4.2.2 MFA of Baseline, Compliance, Ambitious CE scenarios (BSL50, CTC50, ACE50)

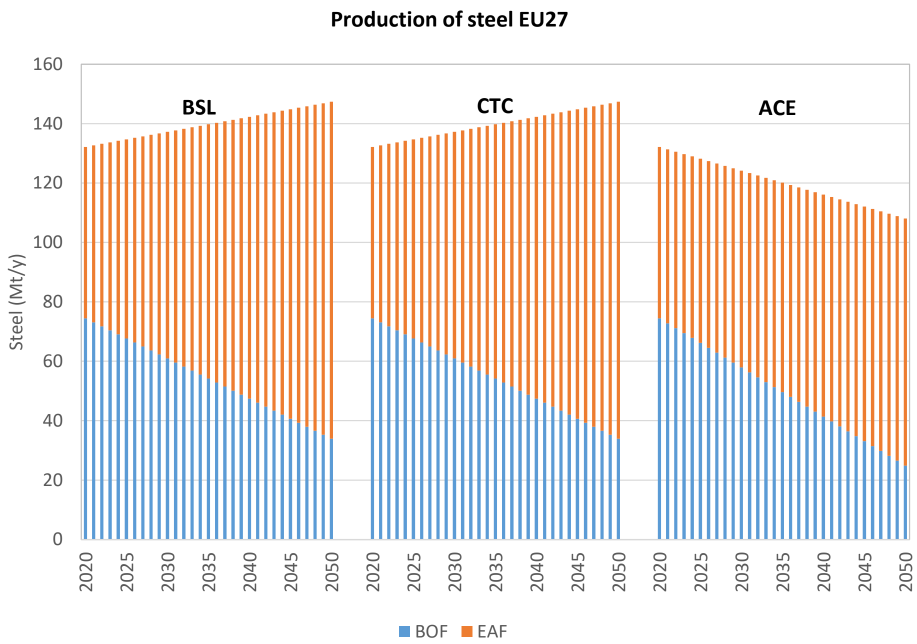
In the following, iron flows in ironmaking, steelmaking, production of finished steel products, manufacturing of end use products and scrap processing are compared for the three scenarios BSL, CTC and ACE up to 2050. Notice that the dynamic MFA approach allows to see mass flows results for each year between 2020 and 2050, making the transition visible. Figure 6 shows the development of the steel production in the three scenarios BSL, CTC, and ACE until 2050. The reduction of functional units R and the reduction of steel intensity per functional unit μ_2/μ_1 (as provided in Table 8; see Text Box 1 for the definition of R and μ_2/μ_1) directly affect the total steel production. Through implementation of these reduction factors in CTC50 and ACE50, the steel production is lower than in the BSL50 scenario, where no reduction of functional units or implementation of circular product types with lower steel intensity is assumed. The levers incurring extension of products lifetime has only limited effect in the period until 2050 but have an effect on longer term. That is because the longer lifetime is attributed to the circular product types, which are introduced in the ACE scenario from 2030 on. However, the lifetime of most steel-using end products is longer than the 20 years between 2030 and 2050, so that there is only little reduction of production volumes due to lifetime extension within this period.

The total volumes of steel used in the production of end use products (Figure 7) follow the evolution of the crude steel production shown in Figure 6. In the BSL50 and CTC50 scenarios, the shares of steel consuming sectors remain mostly constant. However, there are significant shifts in the steel consuming sectors within the ACE50 scenario, caused by the CE levers affecting individual sectors (for details on the levers, refer to Table 7 and Table 8). Most significant is the decrease of steel use for the automotive sectors, notably car (-30%) and trucks (-5%), followed by construction sector, notably buildings (-30%) and infrastructure (-12%), and metal goods, notably packaging (-20%).

As for the flows of scrap, the 'new scrap' flow follows the production volumes, as 'new scrap' flows are defined by production volumes and process yields. Consequently, the 'new scrap' flows remain mostly constant within the BSL50 scenario, while there are moderate reductions in the CTC50 scenario and strong reduction by 39% in the ACE50 scenario.

The development of the collection and processing of old scrap is driven by two different mechanisms. First, the generation of End-of-Life scrap differs for the three scenarios. A reduction of steel consumption as apparent especially in the ACE50 scenario, leads to a reduction of scrap generation. However, the resulting effect occurs with a long time delay due to the long lifetime of most steel consuming products. The second and more relevant mechanism in the observed period is the more effective collection and separation of End-of-Life scrap, which is part of the scenario assumptions as described in section 4.1.3. In the ACE50 scenario, the overall recycling efficiency (i.e. the product of collection rate, sorting rate, and recycling rate) is expected to increase, which leads to an increase of old scrap available for recycling by about 21% between 2020 and 2050, even if the total generated scrap slightly decreases.

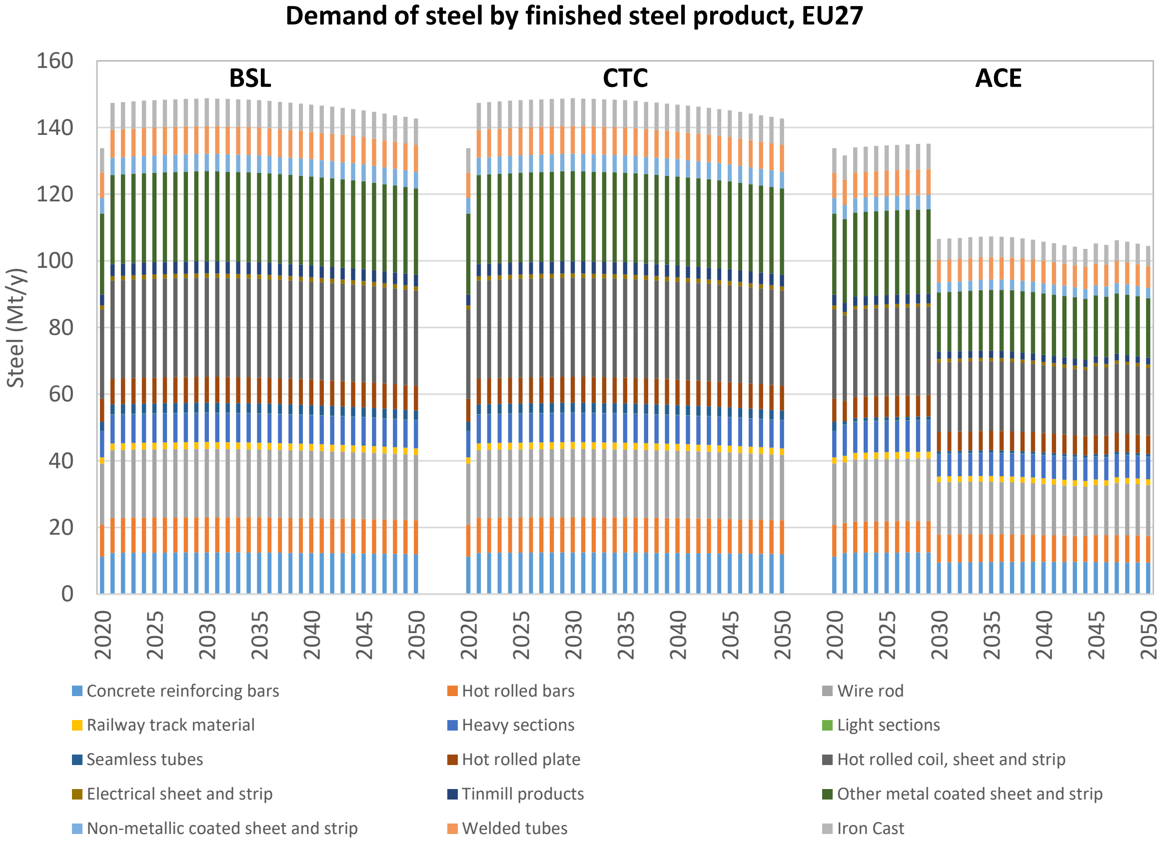
Figure 6. Dynamic evolution of the steel production in EU27, 2020-2050

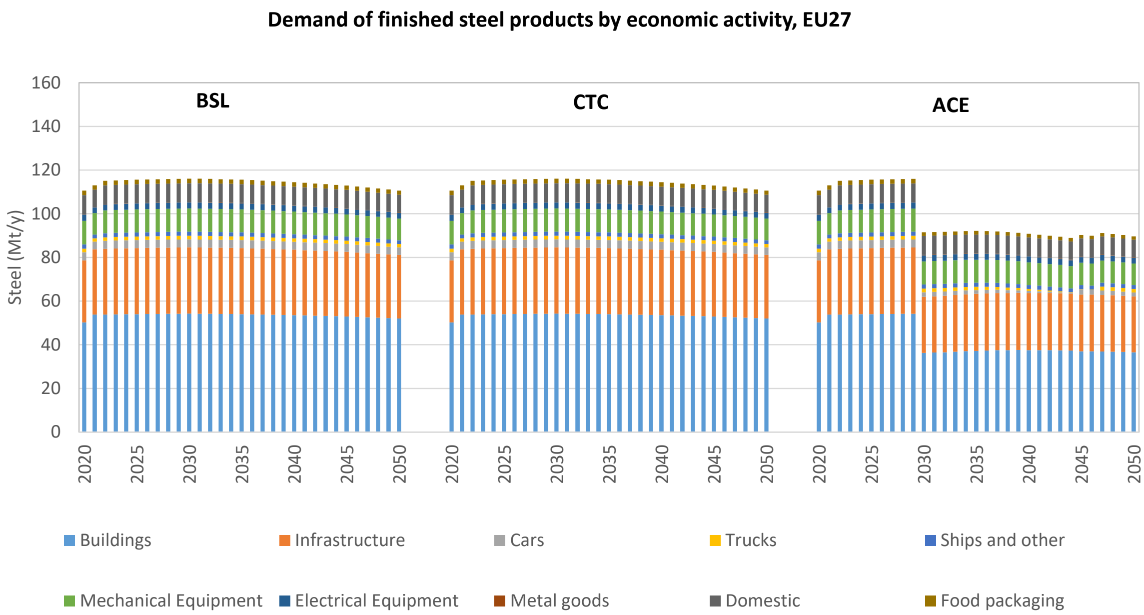


Note: The ratio between BOF and EAF is based on the projections of GECO 2023 for year 2050 (Keramidas et al.; 2023) and interpolated linearly in between 2020 and 2050

Source: JRC elaboration

Figure 7. Dynamic evolution of the finished steel products produced in EU27 (top) and of their flows by final economic sectors in EU27 (bottom), 2020-20500





Note: Numerical values are available in the Supplementary Material (available upon request)

Source: JRC elaboration.

5 Modelling and assessing scrap quality

5.1 Methodology

In addition to the MFA, we apply quality data from Dworak & Fellner (2021) to assess the quality of the recycled material flows. The steel quality data serves to determine the scrap steel qualities and the recycled steel applications in the subsequent period. The data from Dworak & Fellner (2021) provides the quality requirements and typical steel qualities per finished steel product. The quality requirements are given by the tolerated tramp element concentration in steel. Tramp elements are impurities in steel which do not come from alloys, but other elements (such as Cu, Ni, Mo, Cr, Sn) accumulating in steel scrap, with copper being the most ubiquitous tramp element (Dworak and Fellner 2021; Dworak et al.; 2022). The steel quality is distinguished into categories Q1, Q2, Q3, Q4, and Q0. Q1 represents the highest quality (and lowest tramp element content), while Q4 represents the lowest quality. Q0 is an additional category for cast iron and cast steel, for which the tramp element content is not considered.

5.1.1 Defining steel and steel scrap quality grades

The quality is defined by the content of tramp elements per kg of steel as defined building on the work of Dworak & Fellner (2021), Table 9 shows the definition of each quality class.

Table 9. Quality class definition from Dworak & Fellner (2021)

Quality class	Maximum content of tramp elements (% of weight)	Average content of tramp elements (% of weight)
Q1	0.18	0.13
Q2	0.25	0.21
Q3	0.35	0.3
Q4	1	0.4
Primary	-	0.05
Q0	n.a.	n.a.

Note: n.a.: not assessed

Source: JRC elaboration

Each finished steel product and sector combination is assigned to a designated quality class (see Annex 3). These are adopted from Dworak & Fellner (2021). For example, hot rolled bars for buildings are in quality bracket Q4 and thus, have a maximum tramp element content of 0.18% and an average tramp element content of 0.4%. Where Dworak & Fellner (2021) do not provide data on finished steel product and sector combination, the average of the corresponding finished steel products (for which a value is available) was chosen to determine the quality bracket.

In principle, it can be argued that the quality of steel scrap at End of Life can be based on the quality of the original steel material (see Annex 3) when no contamination occurs. However, due to contamination with tramp elements during use (e.g. construction), the post-consumer scrap quality is not identical to the one produced originally and delivered to the sector demanding it. To take this into account, we follow the default approach of Dworak et al. (2022), i.e. when no quality enhancement measures are taken, the actual steel scrap quality is based on the sector where the scrap was used, since this gives a fair indication of the contamination (Table 10).

Table 10. Quality grade of steel originating from the various sectors where it is demanded and used from Dworak et al. (2022)

Sector	Scrap material quality class
buildings	Q4
infrastructure	Q4
cars	Q3
trucks	Q3
Other Transport	Q3
Mechanical Eng	Q3
Electrical Eng	Q3
domestics	Q3
Metal Goods	Q3
packaging	Q1

Source: JRC elaboration

5.1.2 Allocation algorithm for recycled steel to fulfil demands

The steel demands of a given period (year i) are projected based on previous period (year i-1). The overall steel demands per each quality grade are determined based on the demand for finished steel products for each end-use sector (e.g. construction, transport). When this information (quantity demanded by the sector for each finished steel product) is combined with the quality required for each finished steel product (Annex 3) and the associated threshold value of tramp elements content (Table 9), the amounts of each quality grade demanded (Q1 to Q4 and Q0) are determined.

Once the demands per quality grade are known, the supply of recycled steel[21] (for which the quality is also known based on the sector of origin, see section 5.1 and Table 10) can be assigned to the demands. To do this, we apply the following 3-step algorithm:

1. **Direct allocation**: Assign the secondary steel supply to the same quality demand (i.e. scrap of quality Q1 is assigned to demand for Q1, Q2-to-Q2, etc.).
2. **Downgrading**: Assign the remaining secondary steel supply of higher quality material to remaining lower quality demand (i.e. the remaining scrap of quality Q1 is assigned to demand for Q2, then Q1-to-Q3, Q1-to-Q4, etc.).
3. **Dilution**: Assign the remaining supply of lower quality secondary steel to remaining higher quality demand. This can only be achieved when the material is diluted with virgin material, to attain the desired quality. For each combination (i.e. Q4-to-Q1) the amount of virgin material necessary to dilute the tramp element content sufficiently (i.e. to be right-below the thresholds given in Table 9) is calculated. Notice that in the LCA this quantity is credited via virgin steel substitution in the 'default' approach used to address quality. This is then challenged in a dedicated sensitivity analysis (see section 6.1.3).

[21] Recycled steel, not simply scrap. We refer to the material after it has been recycled in the steelmaking, i.e. after applying the technical efficiency of conversion (ca. 89%) in the furnace.

All demand that is not fulfilled after this assignment needs to be fulfilled with virgin (ore-based) steel. On the same note, all supply that is not assigned after this process cannot be used to fulfil EU demand and thus, needs to be exported (else, it would have to be discarded). To credit virgin steel substitution by recycled steel, a *quality factor* is calculated.

The **quality factor** is calculated using an approach that **considers dilution**, which takes place in industry reality[22]. Generally, insufficient quality scrap is diluted, i.e. mixed, with virgin steel (e.g. in BF-BOF route, liquid steel is mixed with scrap to increase quality), to reach demanded quality standards in terms of tramp element content of the final steel produced (whether intermediate or finished steel product). Notice that this is not common in LCA studies as it requires a more sophisticated numerical solution, where dilution-potential is calculated for all scrap qualities. For additional details, the reader is referred to Wagner et al. (2025) where it is explained in detail.

We test this approach in a dedicated **sensitivity analysis** in section 6.1.3.2. Under this, the quality factor considers only the share of virgin (ore-based) steel substitution achieved **without considering dilution**. This means, if 70% of steel scrap can be recycled without dilution and 30% requires dilution then the resulting quality factor is 0.7 (recycled steel is allocated to EU steel demands based on the quality demanded by each demand segment and the replacement of ore-based steel is thus credited as a virgin steel substitution). This calculation is done repeatedly for each recycled steel flow, based on its respective quality and demand. The quality factor is also applied to the exported quantity of scrap to adjust for its quality based on the average quality factor obtained for domestic recycling. This approach can be seen as a conservative approach to reward and credit high-quality scrap recycling, especially if we are in a scenario of reduced demand and/or scrap excess (e.g. a future where developing economies will also generate post-consumer scrap in quantities like the EU today). However, one may argue that it is not representing current practices of the industry where dilution commonly takes place. In a nutshell, considering the impact of dilution in the modelling ‘reduces’ the savings attributed to the lever ‘enhancing quality of recycling’ (i.e. dilution eases the requirements for high-quality scrap as it improves the quality of the final steel).

Since Q0 is an additional category for cast iron and cast steel, it is assumed not to be substitutable with other steel and is thus not analysed. Thus, Q0 material substitutes none other than Q0 material.

[22] What needs to be clear is that we allow dilution in both the approaches abovementioned, but do not credit it (in LCA and LCC) in the approach tested in the sensitivity analysis at section 6.1.3.2.

5.2 Results

5.2.1 Scrap availability and quality, and fulfilment of EU demand

We first present and discuss Figure 8, which provides a summary where the overall scrap availability, according to its quality, is displayed along with the demands for the different quality types in an aggregated form. A more detailed illustration of how scrap quality flows fulfil the specific demands is displayed in the subsequent Figure 9.

From Figure 8a,b,c the first message is that a surplus of scrap is (and will be) generated in the EU if current waste management practices continue business-as-usual. This is material which quality is in excess relative to the demanded quality of the EU market. According to the literature (Dworak et al., 2022, Dworak and Fellner 2021) this mostly corresponds to low-quality steel, rich in tramp elements, which the domestic industry is not willing to take for techno-economic constraints.

The second message is precisely that a manner to make this surplus useful for the purpose of fulfilling domestic demand is to enhance quality of recycling (represented by the lever QLT50, which then feeds into REC50 scenario; see Figure 8b,c), also supported by many other studies (notably Dworak et al., 2022, Dworak and Fellner 2021). This has then a beneficial effect on the ACE50 scenario where, proportionally, more Q1 and Q2 quality are available, and less Q4 relative to the Baseline BSL50 scenario (Figure 8a). This is also reflected in the quality factor, which changes to 1 (i.e. equal to virgin material) in the ACE50 scenario.

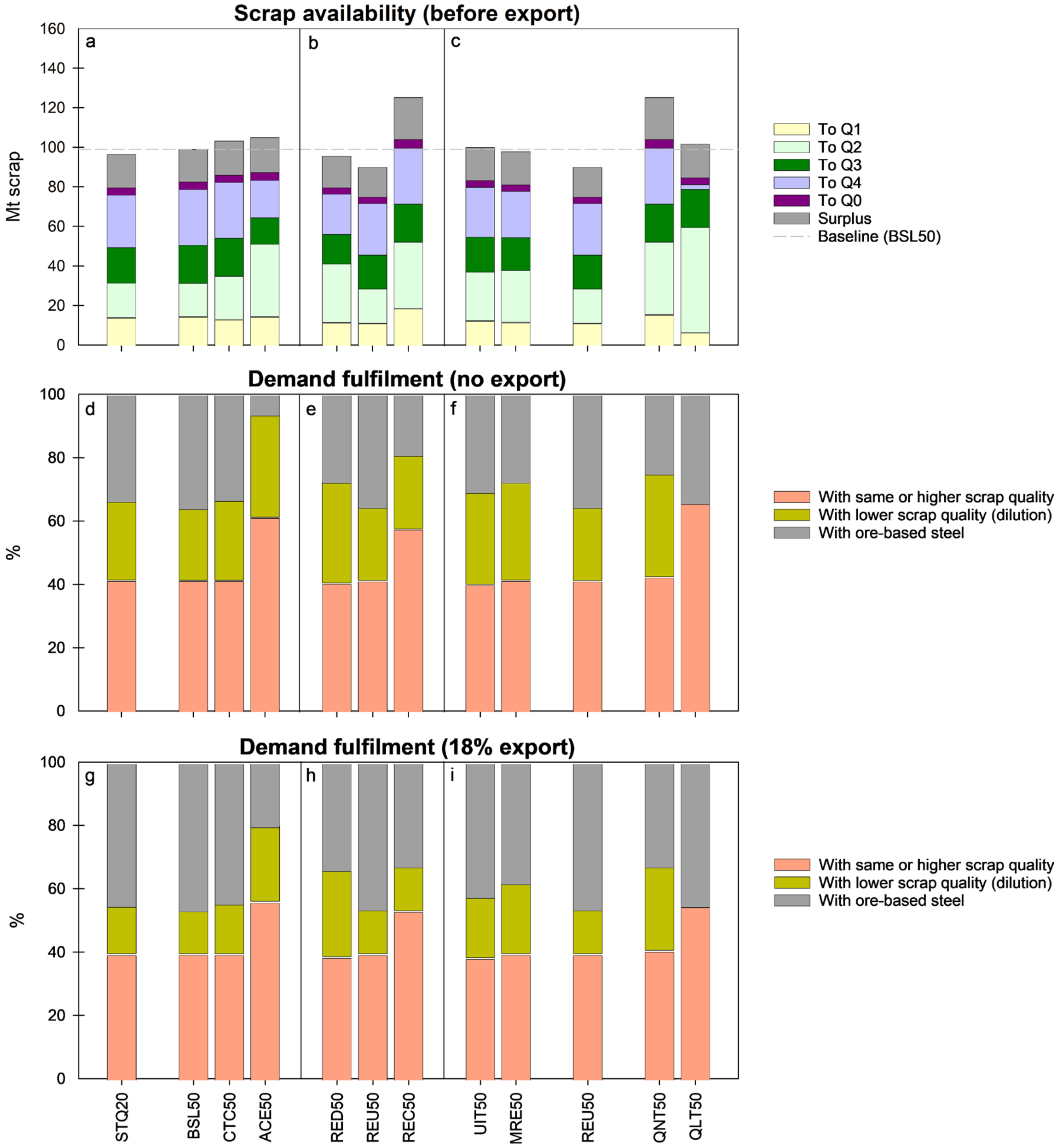
The third message is that the ACE50 scenario (combination of all levers simultaneously) reduces overall primary material demand, thanks to *Reduce/Reuse* levers and to more effective use of scrap by higher quality recycling, thanks to the *Recover* levers (see scenario REC50 in Figure 8e, mainly as a result of lever QLT50; see Figure 8f or Figure 8i). Additionally, it also shows that preventing export would equal more scrap available for fulfilment of the domestic demand. However, this implies applying dilution with primary material to reach the desired output quality demanded (this happens in all scenarios except for those where it is assumed that higher quality recycling is in place, which is reflected in scenarios QLT50, REC50, and ACE50).

A more detailed illustration is displayed in Figure 9. Figure 9(a,c,d) shows again the availability of scrap and associated quality categories (Q1-to-Q4 for steel scrap and Q0, which is a stand-alone category for cast iron) across the scenarios investigated, i.e. the available supply of recycled material. Differently from Figure 8, Figure 9(b,d,f) shows how the specific EU demands (broken down into the steel quality categories Q1-to-Q4 and Q0) are fulfilled. This is a higher level of granularity compared with Figure 8 (d-to-i), where the specific demands are not broken down by quality category, but rather aggregated to show 'how much' of the demand is fulfilled and 'how'. Needless to say, Figure 8 (d-to-i) is directly derived from Figure 9(b,d,f).

Results show that, across all scenarios investigated, high-quality steel scrap (Q1 and Q2) replaces equivalent demands (see Figure 9a) but it is not sufficient alone to cover the full demands for Q1 and Q2 quality categories (see Figure 9b). To this aim, Q3 secondary material is often used to substitute Q1 and Q2 grade virgin material, which means the scrap of quality Q3 needs to be diluted with virgin steel of high quality to reach the quality level required for the demanded end-use applications (see Figure 9b for STQ20, BSL50, and CTC50). A similar fate applies to the lowest scrap grade Q4, used for end-use applications requiring Q4 and Q2 quality category, but where the demand for Q2 needs always to be complemented with virgin steel to reach the desired quality grade. Similarly to Figure 8, Figure 9 also shows that a share of the scrap recovered in the EU (collected and sorted) needs to be exported as it represents a surplus relative to the demanded quality of the EU market.

Among the STQ20, BSL50, CTC50, and ACE50 scenarios, the only scenario that significantly pulls up scrap quality is ACE50 (see Figure 9a) thanks to the *Recover* levers (see Figure 9c vis-à-vis Figure 9d), particularly lever QLT50 (see Figure 9e vis-à-vis Figure 9f). This lever enhances quality of recycling by maintaining scrap material perfectly separated by sector of origin at collection stage. Under these ideal conditions, the scrap quality increases, with higher availability of scrap grade Q1 and Q2 at the expenses of Q4. Under these circumstances, the demands for Q2 and Q3 steel can be fully covered by scrap of the same quality, while the demand for Q1 only partly but to a much larger extent than in the Baseline BSL50 scenario. Since much less Q4 grade scrap is available under these conditions, the demand for Q4 is now covered partly by quality Q3 and partly by virgin steel. Notice also that the lever QNT50 only simulates an increase of the total scrap amount recovered, but not of its quality, and this is illustrated in Figure 9e,f. Notice that Q0 steel is defined as a separate quality segment for cast steel and cast iron, which is assumed not to be substitutable with other steel and is thus not analysed within this report.

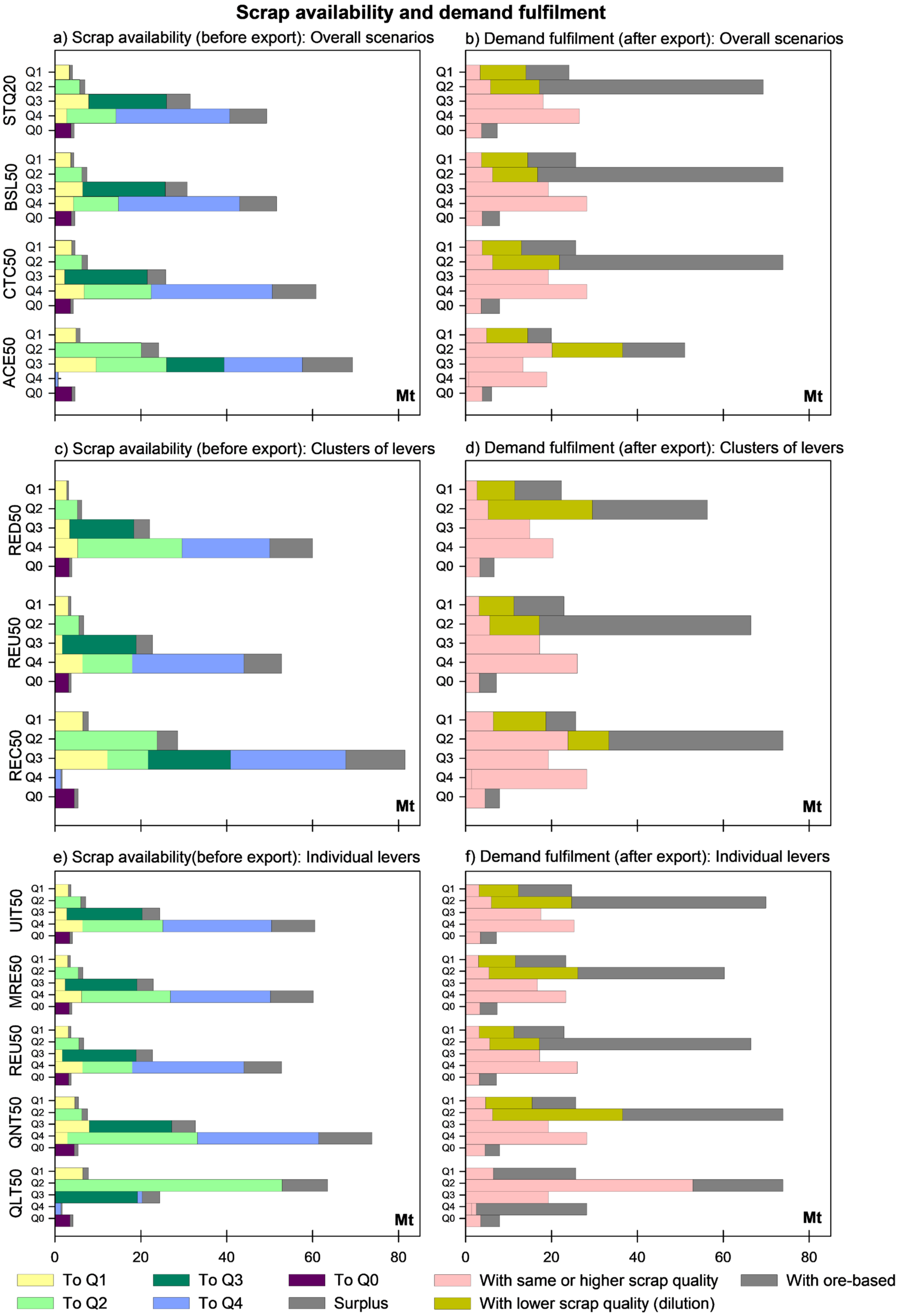
Figure 8. Aggregated results for scrap availability and quality and EU demand fulfilment, under two alternative scenarios (assuming no export of scrap or the current 18% export levels); year 2050



Note: Aggregated results for scrap availability and quality: a) overall scenarios STQ20, BSL50, CTC50, ACE50; b) clusters of levers RED50, REU50, REC50; c) individual levers UIT50, MRE50, REU50, QNT50, QLT50. Aggregated results for demand fulfilment (assuming no export of scrap): d) overall scenarios STQ20, BSL50, CTC50, ACE50; e) clusters of levers RED50, REU50, REC50; f) individual levers UIT50, MRE50, REU50, QNT50, QLT50. Aggregated results for demand fulfilment (assuming 18% export): g) overall scenarios STQ20, BSL50, CTC50, ACE50; h) clusters of levers RED50, REU50, REC50; i) individual levers UIT50, MRE50, REU50, QNT50, QLT50. For example, 'to Q1' refers to the amount of each scrap quality category (Q1 to Q4) used for applications requiring Q1 quality. Abbreviations: STQ20: Status Quo 2020 scenario; BSL50: (Business-as-Usual) decarbonized Baseline 2050 scenario; ACE50: Ambitious Circular Economy 2050 scenario; RE50: Reduce 2050 cluster; REU50: Reuse 2050 cluster; REC50: Recover 2050 cluster; UIT50: Usage Intensity 2050 lever; MRE50: Mass reduction 2050 lever; REU50: Reuse 2050 lever; QNT50: Increase quantity of material recovered 2050 lever; QLT50: Enhance quality of recycling 2050 lever

Source: JRC elaboration

Figure 9. Scrap availability (a, c, e) and demand fulfilment (b, d, f) in the different scenarios, with breakdown in quality classes Q1-to-Q4 and Q0 (cast iron); year 2050



Note: a ,b) overall scenarios STQ20, BSL50, CTC50, ACE50; c, d) clusters of levers RED50, REU50, REC50; e, f) individual levers UIT50, MRE50, REU50, QNT50, QLT50

Source: JRC elaboration.

5.2.2 Virgin (ore-based) steel demand and Circular Material Use Rate

Figure 10 shows the calculated CMUR along with the 'Virgin (ore-based iron) Steel Demand' (i.e. demand for virgin steel in the EU) under two alternative scenarios, i.e. with or without current levels of scrap exported outside the EU (ca. 18%). Clearly, without export the demand for ore-based steel is decreased.

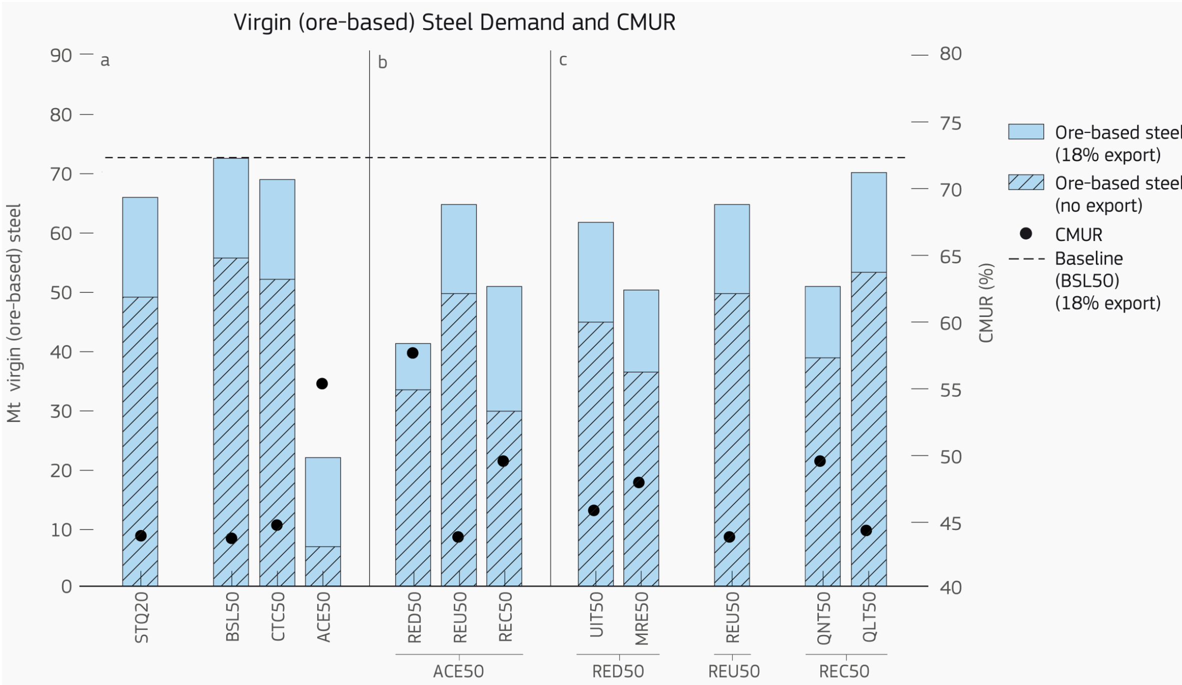
The ACE50 scenario (see ACE50 scenario; Figure 10), which includes high-quality recycling, shows a high-quality scrap dominated pattern with reduced ore-based steel demand owing to the effect of the reduction- and reuse-oriented levers. This demonstrates that integrating *Reduce*, *Reuse*, and *Recover* levers greatly reduces virgin (ore-based) material demand.

Based on the approach used in this study[23], we calculate the CMUR between 45% (STQ20; Figure 10) and 56% (ACE50; Figure 10). The current high level of 45%, as indicated by the Status Quo result, is a consequence of the high end-of-life recycling rate of the material (currently above 70%). The *Reduce* cluster brings the CMUR to 59%, while the Recover cluster to 51%. *Reuse* does not have a major effect. Notice that the lever on quality of recycling (QLT50) does not affect the CMUR as this indicator is not affected by quality, but only by quantity recovered, which under the lever QLT50 remains the same as in the Baseline BSL50.

Notice also that the way the indicator is currently calculated does not reward retaining the material in the EU versus exporting it. Export is instead considered in the calculation as fully equivalent to recycled material within the EU, which means that there is no difference between keeping scrap in the EU market and exporting it.

[23] CMUR is obtained dividing secondary material use, including that exported (i.e. recycled material in line with the Waste Framework Directive 2008), by the overall material use following the formula provided in (Eurostat, 2018).

Figure 10. Demand for virgin (ore-based) steel across the scenarios investigated (expressed as Mt; left-hand) and Circular Material Use Rate (CMUR, expressed as %; right-hand); year 2050



Note: a) overall scenarios STQ20, BSL50, CTC50, ACE50; b) clusters of levers RED50, REU50, REC50; c) individual levers UIT50, MRE50, REU50, QNT50, QLT50. The results are displayed under the assumption of no export or export to the current level of 18% of the scrap collected in the EU. Abbreviations: STQ20: Status Quo 2020 scenario; BSL50: (Business-as-Usual) decarbonized Baseline 2050 scenario; ACE50: Ambitious Circular Economy 2050 scenario; RE50: Reduce 2050 cluster; REU50: Reuse 2050 cluster; REC50: Recover 2050 cluster; UIT50: Usage Intensity 2050 lever; MRE50: Mass reduction 2050 lever; REU50: Reuse 2050 lever; QNT50: Increase quantity of material recovered 2050 lever; QLT50: Enhance quality of recycling 2050 lever

Source: JRC elaboration

5.3 Limitations

The main limitation of the MFA applied in this study is the reliance on one source, i.e. the work by Fraunhofer ISI & European Commission (2023); see also the related publication by Rostek et al. (2022). For example, higher projections for total scrap generation in the EU are given in Dworak et al. (2022); Dworak & Fellner, (2021). While this should be kept in mind when interpreting the results, it should still be noticed that the estimates applied in our study are in line with the figures reported in parallel studies of the European Commission Joint Research Centre, notably Thibaut et al. (2025), where the authors suggest an increase of scrap generated and available in the EU from current 100 to 112 Mt by 2035, of which 80-90 Mt are post-consumer scrap. The figures on EU scrap are also in line with what reported in the preparatory ESPR study (Blanco et al., 2024).

6 Process-based Life Cycle Assessment and Life Cycle Costing

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 macro-economic effects such as spillover effects across countries and economic sectors, effects due to changes in prices, investments, and trades. Sensitivity analyses are performed on the side to test the most critical assumptions related to the methodology.

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 macro-economic effects such as spillover effects, changes in prices, investments, and trades. These are intended to be captured under EEIOA (section 7) and dynamic modelling (section 8) analyses.

6.1 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.

6.1.1 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 focus of the LCA is the EU steel supply chain and its global inter-country linkages, with the overarching goal of quantifying the global environmental impacts associated with a set of CE levers applied in the EU under two different scenarios (CTC50 and ACE50). The Status Quo (STQ20) and the future decarbonised Baseline (BSL50) scenario represent benchmarks of comparison to quantify the impact reductions incurred by the CE levers in selected environmental and socio-economic indicators. It must be noticed that the bottom-up LCA is by nature limited in its ability to capture global effects due to the well-known truncation effect. This is why we later also perform an environmentally extended input-output analysis, which additional value is to capture inter-country interlinkages and spillovers (section 7).

As for the LCA, when analyzing the CE levers individually, we define a functional unit (FU) tailored to each case, which means that we include/exclude parts of the system boundary accordingly. The related system boundary, following ISO14040/44, is expanded to the extent necessary to capture the consequences of the CE lever assessed. We do not alter final consumer demand in the EU or in RoW (*ceteris paribus*). This corresponds to a consumption footprint perspective at global level. For example, increasing recycling in EU incurs reduction of virgin production in the EU with beneficial environmental consequences at global level (more recycled content in the EU products), *ceteris paribus*; alternatively, improving the EU production influences the environmental performance of the material consumed in both the EU and at global level, *ceteris paribus*.

It should be noticed that, while each CE lever studied individually has a tailored FU, when the entire set of CE levers are studied altogether the new FU is the combination of all the individual FUs (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 the EU and global economy that are affected by the CE levers applied within the EU steel economy. It includes all processes from iron ore mining to final disposal via incineration or landfilling, as well as import-export flows except for the use phase, which is out of our scope (Figure 11). 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, recyclates and energy that are generated by managing the waste are credited by assuming the displacement of the counterparts. Background life cycle impact assessment data are obtained from the ecoinvent v3.9 database taking the 'allocation at the point of substitution' system model (Wernet et al., 2016). To model the electricity and heat production mixes, the official GECO projections of the European Commission Joint Research Centre are used (Keramidas et al., 2023).

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"* (p. 5). 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 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 (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) but does not follow each step systematically.

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 included in the EF v3.1 method were 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 has been used (Astrup et al., 2012; Clavreul et al., 2014).

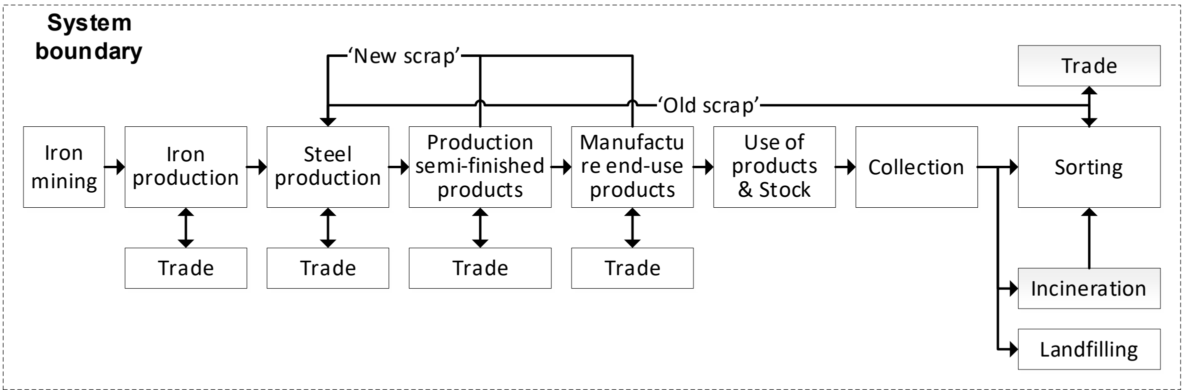
Finally, as it is common practice to use scrap together with virgin steel in the production process, the Circular Footprint Formula (CFF), and, specifically, the material part of the formula has been applied to consistently allocate burdens and credits to producers and recyclers between two life cycles [Equation 1]. The function of the A factor is the allocation of the burdens and credits between two life cycles reflecting the market reality. In the case of steel, an A factor equal to zero is assumed as the demand for scrap is much higher than the supply. We follow the logic that from a market perspective the demand and supply cannot be at the same time constrained, i.e. either A=0 or A=1. While this simplifies the assessment, we also tested the results using the value A=0.2 in line with European Commission (2022) recommendation for PEF of metal products, which represents low offer of recycled materials and high demand.

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

[Equation 1]

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: proportion of material in the input to the production that has been recycled from a previous system.
R_2: 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.

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



Note: Pre-consumer scrap from production, forming and fabrication is called 'new scrap', while post-consumer scrap is called 'new scrap'. Transport is also included in the assessment but not shown in this illustration for simplicity. The impacts of the use phase are excluded from our assessment

Source: JRC elaboration

6.1.2 Modelling assumptions and life cycle inventory

While the processes used to build the Life Cycle Inventory underpinning this study are mainly based on the inventories of ecoinvent 3.9.1 processes complemented by scholarly references, additional details on the processes used and costs may be consulted in the Supplementary Material to this study (available upon request).

6.1.2.1 Modelling the background energy system

The projections presented in the GECO 2023 update (Keramidas et al., 2023) are used to calculate the composition of the average energy mix, both for electricity, industrial heat (specific to the sector analysed), district heating, and space heating, of the EU and non-EU countries 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 mix. In this scenario, the targets of the NDC towards GHG reduction are considered in the medium and the longer term. In the NDC-LTS scenario it is assumed that the objective 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 and other sectors are also decarbonised. However, for the sake of simplicity, the decarbonization of the transport sector is not considered in our LCA.

Within the NDC-LTS scenario, the electricity grid is decarbonised due to high shares of renewables in the mix, but also because of the implementation of Carbon Capture and Storage (CCS). As mentioned, ecoinvent datasets have been used for modelling 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, have been 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 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).

While for electricity the general GECO 2023 EU electricity mix is used, data for industrial heat is sector specific. Therefore, data specific for the EU steel sector are employed, which exhibit a 63% coverage rate for CCS in 2050 according to the projections of the GECO 2023. The exact composition of the 2050 GECO-based electricity and heat mix is provided in the Supplementary Material to this study (available upon request).

6.1.2.2 Modelling the material supply chain

Steel making

After elaborating the GECO projections from Keramidas et al. (2023), steelmaking is modelled as BF-BOF route (82 Mt; 56% of total production) and EAF route (63.5 Mt; 44% of total production) in 2020 and BF-BOF route (ca. 36 Mt; 23% of total production) and EAF route (ca. 119 Mt; 77% of total production) in 2050. Steel imports are modelled additionally (3.2 Mt of steel in 2020 and 3.4 Mt in 2050) to fulfil demand that is not covered by primary and secondary domestic production (see MFA description). The composition of imported steel is based on the average of the EU production per finished steel product. Per steel production route, corresponding steelmaking data from ecoinvent datasets for "Rest-of-the-World" (RoW) geographies is used. Where not further specified, the ecoinvent datasets for production of low-alloyed steel are used as proxy to represent different steel varieties, i.e. low-alloyed, unalloyed and high-alloyed steels, since data availability on steel types is limited. When data is available on the steel type per finished steel product (e.g. chromium steel, cast iron) the corresponding ecoinvent processes are used.

To retain an influence on the modelling where the MFA and energy mix inputs can be accurately represented, selected ecoinvent processes are isolated. The iron input to steelmaking is isolated to allow the manipulation of the scrap and imported iron shares as defined in the MFA (section 4.2 and Supplementary Material, available upon request). The energy mix for steel and iron production is isolated in a similar manner, to account for the GECO energy mix and to model CCS in 2050.

The CCS is modelled for domestic iron and steel production. For domestic iron production CCS is modelled by removing the process CO_2 emissions at steelmaking and replacing hard coal and natural gas inputs from the original ecoinvent dataset with the GECO 2023 (steel) industrial heat mix for 2050. The heat input is calculated as a function of the lower heating value of the replaced hard coal and natural gas inputs, to maintain energy balance. The CCS for domestic steel is included in a similar way. The process CO_2 emissions are removed and hard coal, natural gas, and coke are replaced with a quantity of industrial heat matching their lower heating values, to maintain energy balance. This modelling approach thus overestimates other non-CO_2 emissions (from natural gas, coal used in the original ecoinvent dataset) like NO_x and SO_2, as for these no correction was possible.

Finished steel products

The finished steel products modelled are concrete reinforcing bars, hot rolled bars, wire rod, railway track material, heavy sections, light sections, seamless tubes, hot rolled plate, hot rolled coil, electrical sheet and strip, tinmill products, other metal coated sheet and strip (galvanized), cold rolled coil, and welded tubes. The flow of each finished steel product and finished steel product import is based on the projections illustrated in section 4.2 (MFA results). A share of the input material used in finished steel product manufacturing ends up into scrap or export based on MFA (see section 4.2 on MFA results). The inventories used to describe or proxy each finished steel product are from ecoinvent v3.9 and may be consulted in the Supplementary Material to this study (available upon request). A change to the ecoinvent inventories was implemented by replacing the energy mix used for finished steel product manufacturing in the original dataset with the energy mix derived from the GECO 2023, as earlier described.

Manufacturing of end-use goods (finished products containing steel)

To describe the metal working stage to manufacture end-use goods (finished products containing steel, e.g. cars, industrial equipment, and packaging) a generic metal working process from ecoinvent was used (the process represents metal working and includes a consumption of electricity and heat per unit of steel processed and put into a final product). This metal working was not applied to the buildings and infrastructure construction sectors, as it is assumed that these sectors do not process finished steel products as extensively as e.g. the transport and packaging sector. A share of the input material used in manufacturing ends up into scrap or export based on MFA (section 4.2 on MFA results). A change to the ecoinvent inventories was implemented by isolating the energy mix for end-use goods manufacturing to integrate the GECO 2023 energy mix, as described earlier.

Transport

The transport is modelled using ecoinvent transport data. For all EU transports the per kg ecoinvent transport data for EU pig iron is applied to all steel-related transport processes. European transports are accounted for at several different stages (i.e. at the pig iron to steel production transport, at steel to finished steel product manufacturing, finished steel product to end-use goods manufacturing, waste transport, waste to recycling, waste to final disposal). For all imports instead, the (km) per kg transport data for the global steel market is used as a proxy.

End of Life

The material flows entering the End of Life are determined as a percentage of the inflows, in line with the partitioning coefficient suggested in the MFA by Rostek et al. (2023). Part of the material flow to End of Life is generated by stock (see MFA by Rostek et al.; 2023). The waste streams originating after use are CDW, MW, WEEE, ELV, IEW, and INEW[24]. The collection rate used for 2020 and 2050 may be consulted in the MFA by Rostek et al. (2023) (Table 13 in Rostek et al. 2023). A fraction of the steel is unaccounted for after use (dissipated) and a fraction is not collected. The collection is modelled as regular transport. In the specific case of packaging waste, a deposit refund system (DRS) was added additionally to simulate this specific collection system for packaging waste. In 2020, the DRS coverage for steel waste packaging in the EU is estimated at 14% based on DRS coverage data provided by Arcadis et al. (2023)[25] and Cordle (2019)[26], i.e. 14% of the total steel waste packaging is on average covered by DRS in the EU in 2020. The energy use for the reverse vending machine is at 0.074 kWh per kg of steel (Cordle, 2019). While steel collected via DRS moves to centralized sorting, other packaging is collected with MW, via separate and residual waste collection. For DRS, a collection vehicle of 10t with consumption of 20 L per tonne scrap collected is used. For the remaining packaging collected via separate collection and residual waste collection, the steel-related transport process is used (see above). The collected scrap is transported to a centralized sorting plant prior to recycling for recycled steel production. The modelling of the sorting facility is based on the ecoinvent process for sorting and pressing of iron scrap. The scrap sorting plant consumes 10 kWh, 100 L diesel per tonne treated and has a default sorting rate of 92% for steel and iron scrap (Albizzati et al.; 2024, Table S.24). Sorted scrap is transported to steel making factories for recycling. A change to the ecoinvent inventories was implement by isolating the energy mix for end-use goods manufacturing, to account for the GECO 2023 energy mix.

For the specific case of the lever QLT50 ('enhancing recycling quality'), a more refined sorting was modelled assuming that dedicated scrap sorting takes place at the level of waste generated by each sector, including a complete separation from other materials before melting, and that each sector-specific scrap flow is kept separate so as to maintain the quality grade of the scrap and avoid cross-contamination with scrap of lower grade originated from other sectors. For this, a consumption of 0.03 kWh electricity per kg of steel scrap entering sorting is used, based on the

[24] CDW: Construction and Demolition Waste; MW: Municipal Waste; WEEE: Waste Electric and Electronic Equipment; ELV: End-of-Life Vehicles; IEW: Industrial Electrical Waste; INEW: Industrial Non-Electrical Waste.

[25] European Commission, Directorate-General for Environment, Assessment of options for reinforcing the Packaging and Packaging Waste Directive's essential requirements and other measures to reduce the generation of packaging waste – Appendices, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2779/450320.

[26] Table A1 & A2 in Cordle, Mark, et al. "A Deposit Refund System for the Czech Republic." Final Report. Eunomia Research & Consulting Ltd. Pozyskano z https://www.eunomia.co.uk/reports-tools/deposit-refund-system-czech-republic (2019).

improved shredding and magnetic separation technology presented in the study of Daehn et al.; 2019).

In general, across all 2020 and 2050 scenarios, the recycling process is modelled following Rigamonti et al. (2009)[27]. The process from Rigamonti et al. (2009) is modified to reflect a is modified to reflect a recycling efficiency of 88.4%, based on data for EAF based steel production efficiency from ecoinvent.

Uncollected and unsorted scrap is sent to disposal, in line with their current respective shares in the EU for residual waste treatment and these shares' extrapolation to 2050 (landfill and incineration; 46% and 54% in 2020 and 43% and 57% in 2050). The landfill and incineration technologies are modelled material-specific (i.e. energy recovery and emissions are modelled based on the input-waste material fraction, in this case steel) following previous work of the same authors. We further assume that steel and iron are recovered from bottom ash, with material-specific recovery rate of 80% conforming with previous studies of the same authors.

Quality of scrap and substitution of primary material

The substitution of virgin material by recycled material depends on the respective quality classes. In this study the quality of recycled steel is defined following the quality assessment of post-consumer scrap suggested in Dworak et al. (2022). See section 5 and associated annex for a definition of the steel qualities. As a default, there are pre-assigned steel scrap qualities based on end-use sector following the approach suggested in Dworak et al. (2022). For example, all steel that has been used in the construction sector is assigned to Q4, the lowest quality, due to high contamination with tramp elements in this sector (see Annex 3 for a comprehensive list). In general, the result of the recycling process can be seen as several pools of steel melt of different qualities (i.e. different recycled material qualities).

An allocation algorithm assigns the supply of recycled steel to the demand for steel, while considering the quality requirements of the steel demands (section 5.1.2). In the default calculations, the recycled steel produced replaces the average steel mix, which is dominated by EU steel (95%). More information on the inventory may be found in section 6.1.2.2.

6.1.3 Sensitivity analysis

6.1.3.1 Background energy system

This 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) is challenged by considering the energy mixes calculated under the Reference Energy scenario conditions. The GECO 2023 Reference Energy 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 action plans are not reached

[27] Also see Rigamonti, L., 2007. Valutazione dei percorsi di recupero di materiali e di energia in sistemi integrati di gestione dei rifiuti urbani [in Italian]. Polytecnic of Milan.

(Keramidas et al., 2023). Therefore, the energy mix is overall less 'green', and the application of CCS is limited, both for EU and non-EU countries.

6.1.3.2 Methodological aspects: A-factor and quality

This sensitivity analysis is conducted on key LCA methodological choices, namely i) A-factor applied in the Circular footprint Formula, ii) approach to model quality of recycling. As for the A-factor, the default value of zero is challenged applying a value of 0.2, which is the default value recommended for the A-factor for metals in the PEF methodology.

With respect to modelling of quality in recycling, the approach used as default in the assessment is that recycled steel is allocated to steel demands based on quality and the replacement of virgin counterpart is credited environmentally via virgin steel substitution. Generally, insufficient quality scrap is diluted, i.e. mixed, with virgin steel (e.g. in BF-BOF route, liquid steel is mixed with scrap to increase quality) to reach demanded quality standards in terms of tramp element content of the final steel produced (whether intermediate or finished steel product). In the default approach, this dilution is credited in the LCA by considering the displacement of virgin steel, which reflects current practices in industry. In the sensitivity analysis, this is tested with an alternative approach where we do not credit dilution[28]. This is a rather conservative approach reflecting the uncertainty and challenges associated with diluting steel scrap. For example, recyclers need to have prior knowledge of scrap quality to dilute efficiently, which can be limited in practice. In a nutshell, considering the effects of dilution in the modelling 'reduces' the savings attributed to the lever 'enhancing quality of recycling'. This is simply because dilution can ease the requirements for high-quality scrap through improving the quality of the final steel.

Notice that the default approach abovementioned is not common in LCA studies as it requires a sophisticated numerical solution, where dilution-potential is calculated for all scrap qualities. For additional details on this approach, the reader is referred to Wagner et al. (2025).

6.1.3.3 Subjection to alternative socio-economic futures

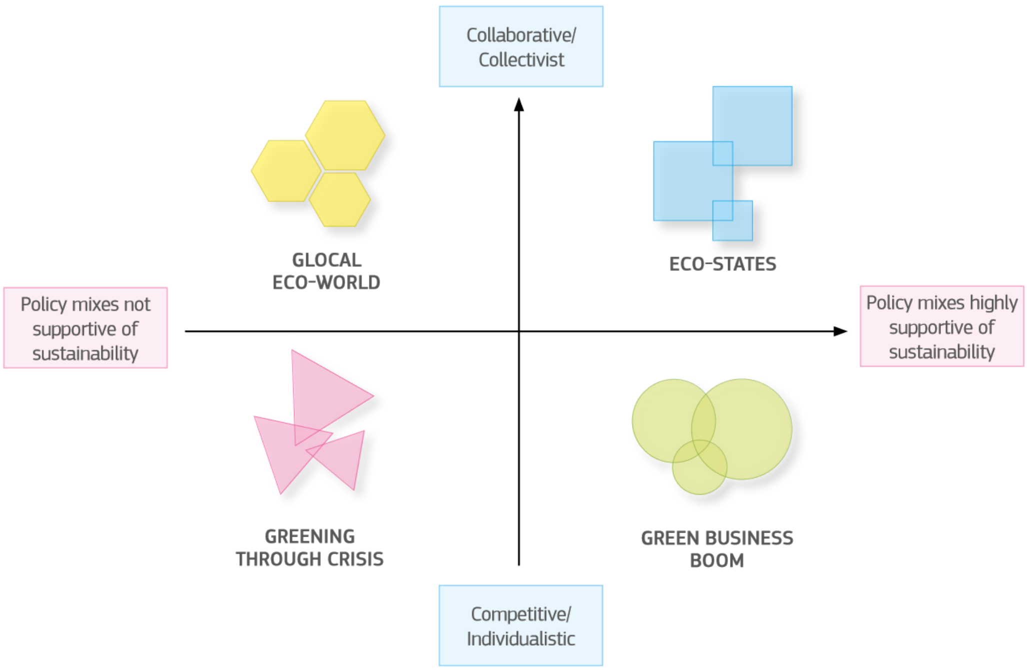
With the current design of the analysis, there is an underlying assumption that the socio-economic system on which the industrial system is based will not change significantly. It is thus expected that technological and socio-economic trends will continue as per the historical trajectory. Taking an anticipatory 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 performative (Börjeson et al., 2006). A well-known set of scenarios used in integrated assessment models are for example the 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 plausible 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

[28] What needs to be clear is that we allow dilution in both the approaches, but do not credit it with virgin steel substitution in the approach tested in the sensitivity analysis.

rather than socio-economic aspect, 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.

These normative scenarios are separated into a 2x2 matrix with the axes of policy mixes either supportive or not supportive of sustainability and either a collaborative or competitive outlook on society (European Commission, 2023a). This results in four different background scenarios, into which the current analysis of ACE50 in the steel 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 ambitious ACE50 scenario of the analysis would fare in these different futures. This will enable policy makers to take more informed decision, by pushing the thinking towards implications of ACE50 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: Matti el al. (2023, p. 101).

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.

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 CTC50, 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.

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.

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 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. To become more resilient and efficient, the EU is in competition for raw materials and initiates strategic trade cooperation with selected countries.

6.1.4 Life Cycle Costing

The Life Cycle Costing (LCC) is performed following state-of-the art approach 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.

In an LCC, two types of costs are accounted for, namely internal and external costs (which assign a price to the so-called externalities). Internal costs include budgets costs (i.e. costs incurred by the different actors in the supply chain), usually distinguishing between operating and capital costs (OPEX and CAPEX) and 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 herein estimated in line with De Bruyn et al. (2018). The prices proposed in De Bruyn et al. (2018) include prices for emissions to air/soil/water, but not for other disamenities, such as noise, odour, accidents. In particular, the cost of process-specific CO_2 emissions occurring at iron and steelmaking (i.e. direct air emissions at stack) is given an external price of 100 EUR t^{-1}.

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). The former includes all internal costs (i.e. both budget costs and transfers, including environmental taxes such as landfill or incineration tax, energy taxes, etc.), while the latter sums the monetised environmental emissions that are currently non-internalised to the internal costs (i.e. budget costs and transfers), both expressed as shadow prices. 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, internal costs and external costs occurring in the future are neither discounted nor corrected for inflation to ensure consistency with the LCA. All costs are expressed as EUR2022.

6.2 Results

This section presents the results obtained for Climate Change, Environmental Life Cycle Cost, and Full Environmental Life Cycle Cost. Positive values represent a burden for the environment or a cost for the economy, while negative results reflect savings for the environment or revenues. The results for the remaining environmental impact categories are presented in Annex 4. All the results presented are calculated considering the energy mixes calculated based on the NDC-LTS scenario, for both the EU and non-EU, an A factor equal to zero in the Circular Footprint Formula (CFF), and the default approach for assessing quality in recycling. The results for Climate Change relative to the sensitivity analyses performed are presented in section 6.2.4.1 and 6.2.4.2.

6.2.1 Climate change mitigation

The Climate Change impact, quantified in million tonnes of CO_2-equivalent emissions (Mt CO_2-eq) for the entire system, is depicted in Figure 13. The Status Quo 2020 impact, for the system boundary considered in the bottom-up LCA, is estimated at 269 Mt CO_2-eq. of which production is 160 Mt CO_2-eq. (when including recycling savings, i.e. 381-221 Mt CO_2-eq.; Figure 13), manufacturing 57 Mt CO_2-eq., Import 8 Mt CO_2-eq., Export 1.5 Mt CO_2-eq., and waste management 42 Mt CO_2-eq (with 221 Mt CO-eq. savings, as abovementioned). The BSL50 scenario (150 Mt CO_2-eq.) shows a reduction in emissions of 119 Mt CO_2-eq., a 44% decrease from the Status Quo 2020 scenario. This decline occurs despite a projected 19% growth in EU steel demand and production by 2050 since emission reductions are expected from the decarbonization of energy sources and the adoption of carbon capture and storage technologies across the EU and beyond. The CTC50 scenario (145 Mt CO_2-eq.) yields a 3% Climate Change mitigation relative to the Baseline BSL50 scenario (4.8 Mt CO_2-eq.), suggesting that the steel scrap material targets considered in this study are insufficient for substantial GHG emission cuts. In the ACE50 scenario, the impact on Climate Change equals 69 Mt CO_2-eq (all CE levers implemented simultaneously), a 54% (81 Mt CO_2-eq.) decrease from the Baseline BSL50 scenario[29]. The most significant contributions arise from product demand reduction and more efficient scrap utilization (higher collection and quality scrap supply). Given the predicted growth in steel demand, energy decarbonization alone will be inadequate for a net-zero emissions supply chain. Circular economy strategies offer significant potential to bridge this gap. However, this also leads to reduced recycled material availability, diminishing the material substitution savings as illustrated in Figure 13.

Focusing on the effect of the individual levers and of the clusters *Reduce/Reuse/Recover* separately: for the *Reduce* levers, the lever MRE50 ('mass reduction') incurs a 23% impact reduction (35 Mt CO_2-eq.) and the lever IUT50 ('increase usage intensity') a 12% (18 Mt CO_2-eq.), thanks to lower burdens of production. Overall, the combination of the *Reduce* levers leads to 33% (49 Mt CO_2-eq.) Climate Change mitigation effect in comparison to BSL50. The lever REU50 (*Reuse*) reduces impacts by 10% (15 Mt CO_2-eq.) relative to BSL50, echoing the *Reduce* levers in both lower production emissions and decreased virgin material substitution benefits. For the *Recover* cluster of levers, the lever QNT50 ('increase collection') stands out with a 21% impact reduction (31 Mt CO_2-eq.), thanks to higher substitution of virgin material, while QLT50 ('enhance quality recycling')

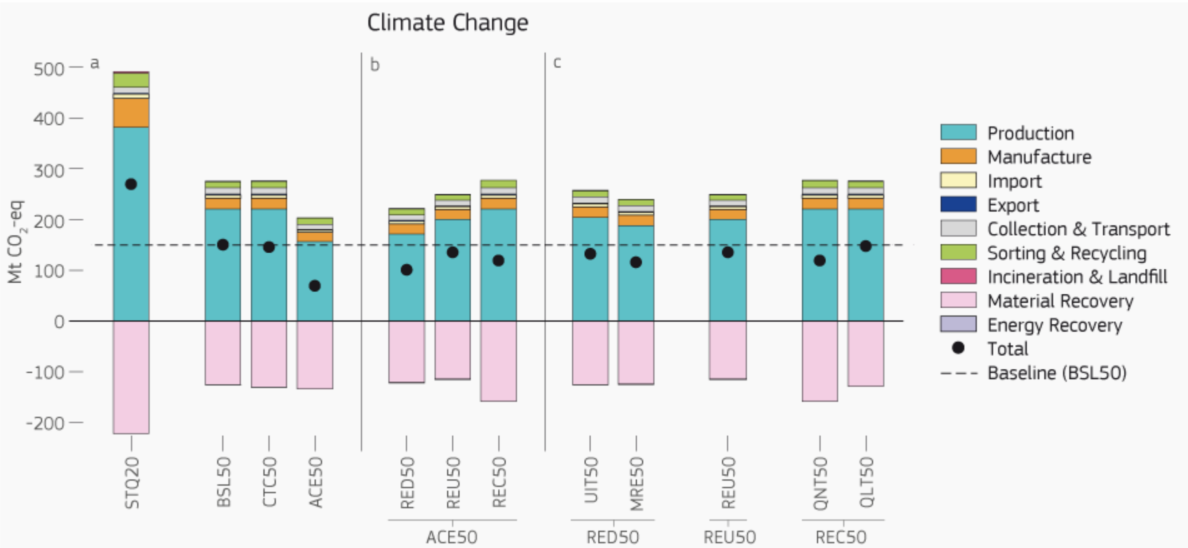
[29] When including the levers implying significant behavioural changes the savings of the ACE50 scenario raise to 99 Mt CO_2-eq. relative to the baseline BSL50 scenario (total system impact: 51 for ACE50 versus 150 Mt CO_2-eq. for BSL50).

reduces the impact by 2% relative to the Baseline BSL50 scenario (3 Mt CO_2-eq.) according to the default approach used to address quality. Overall, the combination of the *Recover* levers leads to 21% Climate Change mitigation effect (31 Mt CO_2-eq.) in comparison to the Baseline BSL50 scenario.

6.2.2 Other environmental impacts

Trade-offs due to increased use of renewable energies and associated biomass and material use for the technologies is observed for the transition from the Status Quo (STQ20) to Baseline (BSL50) in the impact categories Ozone Depletion, Eutrophication terrestrial, Ecotoxicity, Human Toxicity, non-cancer, Land Use, Water Use, Resource Use – Minerals and metals. These impacts are reduced drastically in the ACE50 scenario thanks to the *Reduce* levers. The remaining impact categories follow the trend observed for the category Climate Change. Details may be consulted in Annex 4.

Figure 13. Results for Climate Change expressed as Mt CO_2-eq per entire system annually (year 2050)



Note: a) overall scenarios STQ20, BSL50, CTC50, ACE50; b) clusters of levers RED50, REU50, REC50; c) individual levers UIT50, MRE50, REU50, QNT50, QLT50. Abbreviations: STQ20: Status Quo 2020 scenario; BSL50: (Business-as-Usual) decarbonized Baseline 2050 scenario; ACE50: Ambitious Circular Economy 2050 scenario; RE50: Reduce 2050 cluster; REU50: Reuse 2050 cluster; REC50: Recover 2050 cluster; UIT50: Usage Intensity 2050 lever; MRE50: Mass reduction 2050 lever; REU50: Reuse 2050 lever; QNT50: Increase quantity of material recovered 2050 lever; QLT50: Enhance quality of recycling 2050 lever

Source: JRC elaboration

6.2.3 Life Cycle Costing

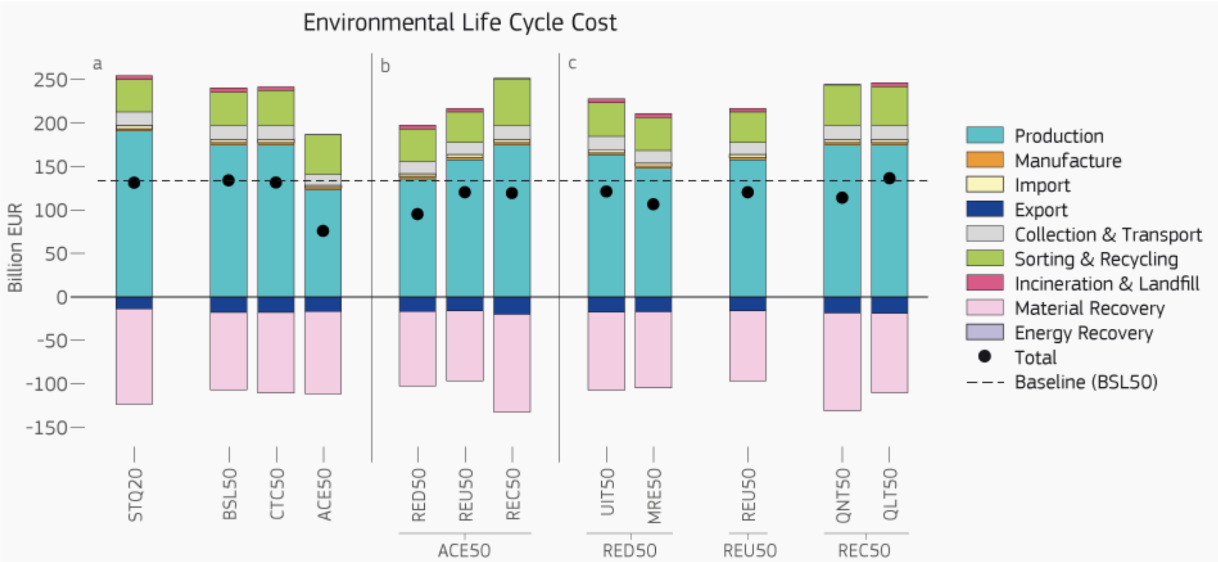
Figure 14 presents the Environmental Life Cycle Cost (ELCC) results, expressed in billions of EUR for the entire system assessed. For the Status Quo 2020 scenario, environmental costs amount to EUR 131 billion. For the BSL50 scenario, the environmental costs amount to EUR 134 billion, reflecting a 2% increase from the Status Quo costs of EUR 131 billion, mainly due to increased demand (Figure 14a). The CTC50 scenario (EUR 131 billion) shows a cost reduction of 2% (EUR 3 billion) relative to the Baseline BSL50 scenario, suggesting that the steel material targets considered in this study do not lead to significant cost savings overall. The ACE50 scenario decreases environmental costs to EUR 76 billion, a 43% (EUR 58 billion) relative to the BSL50 scenario (Figure 14a). This substantial decrease is largely attributable to the diminished demand and the associated production cost savings, further amplified by efficient resource input reduction via scrap.

The *Reduce* levers incur a cost reduction of 29% relative to the Baseline BSL50 scenario (ca. EUR 95 billion; Figure 14b) while the *Reuse* lever of 10% (ca. EUR 14 billion; Figure 14b) thanks to reduced production costs. The *Recover* levers incurs a cost reduction of 11% relative to the Baseline BSL50 scenario (ca. EUR 14 billion; Figure 14b) due to higher revenues from recycling sales that more than compensates for increased costs of collection, sorting and recycling.

Focusing on the effect of the individual levers separately, amid the *Reduce* levers, MRE50 ('reduce mass') and UIT50 ('increase use intensity') incur 20% and 10% environmental cost reduction relative to the BSL50 scenario, respectively, due to lower burdens of production (Figure 14c). The REU50 (*Reuse*) lever incurs 10% cost reduction relative to the BSL50 scenario (Figure 14c), due to lower burdens of production. The *Recover* levers QNT50 and QLT50 incur about 15% cost reduction and slight cost increase relative to the BSL50 scenario, respectively. Cost savings derive from scrap sales while the cost increases relate to expenses for advanced sorting (Figure 14c).

The results for the Full Environmental Life Cycle Cost (FELCC; Figure 15) follow the trend shown for the ELCC and for Climate Change impact category. External costs contribute significantly to the Full Environmental Costs across the scenarios investigated (EUR 22-54 billion, corresponding to a share of around 22-29% of the FELCC; see Figure 15a), and are reduced significantly under the ACE50 scenario where the FELCC is estimated at EUR 101 billion, i.e. a 41% decrease from the Baseline BSL50 scenario equalling EUR 172 billion. Amid the clusters of levers, the *Reduce* cluster reduce FELCC by 28% relative to the BSL50 scenario (EUR 48 billion; Figure 15b), *Reuse* by 10% (EUR 17 billion; Figure 15b), and the *Recover* cluster by 9% (EUR 16 billion; Figure 15b).

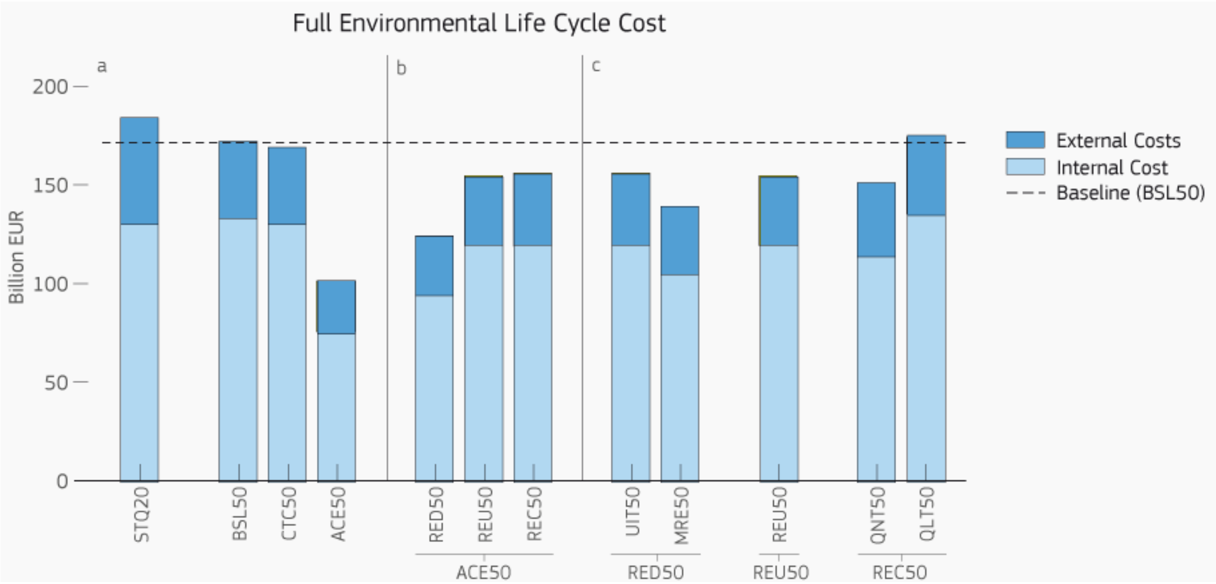
Figure 14. Results for Environmental Life Cycle Cost (ELCC), expressed as billion EUR per entire system annually (year 2050)



Note: a) overall scenarios STQ20, BSL50, CTC50, ACE50; b) clusters of levers RED50, REU50, REC50; c) individual levers UIT50, MRE50, REU50, QNT50, QLT50. Abbreviations: STQ20: Status Quo 2020 scenario; BSL50: (Business-as-Usual) decarbonized Baseline 2050 scenario; ACE50: Ambitious Circular Economy 2050 scenario; RE50: Reduce 2050 cluster; REU50: Reuse 2050 cluster; REC50: Recover 2050 cluster; UIT50: Usage Intensity 2050 lever; MRE50: Mass reduction 2050 lever; REU50: Reuse 2050 lever; QNT50: Increase quantity of material recovered 2050 lever; QLT50: Enhance quality of recycling 2050 lever

Source: JRC elaboration

Figure 15. Results for Full Environmental Life Cycle Cost (FELCC), expressed as billion EUR per entire system annually (year 2050)



Note: a) overall scenarios STQ20, BSL50, CTC50, ACE50; b) clusters of levers RED50, REU50, REC50; c) individual levers UIT50, MRE50, REU50, QNT50, QLT50. Abbreviations: STQ20: Status Quo 2020 scenario; BSL50: (Business-as-Usual) decarbonized Baseline 2050 scenario; ACE50: Ambitious Circular Economy 2050 scenario; RE50: Reduce 2050 cluster; REU50: Reuse 2050 cluster; REC50: Recover 2050 cluster; UIT50: Usage Intensity 2050 lever; MRE50: Mass reduction 2050 lever; REU50: Reuse 2050 lever; QNT50: Increase quantity of material recovered 2050 lever; QLT50: Enhance quality of recycling 2050 lever

Source: JRC elaboration

6.2.4 Sensitivity analyses

6.2.4.1 Sensitivity analysis I: testing energy mix assumptions

Figure 16 outlines the impact of different energy mixes on Climate Change, expressed as CO_2-equivalent emissions (Mt CO_2-eq) for the entire system assessed. The analysis compares results obtained using the energy mix from the GECO 2023 NDC-LTS scenario against those using the GECO 2023 Reference scenario.

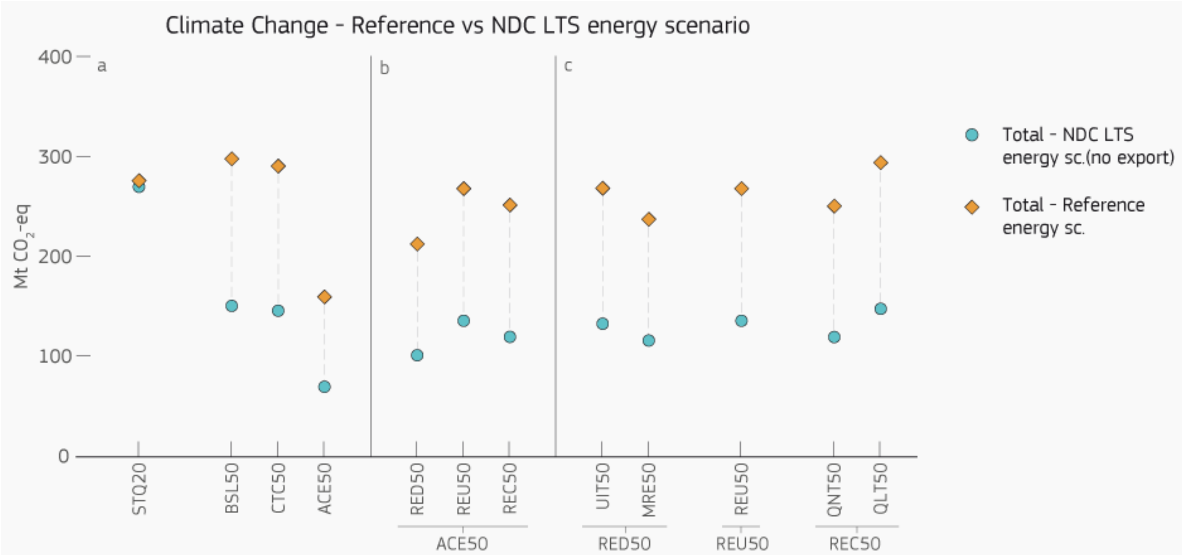
As expected, the results show that under the Reference scenario energy mix the net GHG emissions are substantially higher compared to the NDC-LTS case. For the 'Status Quo' scenario, emissions remain unchanged between the default and sensitivity analysis, as neither decarbonization efforts nor CCS technologies differ in 2020 between the GECO NDC-LTS and the Reference scenarios.

The increase in emissions within the Reference scenario is predominantly due to higher production activity emissions. Additionally, emissions from manufacturing, collection, sorting, and recycling also rise in this scenario. Although virgin steel production is more emission-intensive, leading to greater calculated savings from recycling, these savings are insufficient to offset the overall uptick in emissions caused by the energy mix used and the lack of CCS.

The GHG reduction potential of each lever relative to the BSL50 scenario is similar in percentage terms when comparing the results obtained using the (GECO) Reference energy scenario with the default (GECO) NDC-LTS energy scenario. Specifically, the ACE50 scenario under the (GECO) Reference energy scenario shows a 47% reduction in Climate Change impact relative to the

Baseline, closely aligning with the 54% reduction observed under the NDC-LTS energy scenario. However, in absolute terms, the absolute net GHG emissions for ACE50 scenario under the (GECO) Reference energy scenario are 130% higher (159 vs 68 Mt CO_2-eq.) than those obtained using the default NDC-LTS energy scenario (Figure 16). This highlights the significant influence of energy decarbonization and CCS on the overall emissions profile.

Figure 16. Sensitivity analysis I: testing energy mix assumptions



Note: Comparison of the impact of the scenarios assessed on the Climate Change category when applying the GECO NDC-LTS and the GECO Reference energy scenarios; results are expressed as Mt CO_2-eq per entire system annually (year 2050); a) overall scenarios STQ20, BSL50, CTC50, ACE50; b) clusters of levers RED50, REU50, REC50; c) individual levers UIT50, MRE50, REU50, QNT50, QLT50. Abbreviations: STQ20: Status Quo 2020 scenario; BSL50: (Business-as-Usual) decarbonized Baseline 2050 scenario; ACE50: Ambitious Circular Economy 2050 scenario; RE50: Reduce 2050 cluster; REU50: Reuse 2050 cluster; REC50: Recover 2050 cluster; UIT50: Usage Intensity 2050 lever; MRE50: Mass reduction 2050 lever; REU50: Reuse 2050 lever; QNT50: Increase quantity of material recovered 2050 lever; QLT50: Enhance quality of recycling 2050 lever

Source: JRC elaboration

6.2.4.2 Sensitivity analysis II: testing methodological aspects

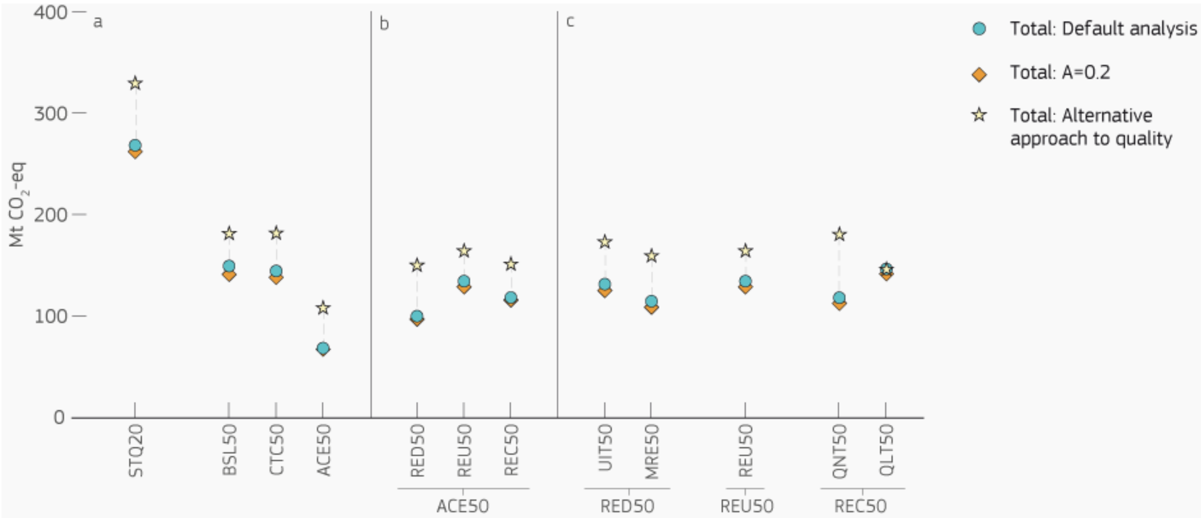
Figure 17 presents the analysis of Climate Change impacts under varying i) A-factor (A=0.2 instead of A=0) and ii) modelling approach to quality (see section 5.1).

Setting A-factor to zero means that the environmental impacts and savings of recycling are fully accounted for at the product's End-of-Life. This directly affects the material substitution calculations within the same life cycle, as all savings and burdens from End-of-Life recycling are recognized immediately and attributed to the product itself. Conversely, an A-factor of 1 assigns all recycling-related environmental impacts and savings to the subsequent production phase, meaning that any impacts/savings from material substitution at the End-of-Life will only be reflected in the subsequent period's accounting (subsequent life cycle). An A factor of 1 is not modelled as it makes hardly sense for scrap for which the market demand is much higher than the supply.

Net emissions across the different A-factor scenarios are mostly consistent, with minor variations stemming from the different treatment of production and End-of-Life impacts. Each lever's emission reduction potential, when compared to the BSL50 scenario, remains similar across the different A-factor scenarios in percentage terms, i.e. the choice of A=0 or A=0.2 does not change the outcome and conclusions of the study.

Applying an alternative approach to model quality significantly affects the results by increasing the GHG emissions in most scenarios. The quality factor applied in the CFF does not account for dilution and, therefore, does not credit emission savings from recycling to the same extent as in the default approach. This leads to an increase in GHG emissions, which can be seen when comparing the GHG emissions in the BSL50 scenario of 182 Mt CO_2-eq compared to 150 Mt CO_2-eq in the default approach. The QLT50 scenario, which employs the 'enhance quality of recycling', does not differ between the default approach and the alternative one, applied in this sensitivity analysis. Since the lever leads to a recycled steel flow of sufficient quality to eliminate the need for dilution, it results in the same quality factor numerically. Since the ACE50 scenario, due to the combination of levers underlying it, requires more dilution proportionally than the BSL50, the GHG savings incurred in ACE50 scenario (impact equal to 109 Mt CO_2-eq. in this sensitivity analysis compared with 69 Mt CO_2-eq. in the default approach) relative to the Baseline (BSL50) scenario are reduced, and now equal 73 Mt CO_2-eq compared with 81 Mt CO_2-eq. in the default approach.

Figure 17. Sensitivity analysis II: testing methodological choices (A factor and approach to quality)



Note: Comparison of the impact of the scenarios assessed on the Climate Change category when applying i) A=0.2 in the CFF (instead of A=0 used in the default analysis) and ii) an alternative approach to model quality in the CFF, which does not consider dilution (which is instead considered in the default analysis); results are expressed as Mt CO_2-eq per entire system annually (year 2050). Abbreviations: STQ20: Status Quo 2020 scenario; BSL50: (Business-as-Usual) decarbonized Baseline 2050 scenario; ACE50: Ambitious Circular Economy 2050 scenario; RE50: Reduce 2050 cluster; REU50: Reuse 2050 cluster; REC50: Recover 2050 cluster; UIT50: Usage Intensity 2050 lever; MRE50: Mass reduction 2050 lever; REU50: Reuse 2050 lever; QNT50: Increase quantity of material recovered 2050 lever; QLT50: Enhance quality of recycling 2050 lever

Source: JRC elaboration

6.2.4.3 Sensitivity analysis III: testing external conditions assumptions

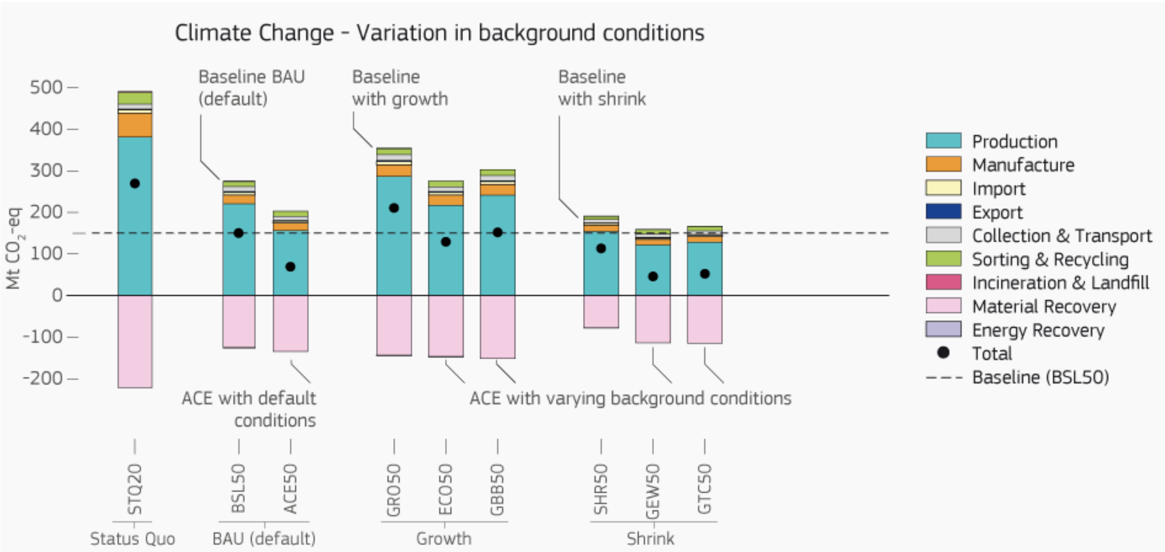
Figure 18 presents the Climate Change impacts, quantified as million tonnes CO_2-equivalent emissions (Mt CO_2-eq) for the entire system, under varying background conditions. Two new Baselines are introduced, i.e. a growth-oriented (GRO50) and a shrink-oriented Baseline (SHR50). For each of these two alternative Baselines, two scenarios are illustrated representing alternative configurations of the economy and society. The levers are implemented under these alternative configurations to derive results for the Ambitious Circular Economy scenario under these changed conditions (i.e. 'eco-state' or ECO50, 'Green Business Boom' or GBB50, 'Glocal eco-world' GEW50, and 'Greening through Crisis' GTC50). The results can then be compared against the ACE50 scenario.

The results show that under a growing economy (growing larger than what assumed in the BSL50 scenario), the impact on Climate Change is expectedly higher than in the BSL50 scenario. Upon implementation of ambitious CE levers, such impact is mitigated (see ECO50 and GBB50). However, this mitigation effect is expected to be much larger under an 'Ecostate'-like scenario rather than a 'Green-Business-Boom' scenario. This reflects the perspectives of experts who consider much less likely an effective implementation of the levers under a 'Business-oriented' societal model.

Under shrinking economy (SHR50) the impact on Climate Change is expectably lower than in the Baseline. Upon the implementation of ambitious CE levers, such impact is further mitigated (see GEW50 and GTC50) and is comparable to what observed in the ACE50 scenario The results also suggest that the Climate Change mitigation obtained in the ACE50 scenario represents a very ideal situation where the levers effectiveness equals 100%. Such mitigation, assuming an effectiveness of the levers well below 100%, is significantly reduced.

Considering the possible variation in background conditions until year 2050 and the effectiveness of the levers implementation, it can be argued that implementing ambitious CE levers can incur GHG savings ranging between 22% and 60% relative to the Status Quo 2020 (STQ20), if this is taken as benchmark for comparison.

Figure 18. Sensitivity analysis III: testing external conditions assumptions



Note: Comparison of the impact of the scenarios assessed on the Climate Change category when applying different background conditions than the Business-as-Usual; results are expressed as Mt CO2-eq for the entire system (year 2050). Abbreviations: STQ20: Status Quo 2020 scenario; BSL50: (Business-as-Usual) decarbonized Baseline 2050 scenario; ACE50: Ambitious Circular Economy 2050 scenario; GRO50: 'growing Baseline' scenario; SHR50: 'shrinking Baseline'; ECO50: 'Eco-state' scenario; GBB50: 'Green Business Boom' scenario; GEW50: 'Glocal eco-world' scenario; GTC50: 'Greening through Crisis' scenario

Source: JRC elaboration

6.2.5 Limitations

The main limitations of the LCA are summarised as follows:

- Future technologies such as hydrogen direct reduced iron (hydrogen-DRI) need to be included for a more accurate quantification of the future annual GHG savings. The current uncertainty on 'green' hydrogen pathway impacts as demonstrated in the recent study by (Hauschild et al., 2025) was the key reason why we left this technology out. The ecoinvent inventory for 'Low-alloyed steel' is used as a proxy for all steel types, upon adjusting the industrial heat (fuel) and electricity energy mix applied as well as process CO_2 emissions following CCS.

- Prospective life cycle inventories were created up to 2050 to represent the evolution of energy carriers supply (electricity, space heat, district heating, industrial heat), including CCS. However, this was not done for chemicals and other materials that are used throughout the steel supply chain. Similarly, we did not create prospective life cycle inventories for heavy transport fuels. This was done on purpose because of the significant uncertainties associated with the impacts from liquid and gaseous fuels, e.g. biofuels.

- We assume that the electricity consumed by steel production equals the EU average market for electricity calculated based on the GECO. Similarly, we assume that all steel production uses the EU average steel industrial heat supply, calculated based on the GECO. It should be kept in mind that this is slightly different in the EEIOA where the composition of the markets for electricity and heat are based on the regional market shares as in FIGARO2015 input-output tables. While the assumption done in the LCA is common practice, the approach taken in the EEIOA is considered a better representation of the current regional markets for these energy carriers. Yet, this may not necessarily well represent future (regional) energy market shares.

- Getting the quality of recycling aspect right in LCA is challenging. The way quality is modelled affects the total magnitude of GHG emissions in each scenario assessed as well as the GHG savings relative to the Baseline. With the two approaches to address quality tested in this study the savings incurred in the ACE50 scenario relative to the Baseline BSL50 scenario vary substantially (zero under the sensitivity analysis and 8 Mt CO_2-eq. under the default approach). Given current industry practices involving dilution of scrap to achieve certain output quality, we consider the result of the default approach as closer to reality. Noteworthy, a quality factor close to one is suggested and used in many peer-reviewed LCA publications on steel scrap recycling.

- The share of imports and exports of material flows are kept constant between 2019 and 2050, since this is what the MFA also assumes. Thus, the CE levers modelled in our study do not affect these shares either.

- With respect to (life cycle) costs, the main limitations is the scarce information on costs for reuse and reduction. We could not apply any meaningful cost to these levers in the LCC, while some macro-assumptions could be taken in the macroeconomic dynamic modelling. As for recycling costs, the main uncertainty regards how enhanced quality of recycling can be achieved. A few studies report data and technology paths for waste sorting and recycling when quality recycling is addressed (Daehn et al., 2019). Clearly, more detailed studies are required. Prices are normalised to EUR 2022 accounting for inflation and are not representative of future 2050 prices.

7 Environmental Extended Input-Output Analysis (EEIOA)

EEIOA, based on FIGARO tables, 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 additional value of this analysis is a better understanding of the spillover effects and selected macro-economic indicators such as Gross Value-Added changes, GDP, employment, resource dependency. However, EEIOA does not consider investments, price change effects, and change in trade patterns. Therefore, GDP and employment are captured via Dynamic Macroeconomic Modelling (section 8).

7.1 Methodology

7.1.1 Introduction

Multi-Region Environmentally Extended Input Output (MREEIO) models show the interdependencies between industries and within and between countries as well as between intermediate and final product producers and consumers. These models provide a useful toolbox for assessing social, environmental, and economy-wide impacts of both goods and services of the transition towards a more circular economy (Wiebe et al., 2019), avoiding a cut-off on (economic) flows. MR EEIO tables have the advantage of tracking the transformation of products at each step along the global supply chain and thus fully capturing material flows across increasingly fragmented international supply chains (Wiebe et al., 2019). The major benefit of the approach is that it considers the interactions between different sectors and final demand of the economy and captures the environmental, social, and economic effects of circularity interventions within a single model.

By incorporating explicit exogenous technological and demand change, it is possible to model direct and indirect effects of demand in a what-if scenario, but not to model the dynamic response of an economy, such as macro-economic price changes or systemic rebound effects (Wiebe et al., 2019), which will be assessed later using a different model (FIDELIO). The use of expert-knowledge in the form of exogenous assumptions (e.g., based on material flow analysis in Section 4.2) is considered superior to relying on formal methods to represent behaviours that make technological change endogenous (Wiebe et al., 2018) due to its transparency (Donati et al., 2020). This approach gives the modeller a maximum degree of freedom, but also the responsibility of ensuring that the changes implemented are consistent in both a mathematical and a contextual way. It requires that any induced or rebound effects need to be exogenously included in the model, to make sure it is included in the modelling results. Induced effects refer to secondary economic effects resulting from changes in spending or investments patterns caused by an initial change in economic activity. 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 refers to unintended environmental impacts that occur because of circular economy interventions (Zink & Geyer, 2017).

Modelling CE interventions in an MREEIO framework must be understood as a comparison between a Baseline (e.g. Status Quo or its projection in the future) and a result in which the what-if scenario is achieved (results from the adjusted model, whether (or not) from the prospective IO-tables). The net effect of circularity interventions can be quantified by the difference between the two (i.e. BSL and the ACE scenario) calculation results. The net impact is assumed to represent a measure of the potential effect of a specific circularity scenario (Aguilar-Hernandez et al., 2018).

Exogenous changes can be applied either in the supply and use tables (e.g. Aguilar-Hernandez et al., 2018; Wiebe et al., 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 table system and to ensure the monetary balance is kept. An IO table is generated from these supply and use tables to allow for typical IO analysis.

Aguilar-Hernandez et al. (2018) show, based on a literature review, that IO models are suitable to assess the effects of incorporating circularity interventions by adjusting final demand and technology coefficients (e.g. interindustry relations, factor inputs (e.g. labour and capital), and environmental/social intensity coefficients), although several restrictions are mentioned (see below). Based on the review, a causality sequence of adapting scenarios is deduced for residual waste management, closing supply chains, product lifetime extension (including repair and reuse), and resource efficiency (reducing material input/consumption). Primary sequence refers to the first element of an IO model that can be adapted to represent the implementation of a circularity intervention. Following a causality chain, the secondary sequence denotes the first order of indirect impacts in response to the primary stimulus. A schematic representation if provided with varying, but not quantified, effects.

Literature focussing on (MR) EEIO suggest the use of hybrid units and/or waste accounts to extend the model. The monetary values of IO tables do not effectively address the allocation of resource and waste flows because the monetary values per physical unit can differ significantly in several supply chains (Aguilar-Hernandez et al., 2018). The variation is caused by the assumption of an average (annual) price for materials with diverse physical properties and qualities. Via the direct link between the MFA and the IO analysis, we suggest not to make use of hybrid units and/or waste accounts to extend the model. A lack of data hampers a detailed modelling in hybrid units and/or waste accounts (Aguilar-Hernandez et al., 2018). In our methodological approach, a first assessment of the levers is already simulated in a detailed MFA-model using a mass balance to understand effects across the production network.

Adequately tracking of specific material flows is hampered by aggregated models, for example due to heterogeneity and price variations. Highly aggregated IO tables are too limited to model specific material flows (Aguilar-Hernandez et al., 2018). IO tables in hybrid units (e.g. tangible products, energy and waste in physical units and services in monetary units) and detailed production data (e.g. disaggregation of sectors) would improve IO models for assessing the economic and environmental implications of a circularity transition (Aguilar-Hernandez et al., 2018). 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. Life-cycle inventory data can be used to disaggregate the inputs into the primary vs the secondary industry. The coefficients of the two industries are kept equal for most categories, however, modifications are made to adjust to primary and secondary production for the most important coefficients (at least energy inputs, material input, and emission data). Estimate of the market share of primary versus secondary production are often taken from available statistics. Note that it is important to assume that the output of both sectors, in terms of processed material, is equal (and substitutable) (Wiebe et al., 2019).

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). To provide a forward-looking analysis of policy impacts, it is necessary to projecting IO tables into the future (i.e.

prospective IO tables) (Wiebe et al., 2018). The assessment of prospective impacts relies on exogenous scenarios. Potential choices are the short-term forecasts of the International Monetary Fund (IMF), long-term scenarios in the International Panel on Climate Change (IPCC) database and forecasts of the International Energy Agency (IEA) and the Global Energy and Climate Outlook (GECO). While there is a variety of options, the GECO was identified as most suitable 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 CGE model GEM-E3 for 31 industries that can be used for calibration. Due to its comparatively high level of detail for key variables, the IO structure in the GECO 2022 Baseline[30] allows a closer calibration of the FIGAROe3 tables until 2050.

The monetary tables are supplemented with extension tables covering the environmental and socio-economic impacts. These tables contain data on environmental stressors (e.g. CO_2-emissions) or social data (e.g. employment) per sector and per geographical area in the model.

7.1.2 Selection of the project input-output model

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 as in section 6.1). The following models are considered:

- **FIGARO** (the 2024 FIGARO edition)[31]: The EU inter-country supply, use and input-output tables (developed by Eurostat and the JRC) are part of official EU statistics (2000-2022 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

[30] https://data.jrc.ec.europa.eu/collection/id-00132

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

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.

- **FIGAROe3**[32] (Cazcarro et al., 2025) 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**[33]: 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[34] as well as employment. Hybrid versions and country extended versions of EXIOBASE (EXIOBASE3rx[35]) exist as well.
- **OECD harmonised national Input-Output Tables (OECD IOT tables)**[36]: 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 study. FIGARO has the drawback of the limited sector disaggregation, while FIGAROe3 is currently only available for the year 2015. **Our preference goes to the use of FIGAROe3 model, as it is best to address the needs of this project.** 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. EXIOBASE is the culmination

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

[33] 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

[34] Correspondence tables are found here and here.

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

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

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 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.

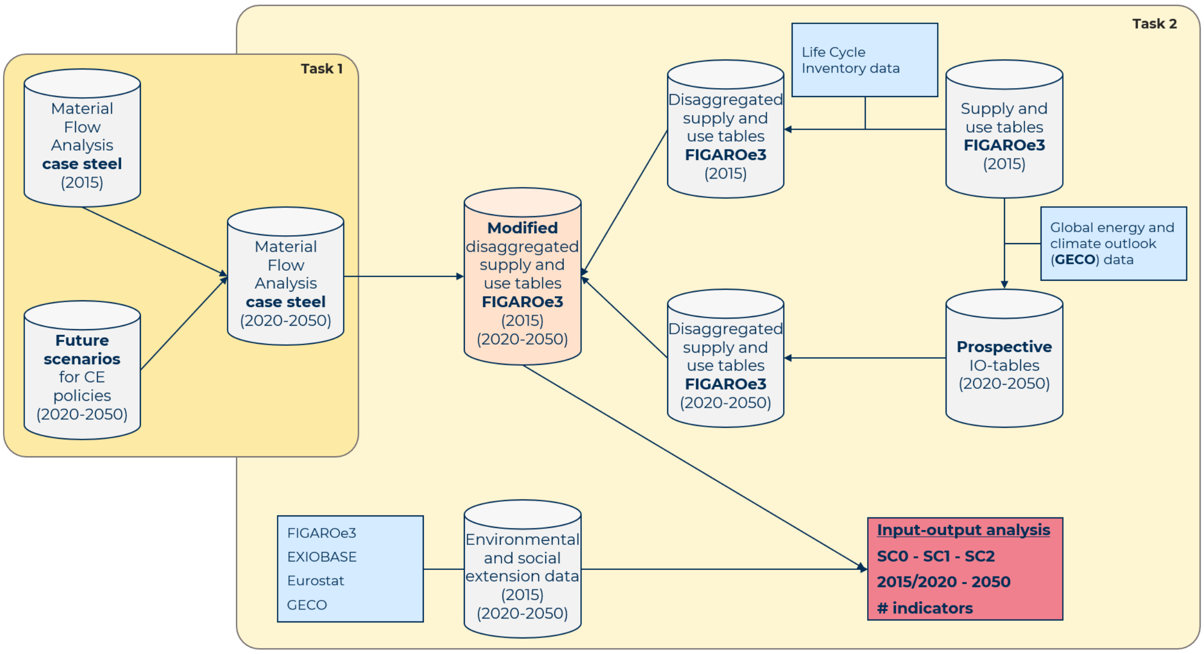
- **The selected model will be expanded to include dynamic analysis. The pre-existence of such a link is a plus:** There is a link between FIGARO (and FIGAROe3) and the dynamic econometric IO model FIDELIO. No link with a dynamic model is available for EXIOBASE or the OECD IOT tables.

7.1.3 Methodology from MFA to IOA

The workflow is visualised in Figure 19, and is supported by Excel-files and an implementation in R. An application of the methodology and more details on the individual steps is elaborated in Annex 5. Model scripts and data files are available upon request.

The workflow builds upon the bottom-up assessments. It directly makes use of the material flows and stocks as determined in the material flow analysis. 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.

Figure 19. Workflow from Material Flow Analysis to (prospective) Input-Output Analysis. SC: generic scenario



Source: JRC elaboration

7.1.3.1 FIGAROe3

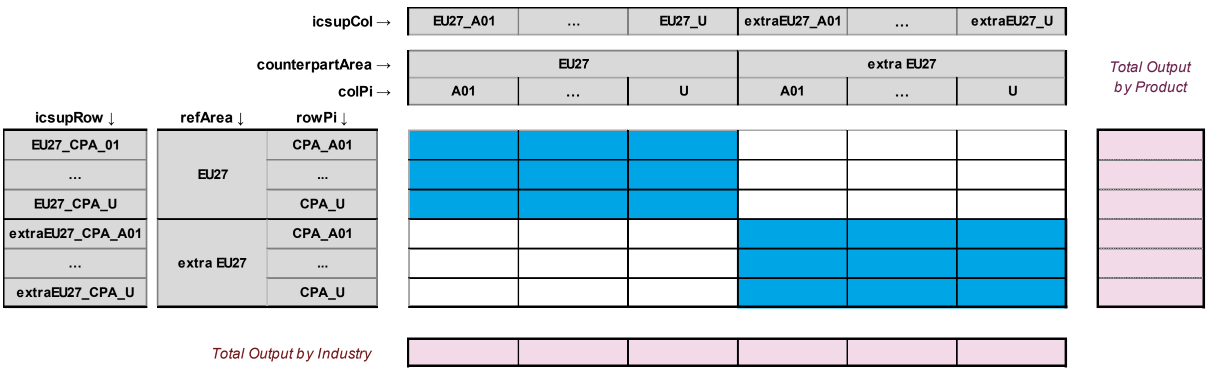
The monetary supply and use tables from the FIGAROe3 model cover 45 geographical areas plus one rest-of-the-world (FIGW1) region. Per region the model details 213 products and 176 industries. Labour accounts detail total employment and employment broken down by gender and skill level. Energy accounts 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 20) 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 20. Schematic presentation of an inter-country supply table, detailing two geographical areas (EU27 and non-EU27). Source: Figure based on FIGARO description tables



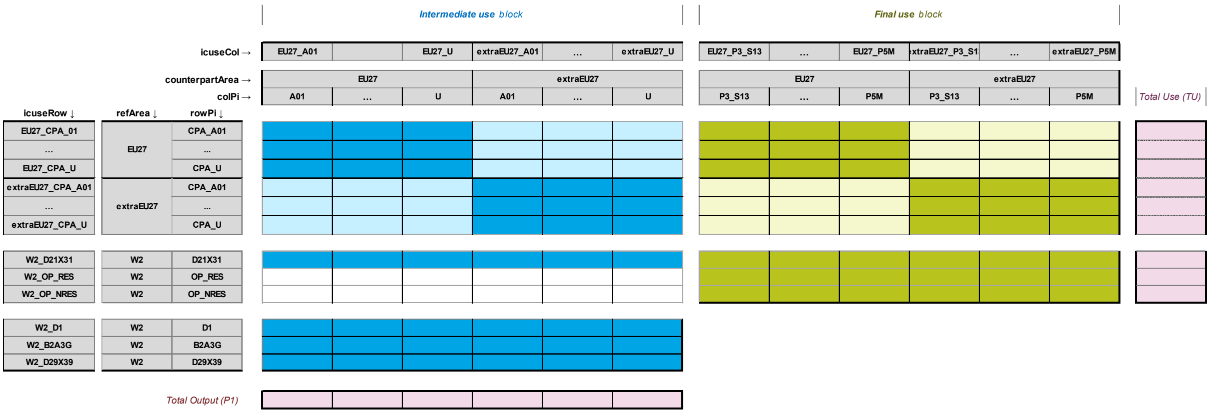
Source: JRC elaboration

An **inter-country use table** (matrix representation shown in Figure 21) 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 21. Schematic presentation of an inter-country use table, detailing two geographical areas (EU27 and non-EU27). Source: Figure based on FIGARO description tables



Source: JRC elaboration

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[37] (Eurostat and European Commission, 2019). The FIGAROe3 database is downloaded from the Joint Research Centre Data Catalogue[38]. This includes the download of the inter-country supply and use matrices (Table 11).

Table 11. 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

Note: please make sure the values are correctly read by the software of choice (Excel, R, others). 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).

[37] https://data.europa.eu/doi/10.2785/385561

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

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[39]: 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).

7.1.3.2 Sector and product disaggregation

Adequately tracking of specific material flows is hampered by aggregated models, for example due to heterogeneity and price variations. Highly aggregated IO tables are too limited to model specific material flows (Aguilar-Hernandez et al., 2018). A disaggregation of products and/or sectors in supply and use tables and/or IO tables in more detailed categories provides a solution to overcome to aggregation error.

Life-cycle inventory data can be used to disaggregate the inputs into the primary vs the secondary industry. The coefficients of the two industries are kept equal for most categories; however, modifications are made to adjust to primary and secondary production for the most important coefficients (at least energy inputs, material input, and emission data). Estimate of the market share of primary versus secondary production are often taken from available statistics. Note that it is important to assume that the output of both sectors, in terms of processed material, is equal (and substitutable) (Wiebe et al., 2019).

7.1.3.3 Extension tables – Environmental Footprint

The Environmental Footprint (EF) method includes 16 impact categories of the environmental footprint method (Annex 7). 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

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

environment. Beylot et al. (2019) 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 (Sanye-Mengual & Sala, 2023).

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.

Text box 2. Extract from Beylot et al. (2019).

Characterization factors for an Environmental Footprint estimate via input-output analyses (Beylot et al., 2019)**:**
Firstly, when it was not possible to match one EXIOBASE extension to a flow in EF2017, a proxy Characterization 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 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. Toxic and ecotoxic 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[40], acidifying gases[41], and ozone precursors[42].

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).

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

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

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

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[43]. 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[44] (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 12. Data download for environmental extensions

Name	Data provider	Type	Last update	Unit
Air Emissions Accounts Matrix (Gg)	FIGAROe3 by JRC	CSV-file	27/02/2024	Gg
F and Fhh from the file IOT_2015_ixi.zip\ satellite	EXIOBASE v3.8.2 by Stadler et al. (2021)[45]	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

7.1.3.4 Extension tables – Financial costs

The extension tables of FIGAROe3 show the generation of value added per sector, disaggregated into 9 categories (Figure 22).

Figure 22. Details on the value-added extension table. Source: FIGAROe3

[43] 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

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

[45] 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

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: JRC elaboration.

7.1.3.5 Extension tables – 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 23).

Figure 23. Details on the employment extension table. Source: FIGAROe3

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: JRC elaboration

7.1.3.6 Extension tables – 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 24. These extension data is available from the EXIOBASE extension tables.

Figure 24. 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: JRC elaboration from 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.

7.1.3.7 Prospective 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 focussing 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 2023 Reference scenario. The GECO 2023 Reference scenario (Baseline) represents a projection of the world economy with corresponding energy demand and greenhouse gas (GHG) emissions. The IO tables are supplemented by energy balances (in physical units) and GHG emissions projections. The database also 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.

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

From the GECO 2023 only the Multi-Regional Input-Output tables for the GECO Reference scenario are available (consisting in the Baseline scenario of the JRC-GEM-E3 model). To align with the NDC-LTS scenario multiple datapoint from GECO 2023 are used to adapt the FIGe3 supply and use tables to reflect future changes following the GECO 2023 NDC-LTS scenario.

First, the IO tables from GECO 2023 (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 2023. 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 2023 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 2023 NDC-LTS scenario (produced with the GEM-E3 and POLES-JRC model[46]). 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 2023 Reference scenario and including the specific data on the GECO 2023 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

[46] Both POLES and GEM-E3 models are used to produce the numbers published under the GECO umbrella, but they are two very different models. POLES is an energy system model and produces the energy and emissions projections; GEM-E3 is based on a MRIO structure and produces the IO tables, which are adjusted to POLES indicators.

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.

7.1.3.8 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:

$$x = A \cdot x + y \qquad \text{Equation 2}$$

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:

$$x = (I - A)^{-1} \cdot y = L \cdot y \qquad \text{Equation 3}$$

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, and 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:

$$E^T = \sum_1^n E_t = \sum_1^n e_t^{int} = \langle e^{int} \rangle \cdot x \qquad \text{Equation 4}$$

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:

$$E^T = \langle e^{int} \rangle \cdot x = \langle e^{int} \rangle \cdot (I - A)^{-1} \cdot y \qquad \text{Equation 5}$$

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 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:

$$E_{ind}^T + E_{dir}^T = \langle e^{int} \rangle . x + E_{dir}^T = \langle e^{int} \rangle . (I - A)^{-1} . y + E_{dir}^T \qquad \text{Equation 6}$$

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 cased 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

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 use covers 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 (i.e. it results in a single value output, per each impact category considered). It is the total impacts (direct and indirect) related to 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 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 the triggers thereof. Due to the large resolution of this matrix, this output is not preferred.

The final demand vector y can be limited to the demand of a single country or region or can capture the full global final demand. In case global final demand in chosen, the complete (global) effects of any (local) changes in the supply and/or use tables are captured. From a global footprint perspective, all changes in the upstream supply networks are included. From a regional footprint perspective (e.g., EU-27), part of the effect of changes applied to supply/use framework will not show up due to extra-EU trade. For example, changes applied to the EU-27 steel industries will affect the EU footprint, but also the non-EU footprint due to extra-EU27 exports of intermediate and finished steel products ending up in non-EU-27 final demand. The more open a sector or material market is, the more an effect of any local changes are attributed to final demand elsewhere.

7.2 Results

This section presents the results of the EEIOA for the impact category Climate Change and for resource dependency (e.g. for iron ore and other metals), employment and value added. A summary of the remaining environmental impact categories may be consulted in Annex 6. The results are presented relative to the Baseline 2050 scenario as reference of comparison (the Status Quo 2020 is also presented as additional information). The difference between the BSL50 and the CTC50 scenario is to be understood as the additional effects obtained from implementing the selected CE policy targets (as considered in the CTC50 scenario); the difference between the BSL50 and the ACE50 scenario is to be interpreted as the additional effects incurred by the full-fledge implementation of the CE levers (as investigated in the ACE50 scenario). While the assessment was primarily conducted on the CE levers not involving changes in final consumer behaviour, the results including consumption driven levers are reported in Annex 6.

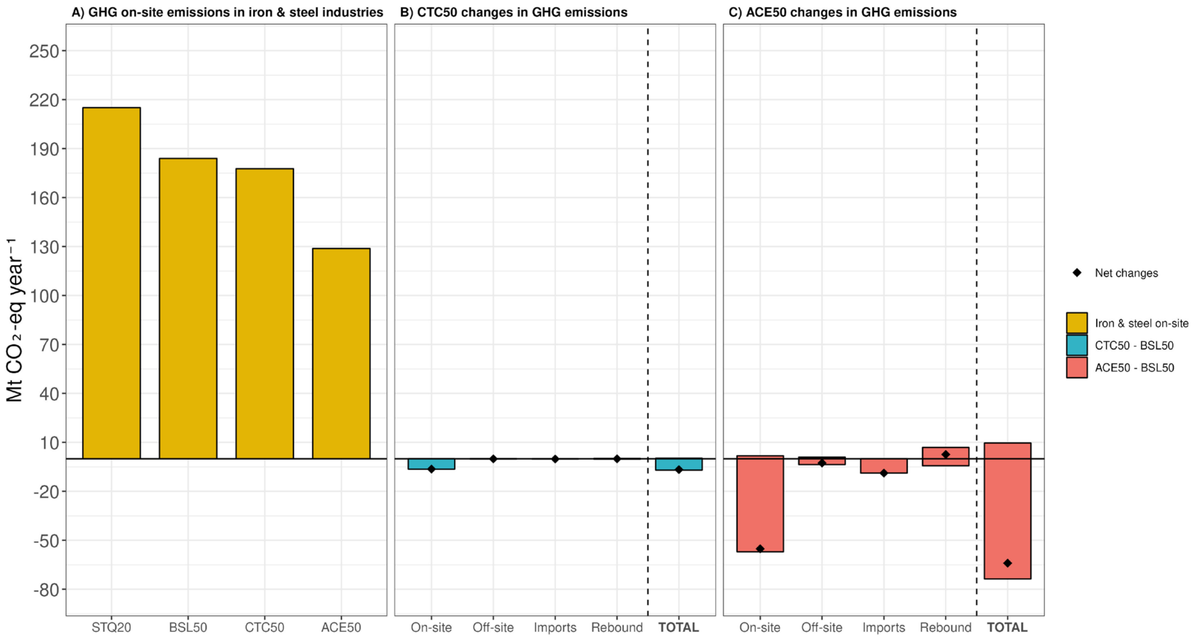
7.2.1 Climate Change mitigation

Figure 25 presents the Climate Change impacts of four scenarios: Status Quo (STQ20), Baseline (BSL50), Compliance with selected Targets on Circular economy (CTC50), and the Ambitious Circular Economy (ACE50) scenario, measured in million tonnes of CO_2 equivalent (Mt CO_2-eq.). The left-side of Figure 25 (Panel A) shows the on-site emissions in the steel industry for each scenario. In the STQ20 scenario, emissions total 215 Mt CO_2-eq., which decrease by 31 Mt CO_2-eq. to 184 Mt CO_2-eq. in the BSL50 scenario due to structural changes associated with the energy transition. The implementation of the selected circular economy targets in the CTC50 scenario leads to a reduction in on-site emissions of 6.3 Mt CO_2-eq. In contrast, the ACE50 scenario results in a more pronounced total reduction of 55 Mt CO_2-eq, accounting for 30% of all on-site GHG emissions in the BSL50 scenario for the EU steel industries.

On the other hand, the right-side of Figure 25 displays the difference in GHG emissions between the CTC50 and the BSL50 scenarios (Panel B), and the difference in GHG emissions between the ACE50 and the BSL50 scenarios (Panel C), 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' emissions refer to direct emissions occurring at steel industries in the EU to satisfy the EU and Rest-of-the-World (RoW)'s final demand of goods and services; 'Off-site' refers to emissions from all other EU industries to satisfy the EU and RoW's demand, specifically, it represents upstream GHG emissions in the steel supply chain occurring in industries located in the EU and providing inputs to the EU steel industries; 'Imports' refers 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 steel products that are being replaced by non-EU exporters for satisfying RoW demand (which remains constant across scenarios); and, 'TOTAL' refers to the sum of 'On-site', 'Off-site', 'Imports', and 'Rebound' GHG emissions.

As shown in Figure 25, 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. In the CTC50 scenario, the implementation of current circular economy policies yields small savings compared to the industry totals, resulting in a total net reduction of 6.7 Mt CO_2-eq, 95% of it occurring in the EU steel industries. In contrast, the ACE50 scenario achieves a more substantial reduction, with a total net reduction of 64 Mt CO_2-eq., equivalent to 35% of all on-site emissions. Notably, reductions in this scenario are primarily driven by the decline in on-site emissions, which accounts for 86% of the net reductions of the total (55 Mt CO2-eq, as mentioned earlier). Additionally, reduced imports of inputs and steel products contribute 8.8 Mt CO_2-eq. to the net reductions, equivalent to 14% of the total. Furthermore, emissions reductions in the upstream supply chain within the EU yield an additional 4.1 Mt CO_2-eq. in net savings. However, the net savings from these three components are partially offset by the replacement of demand outside the EU, resulting in a net emission increase of 2.6 Mt CO_2-eq. If these rebound emissions were not accounted for, as is the case with the LCA method applied earlier, the total net savings of the ACE50 scenario relative to the Baseline BSL50 scenario would be approx. 67 Mt CO_2-eq.

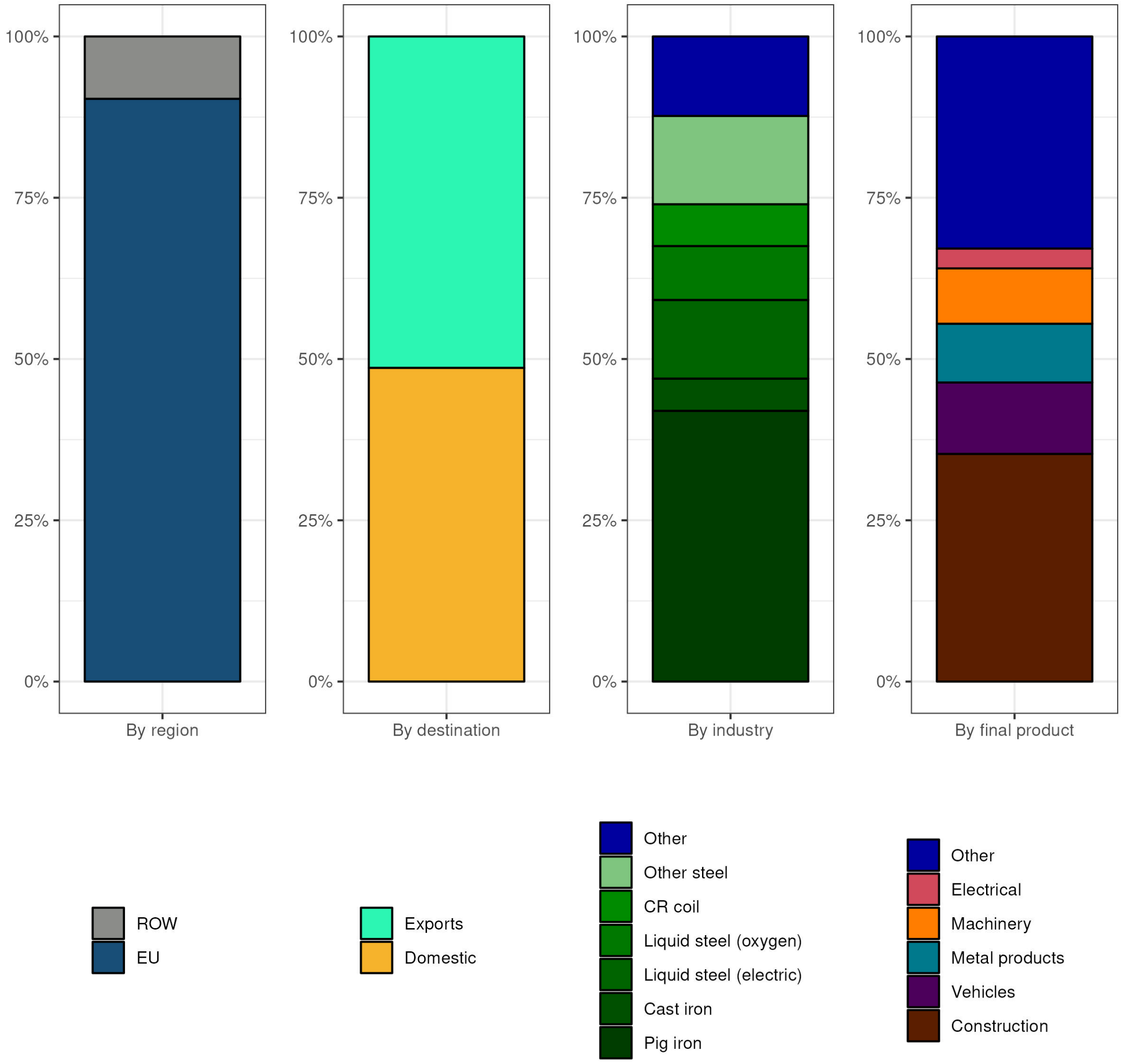
Figure 25. On-site GHG emissions of the EU steel industry for the Status Quo (STQ20), Baseline (BSL50), Compliance (CTC50) and Ambitious Circular Economy (ACE50) scenarios (Panel A), and changes between the Compliance and Baseline scenarios (CTC50-BSL50), and between the Ambitious Circular Economy and Baseline scenarios (ACE50-BSL50) for the EU on-site and off-site emissions, emissions from producing EU imports, rebound emissions abroad, and net savings (Panel B) in million tonnes CO_2-eq. per year (2050)



Note: Panel A) displays the on-site GHG emissions of the EU steel industry for the Status Quo (STQ20), 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 steel 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 steel 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 26. 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 3% are shown individually

Source: JRC elaboration

Figure **26** provides insight into the origin region, destination, industry, and final product driving the total net reduction of ca. 64 Mt CO_2-eq. between BSL50 and ACE50 scenario. The data reveals that most of the impact (90%) occurs within the EU, with only 10% of the savings occurring abroad. Approximately half of the savings are driven by EU final use of products, whereas the other half relates to EU exports to the world. Furthermore, the main activities contributing to these savings occur in the production of steel products, accounting for 88% of the total reduction. The decomposition by final product shows that the construction sector is the primary driver of these changes, responsible for 35% of the total savings, followed by Manufacture of motor vehicles, trailers and semi-trailers ('Vehicles') with 11%, Manufacture of fabricated metal products, except machinery and equipment ('Metal products') with 9%, Manufacture of machinery and equipment n.e.c. ('Machinery') with nearly 9%, and 3% of Manufacture of electrical equipment ('Electrical'). 33% of the savings are attributed to final products, which account for less than 3% of the total reduction, suggesting that steel is a common component in many consumer products.

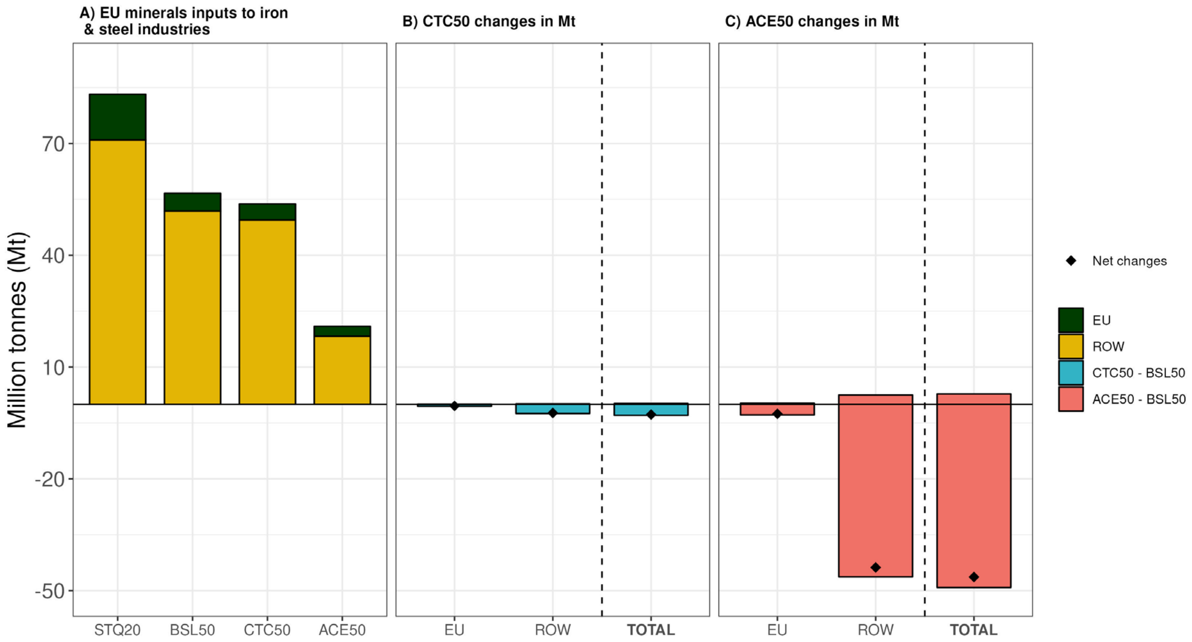
7.2.2 Resource dependency

The EEIOA provides results on the amount of iron and other (critical) raw materials extracted in the different scenarios, i.e. information on the changes in input requirements for the EU steel industry (expressed as Mt), as well as insights on whether the iron ore and other minerals is EU- or RoW-sourced. We use these results to discuss 'Resource dependency' for the EU in this section.

Figure 27 the strategic minerals and iron ore requirements of STQ20, BSL50, CTC50, and ACE50 scenarios, measured in million tonnes. The left-hand side chart (Panel A) shows the total strategic minerals and iron ore requirements of the steel industries for each scenario. In the STQ20 scenario, minerals requirements total 83.2 Mt, which decreases by 32% to 56.6 Mt in the BSL50 scenario. In this scenario, as well as the Compliance scenario, EU extractions satisfy 8% of the total strategic minerals requirements of the steel industry (in yellow), with 92% supplied by the ROW. This share, representing EU dependency on foreign countries, improves by nearly 5 percentage points in the ACE50 scenario.

Likewise the Climate change results, Figure 27 shows the changes in direct and indirect strategic minerals and iron ore requirements along the whole supply chains in the CTC50 (Panel B) and ACE50 (Panel C) scenarios in comparison to the BSL50 scenario. The implementation of current CE policies in the CTC50 scenario leads to small savings of 2.8 Mt, which represents 5% of all Baseline requirements in the steel industry. In contrast, the ACE50 scenario leads to a pronounced reduction, with a total net reduction of 46.3 Mt, which represents 82% of Baseline requirements in 2050. The reduction in ACE50 scenario was decomposed into two components: EU and ROW. Here, it can be observed that net reductions occur primarily in the ROW, which explains 95% of the net savings. In this case, and in contrast to the example of Climate Change, rebound effects due to the replacement of demand outside the EU were not taken into consideration, since the focus is on EU material dependencies.

Figure 27. Strategic minerals and iron ore requirements of the EU steel industry and changes in requirements for the CTC50 and the ACE50 scenarios compared to the BSL50 scenario

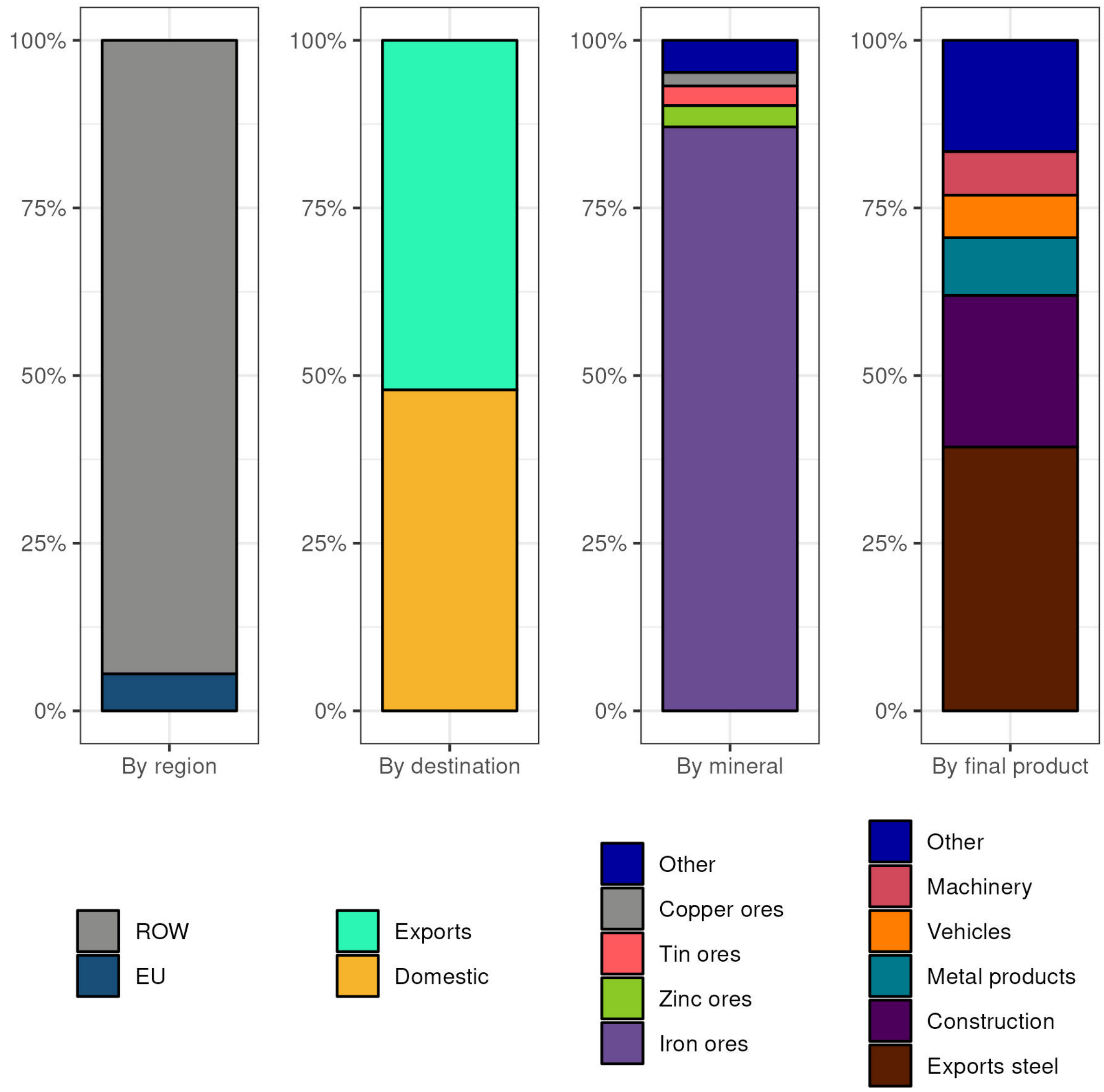


Note: Panel A) displays the mineral requirements in the EU steel industry in the Status Quo (STQ20), Baseline (BSL50), Compliance with selected Targets on Circular economy (CTC50), and Ambitious Circular Economy (ACE50) scenarios; Panel B) displays the changes in extractions between the CTC50 and the BSL50 scenarios; Panel C) displays the changes in extractions between the ACE50 and the BSL50 scenarios. 'EU' refers to the extraction of minerals within the EU, 'ROW' refers to the extraction of minerals within the Rest-of-the-World, 'TOTAL' refers to the sum of 'EU' and 'ROW'. Notice that '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 million tonnes

Source: JRC elaboration

Figure 28 provides information on the origin, destination, final product, and mineral type driving the total net reduction of 32 Mt between BSL50 and ACE50 scenarios. The data shows that 48% of this reduction is attributed to EU domestic consumption while 52% of the reduction is due to lower EU exports of steel products. Beyond exports, the construction sector is the primary driver of these changes, accounting for 23% of the total savings. This is followed by Manufacture of fabricated metal products, except machinery and equipment ('Metal products'), which accounts for 9%, Manufacture of machinery and equipment n.e.c. ('Machinery') with 7%, and Manufacture of motor vehicles, trailers, and semi-trailers ('Vehicles') with 6%. Not surprisingly, most of the savings are related to iron ore, which represents 87% of the total savings, followed by zinc and tin ores with 3% each one, and copper ores with 2%.

Figure 28. Decomposition of the changes in mineral requirements to the EU steel industry between the ACE50 and the BSL50 scenario



Note: Changes between the Ambitious Circular Economy and Baseline scenarios (ACE50-BSL50) for the net savings as percentage of origin region (EU vs. ROW), destination (domestic consumption vs. exports to the world), final product, and mineral type

Source: JRC elaboration

Table 13 provides further details on raw material extractions by mineral type, showing total volumes in relation to total EU requirements (in the Baseline in 2050, i.e. BSL50). It can be observed that the reduction in iron ore accounts for 22% of total iron ore requirements in the Baseline, while two minerals exceed 5% of total requirements: tin ore and zinc ore, which account for 9% and 6%, respectively.

Table 13. EU requirements of strategic minerals and iron ore, and net savings in ACE50 scenario

Mineral ore	Total requirements (BSL50) in kt	Savings in ACE50 in kt	Net savings in %
Iron ores	179,833	-40,348	-22%
Tin ores	15,422	-1,354	-9%
Zinc ores	25,875	-1,482	-6%
Other non-ferrous metal ores	10,409	-557	-5%
Lead ores	7,261	-334	-5%
Nickel ores	16,066	-638	-4%
Gold ores	2,401	-73	-3%
Bauxite and aluminium ores	19,504	-511	-3%
PGM ores	26	-1	-2%
Silver ores	4,692	-101	-2%

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 14 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 15 focuses on changes in the energy inputs to steel industries. The results suggest that circular economy policies have an impact on reducing energy dependencies, with the greatest impact observed on coal supply.

Table 14. Changes in selected products demand in ACE50 in comparison to BSL50 scenario for the total EU economy

Selected product	Quantity reduced	Unit	% total economy
EU electricity production	-12,424	GWh	-2%
EU heat production	-2,953	TJ	-0.3%
Coal and lignite, extraction of peat	-187,509	TJ	-6%
Crude petroleum	-295,324	TJ	-3%
Natural gas	-234,298	TJ	-2%
Other fossil fuels	-9,993	TJ	-0.1%

Source: JRC elaboration

Table 15. Changes in selected products demand in ACE50 in comparison to BSL50 scenario for the steel industries

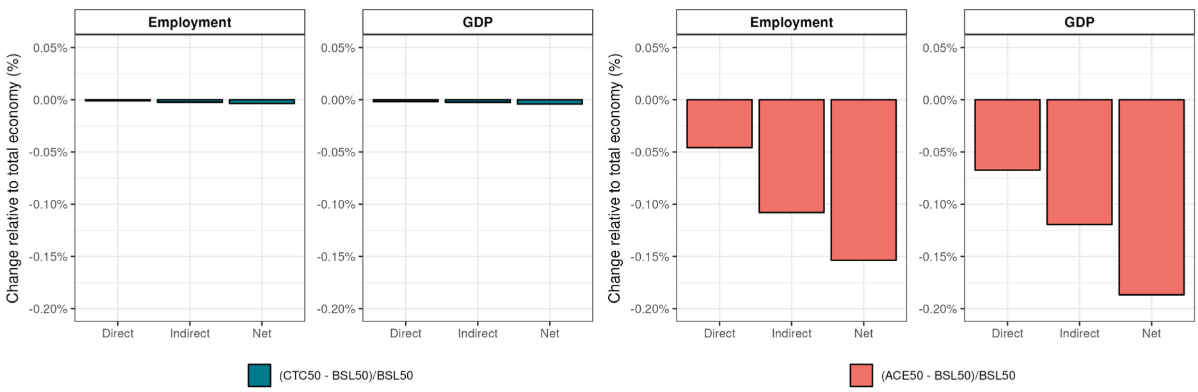
Selected product	Quantity reduced	Unit	% total purchases
EU electricity production	-11,226	GWh	-36%
EU heat production	-28	TJ	-7%
Coal and lignite, extraction of peat	-153,490	TJ	-38%
Crude petroleum	-4,335	TJ	-15%
Natural gas	-77,040	TJ	-22%
Other fossil fuels	-281	TJ	-64%

Source: JRC elaboration

7.2.3 Employment and value added

Figure 29 provides information on the re-allocation of employment and GDP between the Compliance with selected Targets on Circular economy and Baseline scenarios (CTC50-BSL50) and between the Ambitious Circular Economy and Baseline scenarios (ACE50-BSL50). As expected, at the macro level, the CTC50 scenario has a negligible impact on both variables. In contrast, the ACE50 scenario shows a significant impact, with lower production in the steel industry leading to a decrease of 0.05% of total employment projected to 2050. This decrease represents approximately 24% of the jobs in the steel industry. However, the decrease in the upstream supply chain appears more substantial, resulting in a decrease of 0.11%. The decrease in GDP terms is even larger, accounting for 0.07% of the projected figures for 2050 in the steel industries, and 0.12% in the supply chain. The resulting net effects at EU macro-level are a reduction of 0.15% in employment and 0.19% in GDP.

Figure 29. Changes in % of employment and GDP between the Compliance and Baseline scenarios (CTC50-BSL50) (left), and between the Ambitious Circular Economy and Baseline scenarios (ACE50-BSL50) (right) for direct jobs and GDP contribution in the EU steel industry, indirect jobs/GDP in other industries in the supply chain, and net changes relative to the total EU economy



Source: JRC elaboration

7.2.4 Other environmental impacts

Annex 6 reports the results for the remaining environmental impact categories assessed via EEIOA. All in all, the ACE50 shows reductions relative to BSL50 and CTC50 scenarios in all impact categories.

7.2.5 Limitations

The main limitations of the EEIOA are summarised as follows:

- Addressing quality of recycling is complex in EEIOA. Therefore, this CE lever was not specifically incorporated in the EEIOA, which partly explains the different results compared with the LCA.
- The spill-over effects accounted for in EEIOA are only the so-called first round spill-over, i.e. inter-industry and inter-regions effects. For example, a decrease in export of steel products from the EU because of reduced production incurs the effect that foreign demands need to be fulfilled with non-EU suppliers, which may be more impactful than the EU.
- The analysis was conducted statically performing a single shock on the EU economy which includes the full-fledge effect of the CE levers studied. A dynamic analysis, e.g. with a 5y time-interval, is possible as the Material Flow Analysis provides the flows from 2025 to 2050 (Supplementary Material; available upon request) but requires intensive computational effort. For this reason, it was not performed.
- The way the GECO based energy system was implemented in the EEIOA differs from the implementation in the LCA. The decarbonization was modelled starting from the current energy mix used by the EU and global steel sector in Figaroe3 IO tables for electricity and industrial heat. The individual contributions to the electricity and industrial fuel mix (e.g. coal, natural gas, biomass, etc.) were projected up to 2050 based on the decreases or increases reported by the GECO for each EU (same for RoW countries) industry sector, also considering regional differences. This is different from the LCA were an average EU mix (industrial heat used in the steel industries as well as electricity use) was assumed for the entire EU steel sector.

8 Dynamic macro-economic modelling

The transition from a linear to a CE redefines the complex interactions of economic systems. 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 4), LCA and LCC (Section 6), EEIOA (Section 7) and dynamic macro-economic modelling. The Fully Inter-Country Dynamic Econometric Long-Term Input-Output model (FIDELIO) developed by the JRC is applied to add to the insights of the other methods.

In this section an overview over dynamic modelling approaches is given, before the implementation of CE scenarios in the model FIDELIO is described.

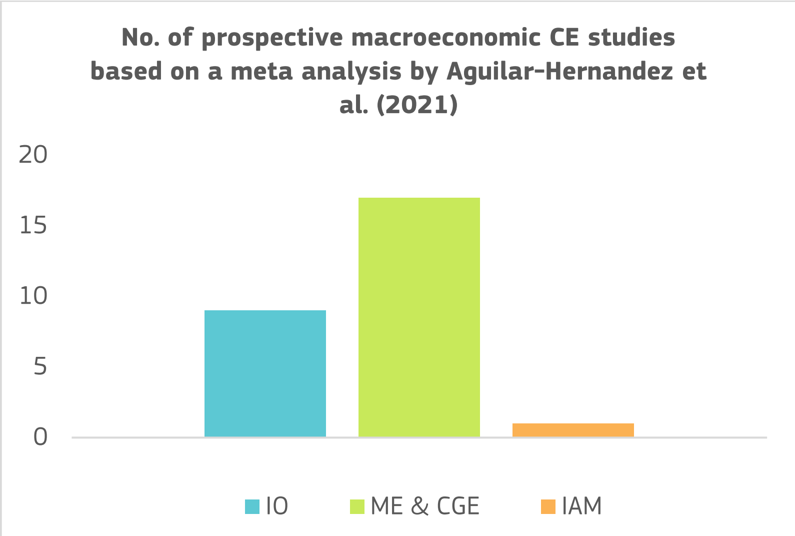
8.1 Methodology

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 Input-Output Analysis (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 on CE are centered on dynamic approaches such as macroeconometric analysis (ME), computable general equilibrium (CGE) models and integrated assessment models (IAM) as shown in Figure 30. 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) but 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-optimizing behaviors (Böhringer & Rutherford, 2015). On the supply side, constant elasticities of substitution 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). The authors found that the economic sectors included in CGE models applied for CE research differed between 15 and 40 sectors.

Figure 30. Overview over prospective macroeconomic CE studies



Note: CGE: Compute General Equilibrium; ME: Macroeconomic; IAM: Integrated Assessment Model. Io: Input-Output

Source: JRC elaboration, based on data from Aguilar-Hernandez et al. (2021)

While CGE models build on a micro foundation rooted in neoclassical equilibrium theory, macro econometric 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 macro econometric 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 consumers, thus final demand (Zink & Geyer, 2017). The quantification of rebound effects is often omitted in CE impact assessments using IOA or LCA (Donati et al., 2020; Wiebe et al., 2019) but can be assessed using dynamic models.

8.1.1 FIDELIO: Model description

FIDELIO is a global demand-driven dynamic macroeconomic model that combines elements of Input-Output Analysis, macro econometric 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. Based on FIGAROe3, 'Electricity, gas, steam and air conditioning supply' can be 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-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. The modules are briefly described here. A detailed description of FIDELIO 4, including all equations, will be available in the forthcoming model documentation (the reader may also refer to the v3 in Rocchi et al., 2019).

8.1.2 FIDELIO: Modelling approach

The modelling approach is divided into two parts. First, the processing of shocks derived from the bottom-up model for FIDELIO. Second, the implementation of the BSL50, CTC50 and ACE50 scenarios in FIDELIO. Using all FIDELIO modules was beyond the scope of this study. It is therefore limited to the full FIDELIO model for the most comprehensive representation of economic interactions.

8.1.2.1 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 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 in FIDELIO.
- **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. basic plastics) still represent only a fraction of a broader sector in FIDELIO (e.g. chemicals and chemical products), 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.

- **Temporal:** This study is part of the ReCalibrateCE project where in addition to the case study on steel, the materials aluminium, cement and plastics are analysed using the same methodological approach. While the MFA for steel provides annual results until 2050, data from the bottom-up MFA/LCA models used for the other materials are available only for the Status Quo and 2050. To implement the bottom-up scenarios from the MFA/LCA model, an interpolation of the CE lever introduction is necessary. For intercomparability of the case studies results, a similar approach is applied for the case study on steel. The implementation of the CE levers thereby starts in 2030 and reaches full implementation by 2050 using an S-shaped logistic growth function. This function is commonly used to model diffusion processes and starts with exponential growth, which slows down until a saturation point is reached (Sterman, 2000).

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.

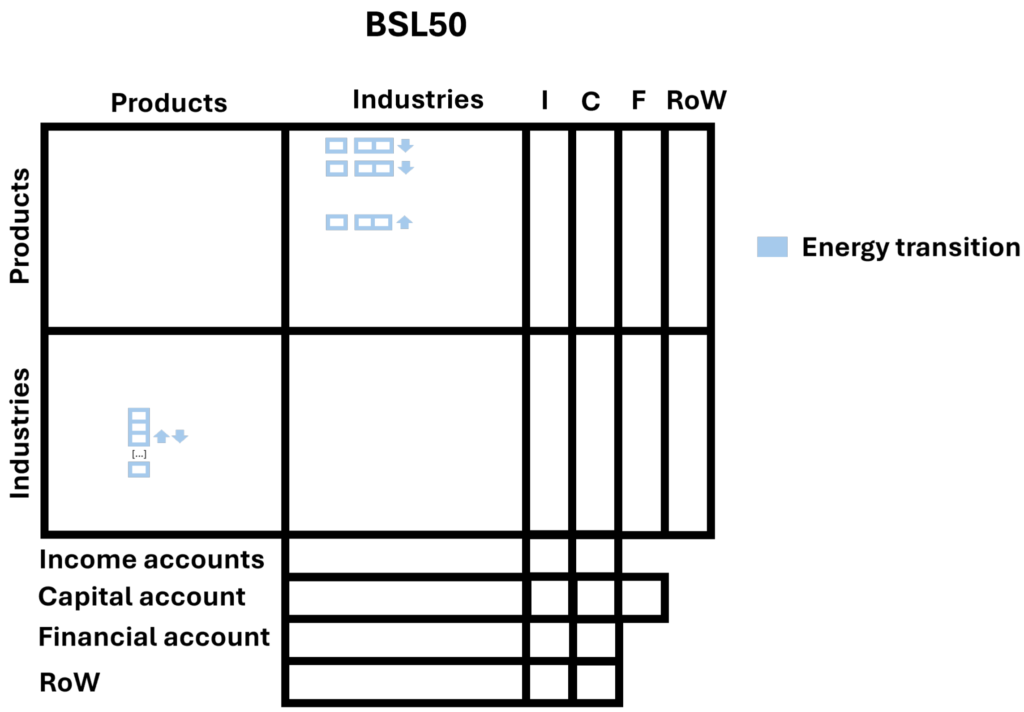
8.1.2.2 BSL50 scenario

For the Baseline scenario BSL50, three main trends are included based on the NDC-LTS scenario from the Global Energy and Climate Outlook 2023: Economic growth, energy transition, electrification.

Thereby, the national GDP growth rates were adjusted to the ones in 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, Coke and refined petroleum products (CPA C19), and Mining and quarrying (CPA B) of fossil energy products. Decarbonization is represented in the BSL50 scenario through a phase-out of fossil fuels in the production of electricity and electrification. This is illustrated in Figure 31.

Electricity is co-produced by 12 main industries in FIDELIO representing fossil and renewable energy carriers. 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 2023 NDC-LTS scenario while increasing renewable energy supply. 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. The changes to the supply matrix are illustrated at the bottom left of Figure 31. In addition, the energy consumption of the energy intensive industries steel, aluminium, cement and concrete and plastics were adjusted using data from the 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 the GECO 2023, this included a phasing-out of fossil fuels such as Coke and refined petroleum products (CPA C19) and 'Mining and Quarrying' (CPA B) while increasing the consumption from 'Electricity, gas, steam and air conditioning' (CPA D35). The intermediate use of the three industries is shown in the matrix at the top centre of Figure 31. For steel, the shift in energy inputs approximates a switch from the BF-BOF to the EAF production route. 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.

Figure 31. Implementation of the energy transition in the BSL50 scenario



Note: C: Capital account; F: Financial account; I: Income account; RoW: Rest-of-the-World. Blue boxes indicate changes in monetary flows within the National Accounting Matrix used by FIDELIO, with increases or decreases shown by the assigned arrows. The colour indicates the scenario

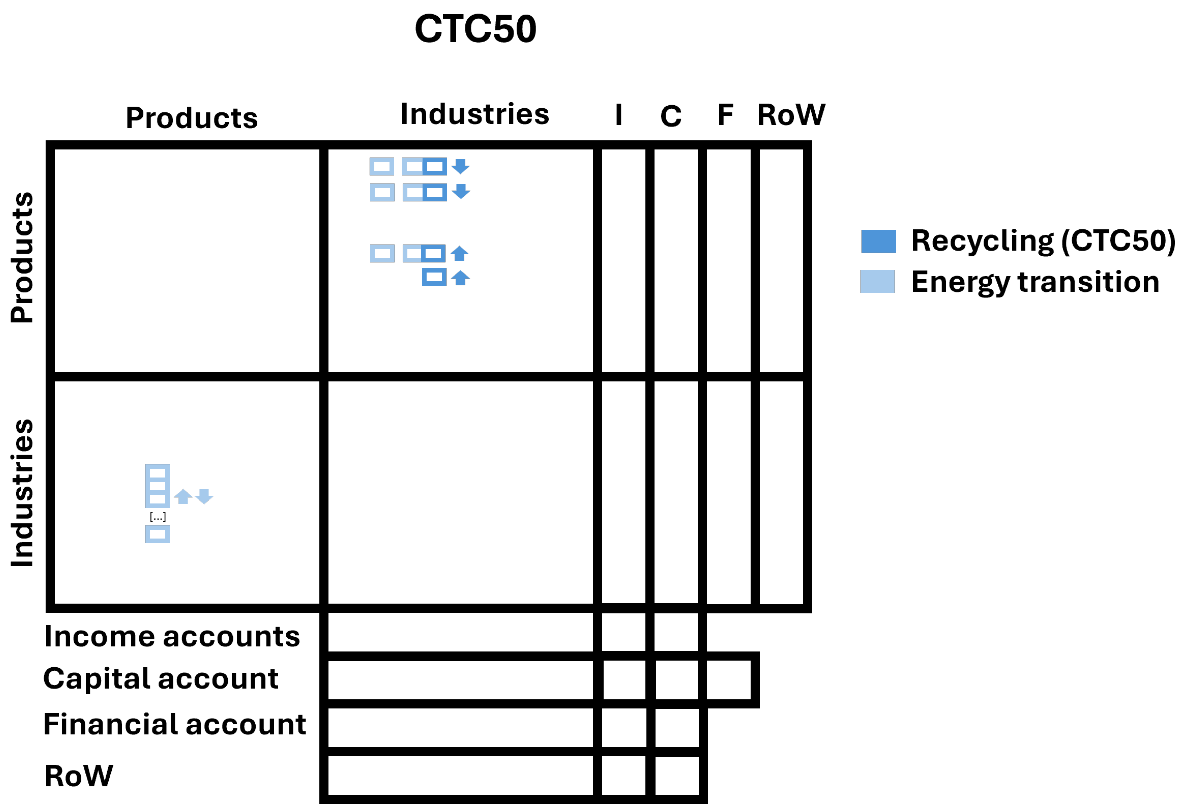
Source: JRC elaboration

Overall, the Baseline covers electrification using an energy mix primarily from renewable energies for import industries and final uses. The GECO 2023 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 scope for this study and therefore net zero is not achieved in the Baseline 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.

8.1.2.3 CTC50 scenario

For the CTC50 scenario an increase of secondary material is added to the decarbonization in the Baseline scenario as described in section 2.2.3. In the CTC50 scenario mining products (CPA B) are substituted with ‘Waste management services’ (CPA E37T39) in the intermediate use of ‘Basic metals’ (C24) following increased recycling to meet EU targets (based on bottom-up results from MFA and LCA; see section 4.2.2 and 6.2 respectively). The decrease in CPA B is counterbalanced by a proportional increase in ‘Waste management services’ (CPA E37T39’, assuming the same price. Given the large uncertainties in forecasting future resource prices, this is considered a feasible approach (Wiebe et al., 2019). The additional switch from BF-BOF to EAF is included by reducing fossil fuel inputs and increasing electricity consumption in the ‘Basic metal’ sector (C24) following the approach in the BSL50 scenario. Figure 32 illustrates the implementation of the four changes in the production inputs of the 'Basic metals' industry column for the CTC50 scenario in addition to the changes in the Baseline (BSL50) scenario.

Figure 32. Implementation of CE shocks in the CTC50 scenario



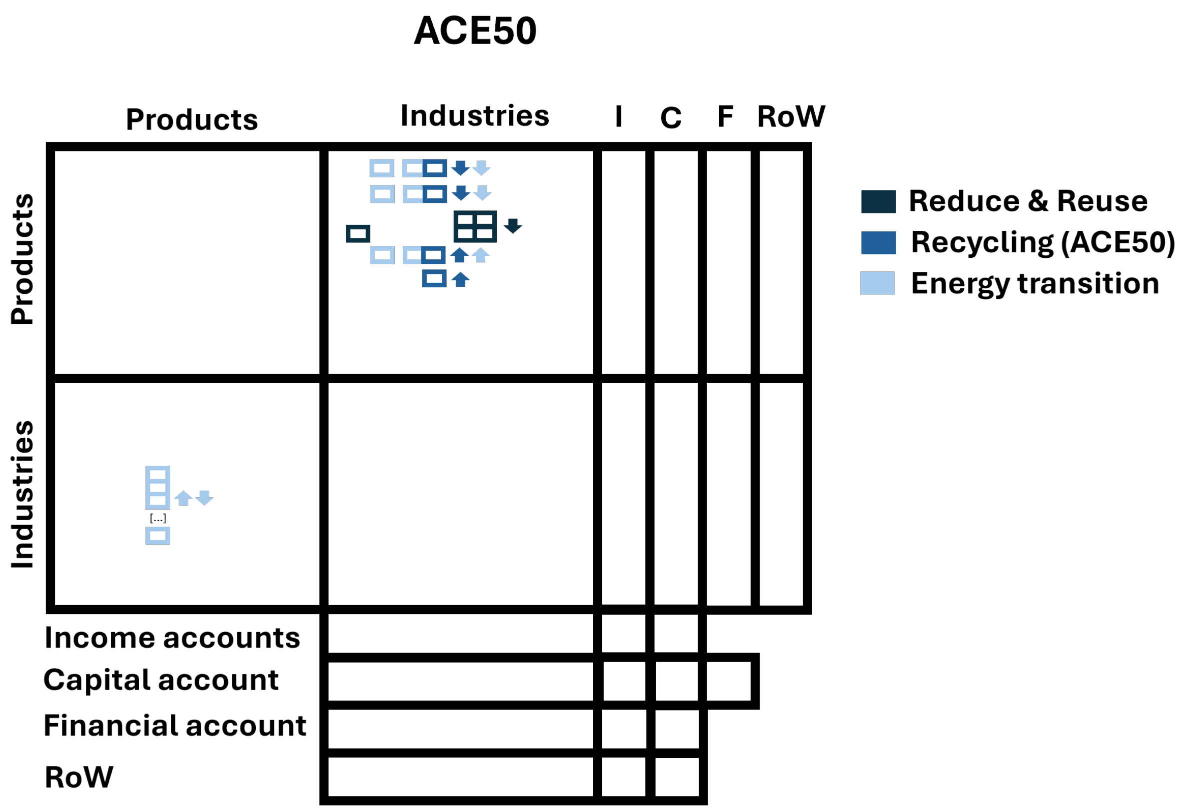
Note: C: Capital account; F: Financial account; I: Income account; RoW: Rest-of-the-World. Blue boxes indicate changes in monetary flows within the National Accounting Matrix used by FIDELIO, with increases or decreases shown by the assigned arrows, colour coded for each scenario

Source: JRC elaboration

8.1.2.4 ACE50 scenario

The ACE50 scenario described in section 3.2 adds material efficiency, limits to overspecification and longer lifetimes of steel parts in end-use goods to the decarbonization scenario BSL50 and scrap inputs for recycling is increased compared with the CTC50 scenario following bottom-up results from MFA and LCA (see section 4.2.2 and 6.2, respectively). Following the implementation in the EEIOA, the new levers in ACE50 are implemented as a reduction in the material use of steel by industries. They cover the industries: Manufacture of food products; beverages and tobacco products (C10T12), Motor vehicles, trailers and semi-trailers (CPA C29) and Construction (F).

Figure 33. Implementation of CE shocks in the ACE50 scenario



Note: C: Capital account; F: Financial account; I: Income account; RoW: Rest-of-the-World. A blue box illustrates a change to a monetary flow in the section of the National Accounting Matrix used by FIDELIO that are either increased or decreased based on the assigned arrows. The colour indicates the scenario

Source: JRC elaboration

The shocks cover Basic metals (CPA C24) and Fabricated metals (CPA C25). 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. 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 metal structures, tanks, cutting tools or locks. The share of steel products in CPA C25 is estimated using data from FIGAROe3 and ProdCom to determine the national market penetration rates of the CE levers in the ACE50 scenario. Using the market penetration rates for steel products as weighing factors, the use of CPA C24 and CPA C25 is reduced for the three respective industries. Overall, nine additional changes to the monetary flows in the intermediate use section of FIDELIO are required for the implementation of the ACE50 scenario, as illustrated in Figure 33.

8.2 Results

The results for GDP, value added, trade, and employment obtained by using the dynamic macro-economic modelling FIDELIO are presented herein. The results are presented relative to the Baseline (BSL50) scenario, which is taken as benchmark. The results are presented relative to the Baseline 2050 scenario as reference of comparison (the Status Quo 2020 is also presented as additional information). The difference between the BSL50 and the CTC50 scenario is to be understood as the additional effects obtained from implementing the selected CE policy targets (as considered in the CTC50 scenario); the difference between the BSL50 and the ACE50 scenario is to be interpreted as the additional effects incurred by the full-fledge implementation of the CE levers (as investigated in the ACE50 scenario).

Notice that we report the results both as total absolute decrease (e.g. billion EUR) and relative decrease (%) compared to the Baseline BSL50 scenario. 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.

8.2.1 Gross Domestic Product and Gross Value Added

The results obtained for the changes in the Gross Domestic Product (GDP) for the CTC50 and ACE50 scenario relative to the BSL50 scenario are presented in Figure 34. Associated changes in Gross Value Added for the EU industry are presented in Figure 35.

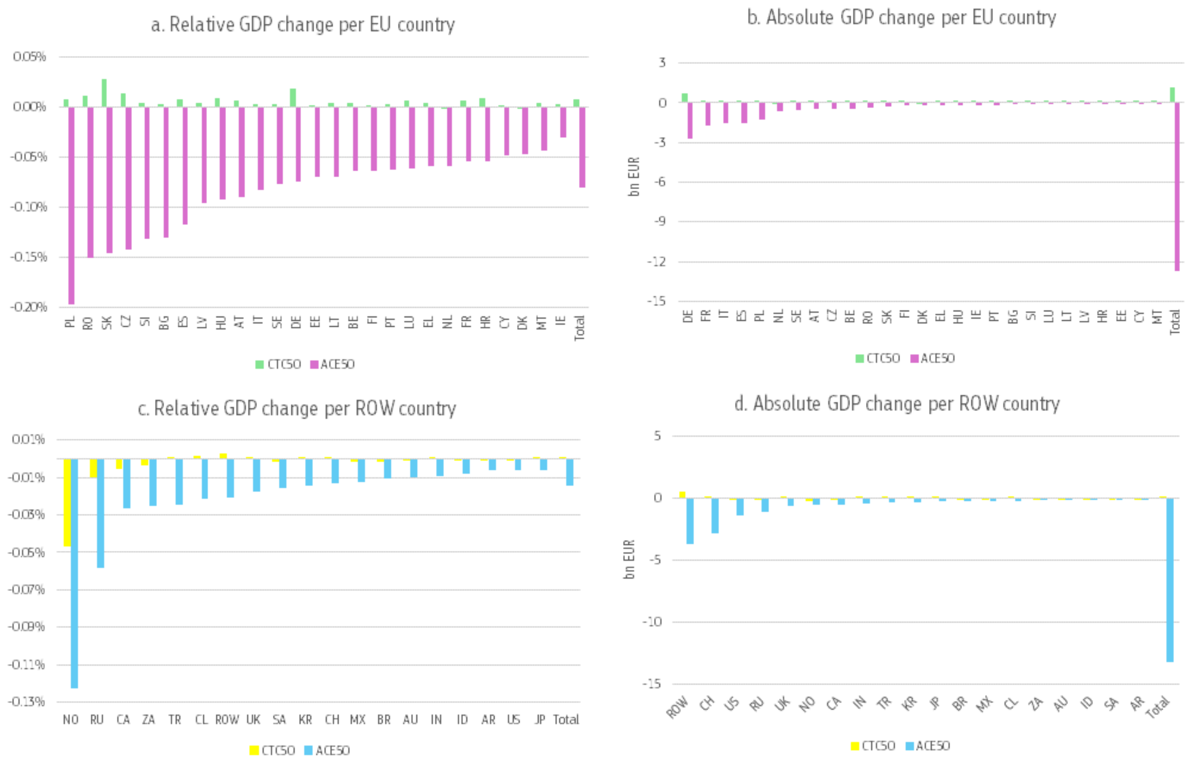
Focusing on the EU, the changes in GDP are negligible for the CTC50 scenario where a slight increase is observed (ca. EUR 0.02 billion) while for the ACE50 scenario there is a decrease of ca. EUR 13 billion relative to the BSL50, corresponding to a 0.014% decrease (Figure 34b and Figure 34a). The highest contributions to the EU GDP loss are Germany, Italy, France, and Spain with decreases the order of EUR 1.5-2.7 billion relative to the BSL50, corresponding to a relative decrease of 0.05-0.08% (see Figure 34b and Figure 34a).

With respect to changes in the Gross Value Added at EU industry level, the results obtained in the CTC50 scenario are negligible, while in the ACE50 scenario the industries mainly affected are 'Manufacture of basic metals' (C24), 'Manufacture of fabricated metal products, except machinery and equipment' (C25), 'Wholesale and trade' (G46), 'Construction' (F), and 'Real estate activities' (L) with decreases in the order of 0.5-2.1 billion EUR (Figure 35b). In relative terms, the most affected sectors are again 'Manufacture of basic metals' (C24) and 'Manufacture of fabricated metal products, except machinery and equipment' (C25), along with 'Repair and installation of machinery and equipment' and 'Distribution and transmission of electricity (D3512-D3513) with decreases in the order of 0.13-2.3% compared with the BSL50 scenario (see Figure 35a).

Regarding non-EU countries, negligible changes in GDP are observed both for the CTC50 and the ACE50 scenario relative to the BSL50 (Figure 34c and Figure 34d), with the top-four regions mostly affected being Norway, Russia, Canada, South Africa and Turkey (see Figure 34c and Figure 34d).

With the EU GDP corresponding to approx. 14% of the global GDP (approx. trillion EUR 111 in 2050), the CTC50 scenario results in a relative increase of the global GDP of 0.006% (increase by billion EUR 1.2), while the ACE50 scenario results in a relative decrease of 0.057% (EUR 26 billion). Overall, the results suggest that the general trend of GDP decline is limited and the EU's position in the global economy is not significantly affected by the attainment of policy targets nor by the implementation of the CE levers.

Figure 34. Effects on GDP for the EU and Rest-of-the-World



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

Source: JRC elaboration

Figure 35. Effects on Value Added for the EU industry

Note: a) Relative change in Value Added for the EU at industry level expressed as percentage for the CTC50 and the ACE50 scenario. 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

8.2.2 Trade

The results for the changes in trade are presented in Figure 36.

We observe an increased surplus in trade balance[47] for the EU equalling EUR 0.64 and 7 billion in CTC50 and ACE50 relative to the BSL50, respectively, corresponding to 0.07% and 0.73% increase. This means that the attainment of the policy targets and the implementation of ambitious CE levers are expected to increase the EU trade surplus (less demand for imports mainly, with exports proportionally less, or not, affected).

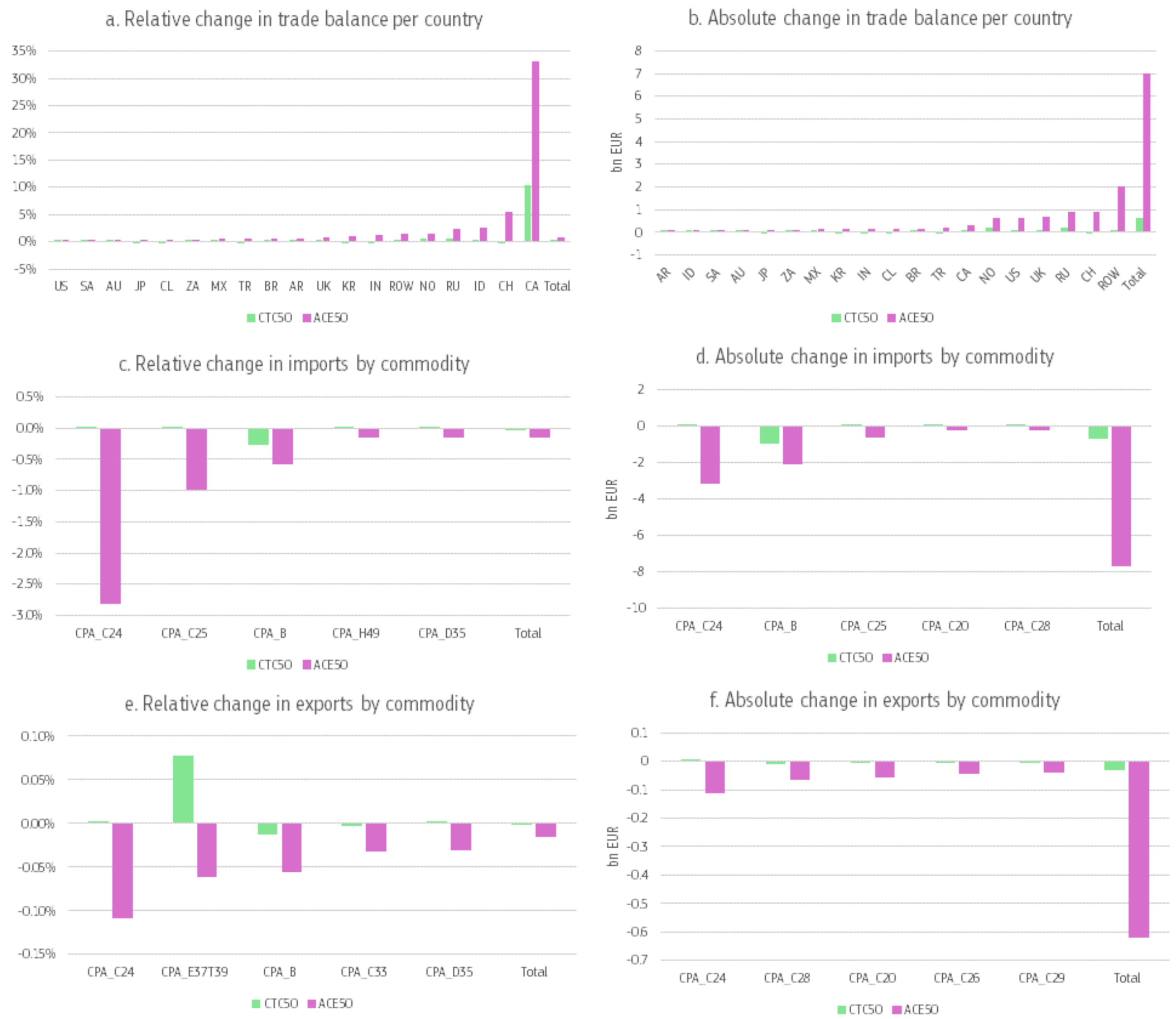
The increased surplus for the EU in both the CTC50 and the ACE50 scenario are due to changes in trade patterns, overall inferring a reduced dependency from non-EU countries. While for the CTC50 negligible changes are observed, for the ACE50 scenario the regions most affected in absolute terms are China, Russia, UK, USA, and Norway with which the trade balance increases in the range EUR 0.59-0.87 billion relative to the BSL50 scenario (see Figure 36b), suggesting a decreased dependency from these regions. In relative terms, the regions most affected are Canada, China, India, Russia and Norway with decreases in the range 1.3-33% relative to the BSL50 scenario (Figure 36a).

With respect to what is imported in the EU, Figure 36c and Figure 36d show what commodities are mainly affected by the changes implemented in the CTC50 and ACE50 scenarios when compared to the BSL50 scenario. Negligible changes are observed for the CTC50 scenario, while for the ACE50 scenario, the main goods affected are 'Basic metals' (CPA_C24), 'Mining and quarrying' (CPA_B), and 'Fabricated metal products, except machinery and equipment' (CPA_C25) in the order of EUR 0.57-3.1 billion or 0.6-2.8% decrease relative to the BSL50 scenario. The total reduction in imports in ACE50 scenario equals EUR 7.6 billion relative to the BSL50 scenario.

Finally, Figure 36e and Figure 36f show what EU exported commodities are mainly affected by the implementation of the CTC50 and ACE50 scenarios as opposed to the BSL50 scenario. Negligible changes are observed for the CTC50 scenario, while for the ACE50 scenario, the main goods decreasing their exports are 'Basic metals' (CPA_C24), 'Machinery and equipment n.e.c.' (CPA_C28), and 'Chemicals and chemical products' (CPA_C20) in the order of EUR 0.05-0.11 billion or 0.01-0.11% decrease relative to the BSL50 scenario. The total reduction in export in ACE50 equals EUR 0.62 billion relative to the BSL50 scenario.

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

Figure 36. Effects on trade balance for the EU



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

Source: JRC elaboration

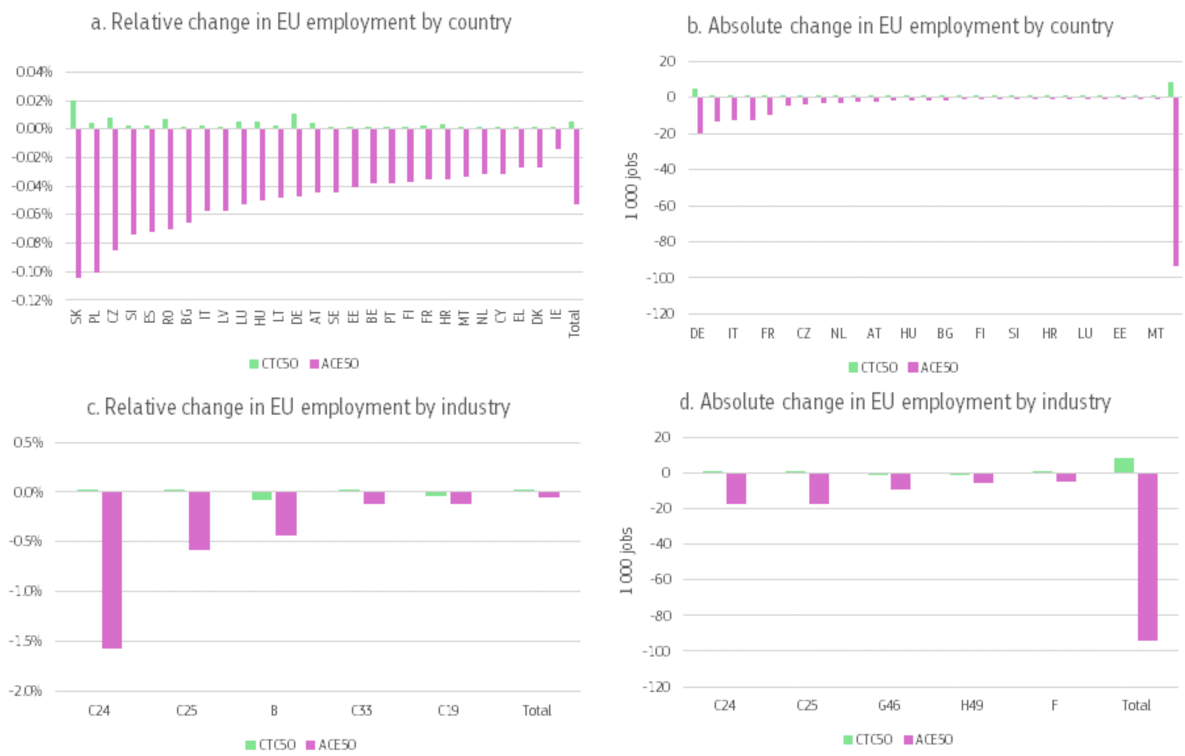
8.2.3 Employment

The results for the changes in Employment are presented in Figure 37.

The total number of jobs in EU in the 2050 Baseline (BSL) scenario is estimated at ca. 177 million. In the CTC50 we observe an increase of 8000 jobs, corresponding to 0.005% increase relative to the BSL50 scenario, while in the ACE50 scenario a decrease of 93000 jobs, corresponding to 0.053% decrease relative to the BSL50 scenario.

In the CTC50 scenario, Germany is the country where the largest increase in job is observed (ca. 4100 jobs, corresponding to 0.01% increase relative to the BSL50 scenario; see Figure 37a and Figure 37a). This result is conditioned by the assumption that the primary route can be reconverted to secondary while maintaining the overall large steel production capacity in Germany. In the ACE50 the main countries affected are Slovakia, Poland and Czech Republic with decrease in the order 0.08-0.1% relative to the BSL50 scenario (see Figure 37a). However, the largest absolute decrease in employment is expectedly in Germany, Spain, Poland, Italy and France, as these are the regions with the largest production capacity (see Figure 37b). As for the industries affected, the results for CTC50 scenario show employment increase in 'Construction' (F), 'Electricity production' (E35), and 'Waste management services' (E37T39) mainly.

Figure 37. Effects on employment in the EU and Rest-of-the-World



Note: a) Relative change in employment by EU country expressed as percentage for the CTC50 and the ACE50 scenario. b) Absolute change in employment by EU country expressed as 1000 jobs for the CTC50 and the ACE50 scenario. c) Relative change in EU employment by industry expressed as percentages for the CTC50 and the ACE50 scenario. d) Absolute change in EU employment by industry expressed as 1000 jobs for the CTC50 and the ACE50 scenario

Source: JRC elaboration

In the ACE50 scenario, the main industries affected are 'Manufacture of basic metals' (C24), 'Manufacture of fabricated metal products, except machinery and equipment industry' (C25), 'Wholesale and trade' (G46), with 9000-17000 jobs decrease, corresponding to 0.1-1.6% decrease relative to the BSL50 (Figure 37c and Figure 37d; notice that the industries mostly affected in absolute terms may not necessarily correspond to those mostly affected in relative terms).

The modelling results show overall a negative trend in job demand. It is important to note that the levers herein studied (extension of the lifetime of products via repairing and remanufacturing, changes in design of products to improve recyclability and new sorting technologies) require additional (and likely different than today's) repairing services, research and development. Nevertheless, the creation of jobs related to the mentioned activities is not modelled for lack of solid data. Hence, the results should be interpreted bearing in mind this limitation.

8.2.4 Limitations

Decarbonization in this study is focused on the energy sector and the four energy-intensive industries of steel, aluminium, 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 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 fine-tuned 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 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 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 CPA B will also lead to a reduction in energy inputs. Another aggregation error is found in industry E37T39 (waste management services), 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 ICIO tables, 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 currently present 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). 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 follows 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. The modular approach allows for the tracking of intersectoral, investment, income and price effects, and increases 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 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 while also increasing employment. This study used a combined approach of material flow analysis and macroeconomic modelling. While this approach is rich in information on stocks and flows of steel, additional data inputs are required to consider the effects on 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 only partially 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[48]. 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 this by adding data on capital expenditure (CAPEX) and operating and maintenance expenditure (OPEX). This study highlights the potential to reduce industrial demand for steel rather than the social innovation and impact of behavioural change of consumers. FIDELIO is well suited to investigate behavioural responses and combining it with a modelling approach that goes beyond the MFA inputs would allow scenarios for consumer behaviour change to be explored in more depth, extending 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 trade pattern modelled in the BSL50 scenario of FIDELIO do not mirror the post Ukrainian-war situation. Therefore, the results for trade balance and patterns with Russia may be overestimated due to the ongoing implementation of EU sanctions.

[48] Partially include because we include the change in waste services for collection and recycling. However, effects on the services or R&D sector are not included.

9 Synthesis and discussion

Section 9.1 synthetizes the results of the different analyses conducted during this study, focusing on the results from LCA, EEIOA, and dynamic macro-economic modelling. Section 9.2 suggests policy actions that would be needed to activate the CE levers investigated in this study.

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

9.1.1 Climate change mitigation and other environmental effects

Our results indicate that the potential of CE to mitigate climate change, additional to what would already be achieved via the sole decarbonization of energy sectors, lies between annual 64 Mt CO_2-eq. and 81 Mt CO_2-eq. (year 2050)[49]. The lower end of the range is obtained via EEIOA, the higher via LCA.

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. And taking the boundary of the LCA as an example, the results of the LCA indicates that the CE levers studied achieve an additional impact reduction on the category Climate Change equal to 54-66% relative to that of the Baseline in year 2050 (the range considers the including or excluding the levers implying significant behavioural changes), i.e. to what would be achieved only via decarbonization of the energy sectors. This considers all GHG emissions occurring on-site and off-site. Taking the EEIOA results, the reduction of EU on-site GHG emissions from steelmaking plants equals 30% relative to what would otherwise happen under the decarbonized Baseline in year 2050.

The individual impacts of the CE levers were studied in detail via LCA. Our results suggest that all the CE levers studied have an important contribution to climate change mitigation. While results for *Reduce* and *Reuse* confirm previous scholars, our findings shine new light on the potential associated with high-quality recycling (*Recovery*). Building on the work of previous authors (notably, Dworak et al., 2022; Dworak & Fellner, 2021), we quantified the environmental effects incurred by enhancing quality of recycling in EU, notably via better collection and sorting of scrap. While illustrating the uncertainties inherently associated with modelling quality aspects via LCA, our findings show that enhancing quality of recycling is key to enable the use of the scrap available in developed economies. This is the case of the EU, especially under increased reduction and reuse CE interventions that ultimately reduce resource demand. Keeping current scrap management practices would on the contrary generate increasing amounts of lower quality scrap, which would not find outlets in the EU market, especially under scenarios of reduced demand by industry (notably for construction). The LCA results indicate that high-quality scrap recycling incurs savings of about 8 Mt CO_2-eq. However, these savings may be completely overlooked when more simplified approaches are followed (shown in a sensitivity analysis).

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 category Climate Change. Both the LCA

[49] This may be further increased to 81-99 Mt CO_2-eq. (calculated for year 2050) when additional demand-based levers, implying significant changes in consumer's behaviour, are included.

and the EEIOA support such general trend in reduction of environmental impacts. No tradeoffs between impact categories are observed upon implementation of the CE studied.

9.1.2 Resource and trade dependency

CE leads to a decrease in the demand for extraction of ores of 27% relative to the decarbonized Baseline by 2050 (corresponding to ca. 46 Mt decrease). For iron ore, this means a 22% decrease in demand relative to the Baseline by 2050 (40 Mt), while the decrease for the other strategic minerals is about 5% relative to the Baseline by 2050 (6 Mt). These figures are calculated via EEIOA and thus account for inter sector and inter country spillover effects.

CE also leads to decreased demand for energy products. Via EEIOA we estimate an EU economy-wide reduction in demand for coal, lignite and peat of 6.2%, crude oil of 2.5%, natural gas of 1.6%, and other fossil fuels of 2% relative to the Baseline scenario, by 2050. For the EU steel industries specifically, this corresponds to a reduction in demand for coal, lignite and peat of 38%, crude oil of 15%, natural gas of 22%, and other fossil fuel of 64% relative to the Baseline scenario, by 2050. The inputs of electricity to the steel industries are also decreased by 36% relative to the Baseline scenario, by 2050.

The reduction in resource dependency reflects decreased import dependency from foreign regions. The results of the dynamic macroeconomic modelling suggest that full-fledge implementation of the studied CE levers increases the net trade balance[50] of EU by annual EUR 7 billion relative to the Baseline scenario, by 2050. This comes with important reduction of imports (EUR >7 billion) from China, Russia, UK and USA as an effect of CE. The imported products most affected in absolute terms are basic steel metal, ores, fabricated metals and vehicles. Exports from the EU are also reduced, although to a much lesser extent. 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. For example, we took cost-neutral assumptions on the light weighting of steel used for vehicles (advanced steel material) and on the lifetime extension. On top, the increase of economic output (employment and GVA) from repair and research services was only limitedly modelled, which calls for further research on these aspects.

9.1.3 Socio-economic effects

As a result of CE levers implementation in the sector, we calculate a decrease in jobs and value added in the EU steel industry. The decrease in value added is in the order of 0.08% of GDP across the entire EU economy relative to the Baseline in 2050, while the decrease in job requirements is in the order of 0.10% across the entire EU economy, relative to the Baseline in 2050.

The most affected industries in relative terms are ‘Basic metals’ (-1.6% employment; -2.3% GVA), ‘Fabricated metal products’ (-0.58% employment; -0.88% GVA), and ‘Mining and quarrying’ (-0.43% employment; -0.51% GVA). The industries ‘Basic metals’ and ‘Fabricated metal products’ together account for about one third of EU GVA and job loss[51].

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[50] The trade balance is calculated as Trade balance = Exports - Imports

[51] Values obtained from the dynamic macroeconomic analysis using the FIDELIO model.

The decrease in GVA in the EU steel sector corresponds to 1:26 of the decrease in GHG emissions in the same sector, suggesting a decoupling of economic growth and GHG emissions incurred by CE[52].

As for costs, we only estimated life cycle costs which offer a limited representation of the actual costs incurred by the economic system because of the CE levers studied. This is especially the case for *Reuse* and *Reduce* levers, for which no solid information on investment and operational costs could be found. For recycling levers, while some studies are available (notably, Daehn et al., 2019; Dworak et al., 2022), they provide limited information on the actual technology investments and operational costs that are incurred by a shift towards high-quality recycling.

9.2 Potential policy instruments to foster CE in the steel 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 is 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 steel 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 EU plastics sector needs a systemic (holistic) policy approach, designing a balanced policy mix targeting all CE clusters and actors involved.

9.2.1 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

[52] Calculated via EEIOA: the decrease in GHG emissions in the steel sector (on-site emissions in EU from the steel production sector only) is 35% relative to the same sector in the baseline; the decrease in GVA in the same sector in the EU is 1.3% relative to the baseline.

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 (Rogge & Reichardt, 2016).

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 9.2.3)
- 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).

9.2.2 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).

9.2.3 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 (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 16, including also a few indicative examples of related measures per category.

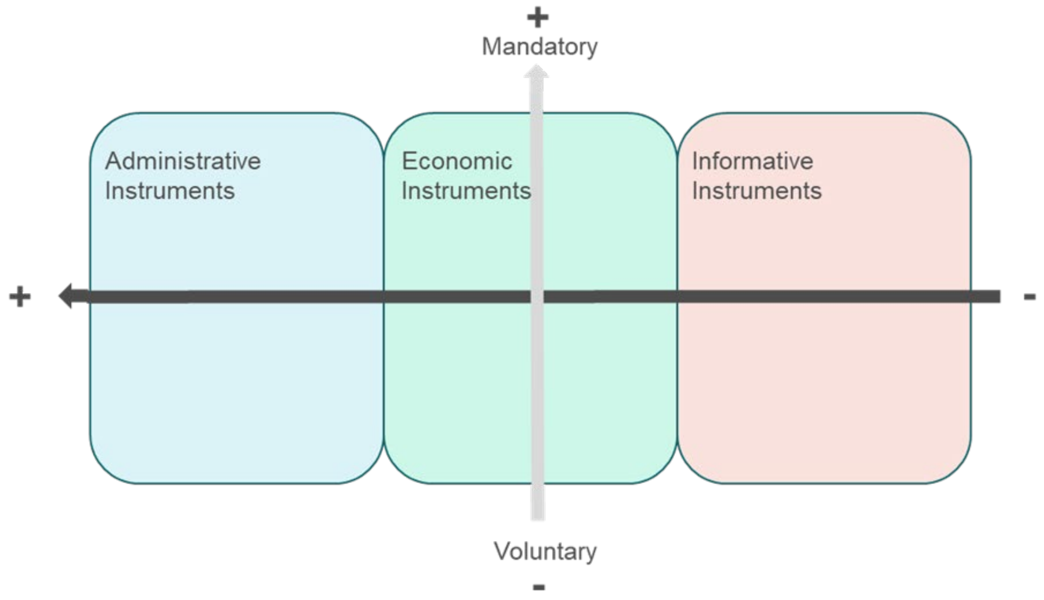
Table 16. Policy instruments typology and examples of measures

	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 38 the potential effectiveness of policy instruments according to their typology is illustrated.

Figure 38. Anticipated effectiveness of policy instruments by type



Source: JRC elaboration

9.2.4 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.

9.3 Policy suggestions to activate the CE levers studied

Table 17 presents a summary of the levers and their quantified effects on climate change mitigation as well as reduction of the (primary) material demand, along with a list of potential policy instruments that can 'activate' the lever and thus produce the desired effect. Description and discussion follows in section 9.3.1, 9.3.2, and 9.3.3.

In total, a mix of nine policy instruments is suggested, additionally to policy instruments that are already in place, to 'activate' the levers investigated in this study. Such instruments cover all the stages of the material life cycle, except for distribution (not shown for simplicity) and ore extraction, which are not addressed by any instrument. Most instruments are of a mandatory nature (all, except for Horizon or similar funding acquisition and best practice guidance for construction). The financial instruments for increasing sorting technology/capacity may be of voluntary or mandatory nature, depending on the implementation scheme. For example, one may propose financial compensation schemes for sorters (or final recyclers) based on the extent to which scrap quality is upgraded during the sorting (or recycling) process. Some of these instruments likely imply an increased (administrative and compliance) burden for selected sectors, mainly manufacture (e.g. recycled content targets under ESPR), but may be necessary to complement supply-side measures such as an enhanced capacity for (quality) recycling in the EU.

Table 17. List of policy instruments that can trigger the effects of the CE levers

R-cluster	Lever	Reduction in GHGs and virgin steel relative to the Baseline	Sector affected	Existing policy instruments?		Policy instruments suggested?	
				What	**Type of instrument & Lifecycle stage**	**What**	**Type of instrument & Lifecycle stage**
Reduce	Increase usage intensity	18 Mt CO_2-eq. (12% reduction); 22 Mt virgin steel (31% reduction)	Railway infrastructure (construction)	**Yes**, administrative and financial instruments are in place for deployment of ERTMS, including budget, governance body, and deployment plans at EU and MS level aiming at intensification of the use of the railway capacity	**Type**: Econ/Admin; Mandatory **Lifecycle stage:** Use (EU)	None, besides to accelerate on implementation, e.g. ensure funding and simplify authorisation & approval procedures	-
			Road infrastructure (construction)	**No** specific instrument in place; on 13.03.2019, the EC adopted a delegated regulation on specifications for the provision of C-ITS, supported by an IA. The delegated regulation did not enter into force following an objection by the Council of the EU	-	- Financial instruments for deployment, e.g. to support upgrading of current infrastructure by local authorities. - Amendment of legislative requirement on truck drivers' safety breaks (resting).	**Type**: -Econ; Voluntary -Admin; Mandatory **Lifecycle stage:** Use (EU)
			Trucks (vehicles)	**No** specific instrument targeting empty miles; however, other policy instruments may achieve it as a co-effect, e.g. Distance-based tools, among the other effects, is expected to reduce empty trips	-	Removing legal restrictions on carriers' ability to pick-up backloads, possibly as part of a more general deregulation of the freight transport system	**Type**: Admin; Voluntary **Lifecycle stage:** Use (EU)
	Reduce mass	35 Mt CO_2-eq. (23% reduction); 11 Mt virgin steel (15% reduction)	Residential and commercial buildings (construction)	**No** specific policy instrument in place, but 'framework policy' such as GPP can be exploited to reduce steel over-specification; on top, best practices can be released.	-	Make GPP mandatory (e.g. requiring use of BIMs or other criteria to reduce overspecification and weight via design); Guidance for best practices	**Type**: -GPP: Admin/Econ; Mandatory -Guidance: Admin; Voluntary **Life cycle stage**: Use (EU)

			Cars (vehicles)	**No** specific policy instrument in place (except for tailpipe CO_2 policies that tangentially could foster light weighting)	-	Horizon and Innovation Funding, market incentives, GPP to foster innovation and uptake of advanced high-performance steel	**Type**: Econ; Voluntary **Lifecycle stage:** Manufacture (EU)
			Packaging (metal goods)	**Yes**, PPWR contains provisions to minimize weight and volume	**Type**: Admin; Mandatory **Lifecycle stage:** Manufacture (EU)	None	-
Reuse	Extend lifetime	15 Mt CO_2-eq. (10% reduction); 7.5 Mt virgin steel (10% reduction)	Residential and commercial buildings (construction)	**Yes**, GPP includes already requirements for design for adaptability, deconstruction and reparability	**Type**: Admin/Econ; Voluntary **Lifecycle stage**: Use (EU)	Make GPP mandatory	**Type**: Admin/Econ; Mandatory **Lifecycle stage**: Use (EU)
			Industrial equipment	No specific policy instrument in place		More research is needed to understand whether this stream requires measures	-
			Cars (vehicles)	**No** specific policy instrument in place, but ELV Regulation may be used as framework policy (COM(2023)451 Final) for specific requirements via Implementing or Delegated Act	-	Implementing or Delegated Act with requirements for design for removal, disassembly and replacement	**Type**: Admin/Econ; Mandatory **Lifecycle stage**: Manufacture (EU).
Recover	Increase quantity of material recovered	31 Mt CO_2-eq. (21% reduction); 22 Mt virgin steel (30% reduction)	Waste management	**Yes**, Recycling targets on quantity exist for steel packaging (PPWR) and for Municipal Waste (WFD)	**Type**: Admin/Econ. Mandatory **Lifecycle stage**: End-of-Life (EU)	Financial incentives for deployment of DRS and of centralised sorting plants on mixed waste	**Type**: Admin/Econ; Mandatory/tbd **Lifecycle stage**: End-of-Life (EU)
	Enhance quality of recycling	2 Mt CO_2-eq. (2% reduction); 2.1 Mt virgin steel (3% reduction)	Waste management	**No** specific policy instrument in place but 'framework policy' such as the EU WFD, ELV Directive and PPWR can be exploited to this aim	-	Financial incentives for sorting technologies deployment and improved definition of quality in Implementing or Delegated Act related to ELV, WFD, PPWR (including quality targets if appropriate)	**Type**: Admin/Econ; Mandatory/tbd **Lifecycle stage**: End-of-Life (EU)

The reduction in GHGs emission and virgin (ore-based) steel use are expressed relative to the Baseline in year 2050, taken as the reference and maintaining current level of export (i.e. values should be interpreted as the additional savings incurred by the levers relative to the Baseline in year 2050); tbd: to be decided

Source: JRC elaboration

9.3.1 Reduce

9.3.1.1 Increase usage intensity

Background: There is significant potential to reduce steel use in the transport sector by increasing the usage intensity of railway infrastructure, road infrastructure, and lorries. This would allow reducing the need for new or expanded infrastructure and the number of transport vehicles for providing the same transport service. The European Rail Traffic Management System (ERTMS) project for instance is key to enhancing the usage rate of railway infrastructure, while the deployment of Cooperative Intelligent Transport Systems (C-ITS) can bring benefits to road infrastructure. Additionally, reducing empty trips by lorries can also contribute to material efficiency. According to Eurostat, empty trips constitute around 22% of total lorry trips in the EU. However, further research is needed to distinguish between actual market failures and optimization-driven factors leading to empty miles (McKinnon & Ge, 2006; McKinnon, 2015).

Policy instruments in place: For railway infrastructure, an extensive set of policy tools has been deployed addressing among other things the possible use intensity, including the Regulation (EU) 2021/1153 establishing the Connecting Europe Facility and the Commission Implementing Decision on the financing of the Connecting Europe Facility. For road infrastructure, the recently implemented distance-based tools in place of time-based vignette system (Directive (EU) 2022/362) indirectly contributes to discouraging empty miles. However, there are no specific instruments targeting empty miles by lorries.

Policy instruments and/or research (further) suggested: To boost the deployment of ERTMS, it has for instance been suggested that a centralized EU-Level ERTMS governance and Program Management could help regulate funding, coordination of National Implementation Plans, resourcing, market uptake, migration, and transition from the old to new system (CER, 2024). For C-ITS deployment, financial instruments, including subsidies to compensate final consumers and other affected bodies (Miller et al., 2016), and the adoption of the proposed regulation by the Commission could be instrumental to ensuring appropriate governance and coordination between stakeholders. For reducing empty trips by lorries, more research is needed to determine whether market failures exist and, if so, which legal restrictions should be removed to reduce empty trips. Removing legal restrictions on carriers' ability to pick up backloads, possibly as part of a more general deregulation of the freight transport system, could be a potential policy instrument.

Increased burdens for industry or consumers: None are suggested, as further investigation is needed to understand if increased use intensity may lead to higher cost of mobility in the short-term.

9.3.1.2 Reduce mass

Background: In buildings, over-specification of steel could be reduced by up to 20%. In cars, advanced high-performance steel offers significant weight reduction potential, enhancing energy efficiency. Packaging has seen gradual weight reduction since 1970, with room for improvement (ArcelorMittal, 2024).

Policy instruments in place: For buildings, there are no specific policies targeting over-specification, though voluntary systems like LEED and lifecycle assessments indirectly address it. In cars, the EU Regulation 2019/631 and the European Strategy for Low-Emission Mobility indirectly encourage lightweight materials. The EU Packaging Directive already promotes packaging weight and volume minimization.

Policy instruments and/or research (further) suggested: For buildings, mandatory Green Public Procurement (GPP) criteria and the use of Building Information Modelling (BIM) are suggested. Release of best practices guidance (such as in UK; see SCI & BCSA, 2024)[53] will also help. For cars, further Horizon and Innovation Funding and market incentives are recommended. No additional measures are proposed for packaging.

Increased burdens for industry or consumers: Suggested policies mainly impact the design and R&D phases, leading to optimized material use and efficiency with minimal additional burdens on (construction) industry or consumers.

9.3.2 Reuse

Background: There is significant potential to extend the lifetime of residential and commercial buildings, especially given the trend of decreasing lifetimes for recent constructions. For industrial equipment, the margins for extension are limited to about 17% due to poor data on equipment lifetimes. For vehicles, extending the lifetime of cars and trucks is possible, but there is uncertainty about the trade-offs between lifetime extension and efficiency loss.

Policy instruments in place: For buildings, Green Public Procurement (GPP) already includes requirements for adaptability, deconstruction, and reparability. For industrial equipment, no specific policies target lifetime extension[54]. The End-of-Life Vehicles (ELV) Regulation provides a framework for vehicles, though no specific lifetime extension policies are in place.

Policy instruments and/or research (further) suggested: It is suggested that GPP be made mandatory for buildings. The ELV Regulation could be updated through implementing or delegated acts to include specific requirements on dismantling, removability, and replaceability for vehicles.

Increased burdens for industry or consumers: Making GPP mandatory for buildings would likely only affect the design phase, with minimal burden on industry or consumers. However, introducing requirements for industrial equipment and vehicles via ESPR or ELV regulations would likely lead to additional administrative and compliance burdens for manufacturers in those sectors.

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[53] Along with the reference provided above, there is an additional UK guidance from the Steel Construction Institute namely: 'High strength steel design and execution guide', available at the link: https://steel-sci.com/assets/downloads/High-Strength-Steel-and-Execution-Guide-P432.pdf?utm_source=publication&utm_medium=download&utm_campaign=sci-p432. The guidance documents provide examples on the replacement of S355 steel with S460 (high strength steel; HSS) for columns and beams applied in storey buildings and in infrastructure. Steel S460 provides ca. 15-20% steel weight savings while costing only ca. 10% more than S355. Savings of CO2 are significant as columns can make up 20% of the total weight of steel in a building and the C-footprint of HSS is just slightly higher than conventional steel. Also, CO2 savings are further increased by lower transport and smaller foundations needed for the buildings, as the weight of the construction decreases.

[54] This is the understanding of the authors upon reading the ESPR workplan.

9.3.3 Recover

Background: Steel material recovery rates from post-consumption waste are currently already high (>70%), but further improvements are possible. Deploying Deposit Refund Schemes (DRS) and centralized sorting plants could recover few additional million tonnes of scrap relative to what would otherwise occur, reaching up to 85% recovery rate. Enhancing the quality of recycling is critical, with potential improvements through better sorting, advanced recycling technologies, and upgrading scrap quality to meet industry demands.

Policy instruments in place: The Packaging and Packaging Waste Regulation (PPWR) sets recycling targets for metal packaging (75% by 2030), and the Waste Framework Directive (WFD) targets municipal waste recycling (65% by 2035). However, there are no specific instruments focused on improving the quality of recycling.

Policy instruments and/or research (further) suggested: The introduction of mandatory DRS systems and the development of centralized sorting for mixed waste could further boost recovery rates. Financial and administrative instruments are needed to support advanced sorting technologies and ensure that higher-quality recycled scrap is retained for EU industries. This could include creating demand for high-quality recycled materials through targets on recycled content in products, like automotive components, and clear definitions of recycling quality in relevant regulations.

Increased burdens for industry or consumers: Mandating DRS in countries with existing collection systems may incur transition costs, especially for Producer Responsibility Organizations (PROs). Centralized sorting plants would require financial support to become economically viable, which could result in higher municipal waste management costs for consumers. Administrative targets on recycled content may increase compliance burdens for manufacturers, but the primary burden would fall on scrap sorters and recyclers.

10 Conclusions

10.1 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 steel sector. The results indicate that the implementation of CE levers can lead to significant reductions in GHG emissions, resource use, and waste generation. The study highlights the importance of a holistic approach to CE, considering the entire life cycle of steel and the interactions between different sectors.

The analysis suggests that the CE levers studied can achieve an additional impact reduction on climate change of between 64-81 Mt CO_2-eq. annually by 2050, on top of what would be achieved by decarbonization of the energy system only[55]. The results also show that CE can lead to a significant decrease in the EU economy requirements of ores (27% relative to relative to the decarbonized Baseline, by 2050) and energy products. An EU-wide reduction was observed in the demand for coal, lignite and peat of 6.2%, crude oil of 2.5%, natural gas of 1.6% and other fossil fuels of 2% relative to the decarbonized Baseline, by 2050.

For the EU steel sector specifically, the decrease in fossil energy carriers equals 28% overall, relative to the decarbonized Baseline, by 2050. Specifically, this means a decrease of about 38% for coal, lignite and peat, 15% for crude oil, 22% for natural gas and 64% for other fossil fuel relative to the decarbonized Baseline, by 2050. Similarly, electricity input decreases by 36% for the EU steel industries. Most of these reductions affect imported products (ca. 94%).

This decrease in demand is positively reflected in the trade balance of the EU, which is estimated to increase by ca. EUR 7 billion annually relative to the decarbonized Baseline, by 2050. This is an effect of reduced imports from the key trade partners (US, UK, Russia, and China). These changes also come along with reductions in Gross Value Added, thus 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, this was only limitedly captured.

The study emphasizes the importance of a 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 increase usage intensity, reduce mass, extend lifetime, recover materials, and enhance recycling quality.

Last, the study shows the potential of combining tools that are too often used in isolation. Linear and static life cycle-based tools are not meant to capture market-triggered effects, price or investment dynamics, and macro-economic rebound effects. For these reasons, not only the economic and social effects of CE cannot be fully captured, but also market-driven environmental effects are overlooked. Accompanying process-based life cycle assessment and costing with

[55] These savings are related to CE levers that do not imply significant behavioural changes. Including these further increase the potential GHG savings to 81-99 Mt CO_2-eq.

environmentally extended input-output and dynamic economic modelling allows better capturing macroeconomic effects (e.g. rebound) and interdependencies between sectors and countries. This significantly improves the information obtained in relation to economic security, e.g. trade balance with the relevant global partners and import reliance. Additionally, these analyses provide socio-economic information (notably GVA, GDP, and employment) that cannot be obtained with life cycle-based tools.

In conclusion, this study demonstrates the potential of CE to contribute to a more sustainable and resource-efficient steel 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.

10.2 Key policy recommendations

The following policy recommendations are designed to support the implementation of the CE levers in the steel sector, with the goal of reducing steel use, promoting sustainability, and minimizing waste.

- ***Reduce*** (increasing usage intensity and reducing mass):
    - Accelerate EU Railways Traffic Management System deployment through established means of Governance and Program Management to enhance the usage rate of railway infrastructure.
    - Deploy Cooperative Intelligent Transport Systems with financial instruments and subsidies to reduce empty trips by lorries.
    - Remove legal restrictions on carriers' ability to pick up backloads to optimize transport services.
    - Implement mandatory Green Public Procurement criteria for buildings to reduce steel over-specification.
    - Provide further Horizon and Innovation Funding and market incentives for cars to promote the use of advanced high-performance steel.
- ***Reuse*** (extending lifetime)
    - Make Green Public Procurement mandatory for buildings to promote adaptability, deconstruction, and reparability.
    - Include requirements on durability, reliability, disassembly, and reparability in the Eco-Design for Sustainable Products Regulation for industrial equipment.
    - Update the End-of-Life Vehicles Regulation to include specific requirements on dismantling, removability, and replaceability for vehicles.
- ***Recover*** (improving recycling rate and quality):
    - Introduce mandatory Deposit Refund Schemes and foster sorting notably by deployment of centralized sorting plants for mixed waste to increase material recovery rates.

- Provide financial and administrative instruments to support advanced sorting technologies and ensure high-quality recycled scrap.
- Create demand for high-quality recycled materials through targets on recycled content in products, such as automotive components.

10.3 Future Research Directions

The study identifies the following limitations and challenges that could be addressed by further research, namely:

- **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 levers implementation in the EU economy.
- **Demand-based levers**: this study only partially assessed the consequences of (final consumers) demand-based levers for the steel sector only. The motivation to discard such levers is mainly related to the fact that many of these imply a limitation of individual freedom. Additional research should explore the socio-economic implications of changing consumer's behaviour towards different or reduced consumption, e.g. focusing on sufficiency. The authors are aware of an ongoing study on these aspects carried out by Cambridge Econometrics on behalf on DG CLIMA.
- **Quality of recycling aspects**: this study investigates the effects of steel scrap quality changes on resource and environmental benefits in detail. However, assessing the effects incurred by changes in recycled material quality is subject to uncertainties because of the underlying approach used to model such effects as well as the possible market-triggered reactions. Further research is encouraged on this topic, e.g. challenging the projections on EU scrap generation (this study is largely based on one source; Fraunhofer ISI & European Commission, 2023).
- **Strengthening integration of bottom-up and top-down tools**: 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**: 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). The model could also serve to assess the effects of increased EU defence spending, generating additional demand in the steel and aluminium sector.

- **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

ACE	Ambitious Circular Economy scenario
BAU	Business as Usual
BF/BOF	Blast Furnace – Blast Oxygen Furnace
BSL	Baseline scenario
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Use
CDW	Construction and Demolition Waste
CTC	Compliance with selected Targets on Circular economy (scenario)
CFF	Circular Footprint Formula
CE	Circular Economy
CEAP	Circular Economy Action Plan
CGE	Compute General Equilibrium
CMUR	Circular Material Usage Rate
DA	Delegated Act
EAF	Electric Arc Furnace
ECO	Ecostate scenario (sensitivity analysis)
EEIOA	Environmental Extended Input-Output Analysis
EF	Environmental Footprint method
ELCC	Environmental Life Cycle Costing
EEMRIO	Environmental Extended Multi-Region Input-Output
ELV	End of Life Vehicle
EoL	End-of-Life
ESPR	Eco-Design for Sustainable Product Regulation
EU	European Union (27 members)
ETS	Emission Trade System (EU)
FELCC	Full Environmental Life Cycle Costing
FU	Functional Unit
GBB	Green Business Boom (sensitivity analysis)
GDP	Gross Domestic Product

GECO	Global Energy and Climate Outlook
GEW	Glocal EcoWorld scenario (sensitivity analysis)
GHG	Greenhouse Gas
GPP	Green Public Procurement
GRO	Growth baseline scenario (sensitivity analysis)
GTC	Greening Through Crises scenario (sensitivity analysis)
GVA	Gross Value Added
HQ	High-Quality
IA	Implementing Act
IAM	Integrated Assessment Model
IEW	Industrial Electrical Waste
IO	Input-Output
IOA	Input-Output Analysis (also called IO)
IOT	Input-Output Tables
INEW	Industrial Non-Electrical Waste
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LQ	Low-Quality
MFA	Material Flow Analysis
MRE	Mass reduction lever
MW	Municipal Waste
NDC-LTS	National Determined Contribution-Long Term Strategy GECO
OPEX	Operational Expenditures
QLT	Enhance quality of recycling lever
QNT	Increase quantity of material recycled lever
REF	Reference energy scenario GECO (sensitivity analysis)
PEF	Product Environmental Footprint
PPWR	Packaging and Packaging Waste Regulation
REC	Recover cluster of levers
RED	Reduce cluster of levers

REU	Reuse cluster (and reuse lever, as they are the same)
ROW/RoW	Rest-of-the-World
R&D	Research and Development
SHR	Shrinking baseline scenario (sensitivity analysis)
STQ	Status Quo scenario
UIT	Increase usage intensity lever
WEEE	Waste electric and electrical equipment
WFD	Waste Framework Directive

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Annexes

Annex 1. Detailed summary of the CE levers investigated in this study

Table A1 summarises the CE levers implemented in the study. More details may be found consulting the Supplementary Material named 'Circular economy levers and scenarios' (available upon request).

Table A1. Overview and first-order effects of levers in the ACE50 scenario. In grey we highlight the levers that imply a substantial change in behaviour. The numbering in column #2 follows for consistency that used in the Supplementary Material 'Circular economy levers and scenarios' (available upon request). Lever #1 regards efficiency improvement within industrial production, which has been excluded given the poor evidence available for further optimization of current production efficiencies

CE strategy	CE lever		Description	Quantification by 2050	First order effects	Sector / End-use	Source
Reduce	2	Reduce service level to reduce size and mass	Reduce the size of residential buildings, including apartments, essentially by reducing square meters per person.	From 46.6 m^2 per person to 20 m^2 per person. Increased usage intensity by 133% or a factors of 2.33.	Reduced **size of the stock** of residential buildings by 57% or a factor of 0.43. Reduced **annual inflow of residential building** by 57% or a factor of 0.43. Reduced **quantity of steel in the stock of residential buildings** by 57% or a factor of 0.43. Reduced **annual inflow of secondary steel** for the construction of residential buildings by 57% or a factor of 0.43. Increased **efficiency in the usage of steel** in residential buildings from 13.5 inhabitants per tonne of steel per year to 31.3. An increase of 132% or a factor of 2.32.	Residential buildings	(Cohen, 2021)
			Reduce the size of all newly manufactured individual cars (the lever focuses on 1.6t SUVs, since it is assumed are the cars with the greatest potential to reduce their mass and size). Considering the new sales as an indication of the demand trend (SUVs represent 49% of the new sales at EU level in the period 2011-2023, ca. 30% at German level), the estimate for the potential reduction in car weight	From 0.32 tonnes of steel per car to 0.29 tonnes of steel per car. Reduced mass by 20.6% or a factor of 0.794.	Reduced **quantity of steel in the stock of cars** by 20.6% or a factor of 0.794. Reduced **annual inflows of primary and secondary steel** used for the production of new cars by 20.6% or a factor of 0.794. Increased **efficiency in the usage of steel** in cars from 583,153 passengers.km per tonne of steel per	Vehicles - cars	(Acea, 2024; Kraftfahrtbundesamt, 2024)

			demanded at EU level would be equal to 20.6% (49%*42%), if 1.6t SUVs were replaced by smaller 1.1t cars (i.e. 49%*42%)		year 734,773. An increase of 26% of a factor of 1.26		
	3.1	Increase usage intensity	Increase the intensity commercial buildings are used, essentially by reducing the demand for office and retail space.	From 10,090 million m^2 of total area of commercial buildings to 8,778 million m^2. Reduced demand for office and retail space, and thus size of the stock of commercial buildings, by 13% or a factor of 0.87.	Reduced **annual inflows of commercial buildings** by 13% or by a factor of 0.87. Reduced **quantity of steel in the stock of commercial buildings** by 13% or by a factor of 0.87. Reduced **annual inflow of secondary steel** for the construction of commercial buildings by 13% or by a factor of 0.87. Increased **intensity of use of commercial buildings** by 13% or a factor of 1.13. Increased **efficiency in the usage of steel** in commercial buildings from 541,449 EUR GDP per tonne of steel to 622,666. An increase of 15% or a factor of 1.15.	Commercial buildings	
			Increase the intensity current road infrastructure is used, essentially by increasing road capacity.	From 537,503 passengers per year and 295,423 tonnes transported per year using current road infrastructure to 720,250 passengers per year and 396,000 tonnes per year. Increased usage intensity of road infrastructure by 34% or a factor of 1.34.	Reduced **quantity of steel in the stock of road infrastructure** by 25.4% or a factor of 0.746. Reduced **annual inflow of secondary steel** for the construction of road infrastructure by 25.4% or a factor of 0.746. Reduced **mass of steel used in the stock of road infrastructure** by 25.4% or a factor of 0.746. Increased **efficiency in the usage of steel** in road infrastructure from	Road infrastructure	(MAVEN, 2019)

					563,510 passengers.km per tonne of steel to 755,000 and from 309,717 tonnes.km transported per tonne of steel to 414,000. An increase of 34% or a factor of 1.34.		
			Increase the intensity current road infrastructure is used, essentially by increasing rail capacity.	From 1,218,731 passengers per year and 1,244,349 tonnes per year to 1,708,000 passengers per year and 1,742,000 tonnes per year. Increased usage intensity of rail infrastructure by 40% or a factor of 1.40.	Reduced **quantity of steel in the stock** of rail infrastructure by 28.6% or a factor of 0.714. Reduced **annual inflow of secondary steel** for the construction of rail infrastructure by 28.6% or a factor of 0.714. Reduced **mass of steel used in rail infrastructure** by 28.6% or a factor of 0.714. Increased **efficiency in the usage of steel** in rail infrastructure from 48,942 passengers.km per tonne of steel to 68,600 and from 49,970 tonnes.km transported per tonne of steel to 69,960. An increase of 40% or a factor of 1.40.	Railway infrastructure	(UNIFE (the European railway industry), 2024)
			Increase the intensity current trucks are used, essentially by reducing the routes conducted by empty trucks.	From 888,893 tonne.km per year per truck to 936,727 tonne.km per year per truck. Increased usage intensity of rail infrastructure by 5.5% or a factor of 1.055.	Reduced **size of the stock of trucks** by 5.5% or a factor of 0.945. Reduced **annual inflow of trucks** by 5.5% or a factor of 0.945. Reduced **annual inflow of primary and secondary steel** for the production of trucks by 5.5% or a factor of 0.945.	Vehicles - Trucks	(T&E, 2017)
			Increase the efficiency of steel used in steel food packaging, essentially by decreasing the weight of the container (light-weighting).	Light-weighting can reduce the material needed to fulfil the same function (packaging food). The reduction of weight in steel	Reduced **annual inflow of packaging** by 20% or a factor of 0.8. Reduced **annual inflow of primary and secondary steel** for the	Metal goods - Food packaging	(ArcelorMittal, 2024)

			From 1980 to 2004 a reduction of around 20% on average of the weight of packaging has been achieved (ArcelorMittal, 2024). We assume that a further 20% reduction potential of the packaging weight can be achieved by 2050.	packaging has been steadily increasing from the 70s to today (ca. 20% on average, from 15%-to-39%). Doing so, there is an increased efficiency of steel used in steel packaging by 26% or a factor of 1.26.	production of packaging by 20% or a factor of 0.8.		
	3.2	Reduce consum-ption to reduce the stock of infrastru-cture and productive assets	Reduce consumption of individual cars, essentially through car sharing.	As a result of car sharing and other trends, the stock of cars decrease by 24% in the EU. Therefore, it is assumed that car-sharing could reduce the current number of cars from 252,604,580 in the EU27 to 191,979,481 cars. Reduced stock of cars by 24% or a factor of 0.76.	Reduced **annual inflow of cars** in the stock by 24% or a factor of 0.76. Reduced **quantity of steel in the stock of cars** by 24% or a factor of 0.76. Reduced **annual inflows of primary and secondary steel** used for the production of cars from by 24% or a factor of 0.76. Increased **intensity of use of cars** by 32% or a factor of 1.32.	Vehicles – cars	The literature suggests a reduction of the stock between 5 and 43%; (Bucsky & Juhász, 2022; Chapman et al., 2024); the mid of the range is similar to the values taken in (Chapman et al., 2024).
	4.1	Substitute a technical solution by a more material-efficient one	Encourage the use of soft modes of transport (e.g. bikes) to substitute the use of cars.	In Copenhagen, the European leader in soft modes of transport, the ratio of number of cars owned to the population is 21.5%, whereas in the average European city this figure is 57.6%. Adopting a similar mode by the EU population living in cities and towns, would decrease the overall use of cars by 46.9%. This would translate to a decrease from 3,498,922 million	Reduced **size of the stock** of cars by 46.9% or a factor of 0.531. Reduced **annual inflow of cars** by 46.9% or a factor of 0.531. Reduced **quantity of steel** in the current stock of cars by 46.9% or a factor of 0.531. Reduced **annual inflow of primary and secondary steel** for the production of cars by 46.9% or a factor of 0.531.	Vehicles - cars	(Itera, 2022)

				passenger.km per year to 1,857,928.			
	4.2	Reduce mass	Reduce the mass of steel used in residential buildings, through addressing overspecification and using advanced high-strength material (i.e. reducing buildings' steel beam mass with no loss in safety or service).	From current 0.098 tonnes of steel per m² to 0.06272. A reduction of 36% or a factor of 0.64.	Reduced **quantity of steel in the current stock** of residential buildings by 36% or a factor of 0.64. Reduced **annual inflow of secondary steel** for the construction of residential buildings by 36% or a factor of 0.64. Increased **efficiency in the usage of steel** in residential buildings from 13.5 inhabitants per tonne of steel per year to 21.1. An increase of 56.3% or a factor of 1.563.	Residential buildings	(Moynihan & Allwood, 2014)
			Reduce the mass of steel used in commercial buildings, through addressing overspecification and using advanced high-strength material (i.e. reducing buildings' steel beam mass with no loss in safety or service).	From current 0.097 tonnes of steel per m² to 0.06208. A reduction of 36% or a factor of 0.64.	Reduced **quantity of steel in the current stock** of residential buildings by 36% or a factor of 0.64. Reduced **annual inflow of secondary steel** for the construction of residential buildings by 36% or a factor of 0.64. Increased **efficiency in the usage of steel** in commercial buildings from 541,449 EUR GDP per tonne of steel to 846,284. An increase of 56.3% or a factor of 1.563.	Commercial buildings	(Moynihan & Allwood, 2014)
			Reduce the mass of steel used in cars, through the use of high strength steel.	From current 0.32 tonne of steel per car to 0.22. A reduction of 31.3% or a factor of 0.687.	Reduced **quantity of steel in the current stock** of cars by 31.3% or a factor of 0.687. Reduced **annual inflow of primary and secondary steel** for the production of cars by 31.3% or a factor of 0.687. Increased **efficiency in the usage of steel** in cars from 583,153	Vehicles - cars	(Bian et al., 2015)

					passengers.km per tonne of steel per year to 1,557,018.5. An increase of 145% or a factor of 2.45.		
Recover	4.2	Increase share of secondary materials	Increase the share of secondary steel used in the production of mechanical equipment	From 25% of total steel used in the production of mechanical equipment to 50%.	Reduced **annual inflow of primary steel** used in the production of mechanical equipment by 33%, or a factor of 0.67, and increased **annual inflow of secondary steel** by 100% or a factor of 2.	Mechanical equipment	Own calculation based on MFA and quality assessment results (quality scenario) (Circle Economy & Bain, 2022)
			Increase the share of secondary steel used in the production of cars	From 25% of total steel used in the production of cars to 50%.	Reduced **annual inflow of primary steel** used in the production of cars by 33%, or a factor of 0.67, and increased a**nnual inflow of secondary steel** by 100% or a factor of 2.	Vehicles - cars	Own calculation based on MFA and quality assessment results (quality scenario) (Systemiq, 2023)
			Increase the share of secondary steel used in the production of trucks	From 25% of total steel used in the production of trucks to 50%.	Reduced an**nual inflow of primary steel** used in the production of trucks by 33%, or a factor of 0.67, and increased **annual inflow of secondary steel** by 100% or a factor of 2.	Vehicles - trucks	Own calculation based on MFA and quality assessment results (quality scenario)
			Increase the share of secondary steel used in the production of locomotives and rolling rail stocks	From 25% of total steel used in the production of locomotives and rolling rail stocks to 50%.	Reduced **annual inflow of primary steel** used in the production of locomotives and rolling rail stocks by 33%, or a factor of 0.67, and **increased annual inflow of secondary steel** by 100% or a factor of 2.	Locomotives and rolling rail stocks	Own calculation based on MFA and quality assessment results (quality scenario)
			Increase the share of secondary steel used in the production of food packaging	From 25% of total steel used in the production of food packaging to 100%.	Reduced **annual inflow of primary steel** used in the production of food packaging by 100%, or a factor of 1, and increased **annual inflow of secondary steel** by 300% or a factor of 3.	Metal goods - Food packaging	Own calculation based on MFA and quality assessment results (quality scenario)
Reuse	6	Increase lifetime	Increase the lifetime of residential buildings, essentially through i) digital product passport for steel components in buildings, ii) design for longevity/ durability, reversible disassembly, maintenance,	From 100 years of current lifetime of residential buildings to 120 years. Increased lifetime by 20% or a factor of 1.20.	Reduced **annual inflow of residential buildings** in the stock by 16.7% or a factor of 0.833. Reduced **annual inflow of secondary steel** for the construction	Residential buildings	See Annex Levers.

			repair, refurbishment, re-use, and recycling, iii) modular design, iv) availability of spare parts, v) Re-use of components or spare parts, vi) re-use of buildings, vii) refurbishment and upgrade.		of residential buildings by 16.7% or by a factor of 0.833. Increased **lifetime of steel** in residential buildings by 20% or a factor of 1.20. Increased **efficiency in the usage of steel** in residential buildings from 13.5 inhabitants per tonne of steel per year to 16.2. An increase of 20% or a factor of 1.20.		
			Increase the lifetime of commercial buildings, essentially through i) digital product passport for steel components in buildings, ii) design for longevity/ durability, reversible disassembly, maintenance, repair, refurbishment, re-use, and recycling, iii) modular design, iv) availability of spare parts, v) Re-use of components or spare parts, vi) re-use of buildings, vii) refurbishment and upgrade.	From 65 years of current lifetime of commercial buildings to 75 years. Increased lifetime by 15.4% or a factor of 1.154.	Reduced **annual inflow of commercial buildings** in the stock by 13.3% or a factor of 0.867. Reduced **annual inflow of secondary steel** for the construction of commercial buildings by 13.3% or a factor of 0.866. Increased **lifetime of steel** in commercial buildings by 15.4% or a factor of 1.154. Increased **efficiency in the usage of steel** in commercial buildings from 541,449 EUR GDP per tonne of steel to 624,832. An increase of 15.4% or a factor of 1.154.	Commercial buildings	For non-residential buildings, the current 65 years are extended to 75 in line with Damgaard et al. (2022), Deetman (2021) and Marinova et al. (2020). Other studies suggest even higher potential (up to 40-50%) but are rather based on model predictions than hard facts.
			Increase the lifetime of mechanical equipment, essentially through i) digital product passport for steel components in equipment, ii) design for longevity/ durability, reversible disassembly, maintenance, repair, refurbishment, re-use, and recycling, iii) modular design, iv) availability of spare parts, v) Re-	From 21.3 years of current lifetime of steel in mechanical equipment to 24.9 years.	Reduced **annual inflow of primary and secondary steel** for the production of mechanical equipment by 15% or a factor of 0.85. Increased **efficiency in the usage of steel** in mechanical equipment from 458 million tonnes of materials consumed per million tonnes of steel per year to 536. An increase of 17% or a factor of 1.17.	Mechanical equipment	(Cooper & Allwood, 2012) suggest that for steel industrial equipment a lifetime extension of 17% can be achieved through reuse (corresponding to a reduction in the demand for steel of 15%).

			use of components or spare parts, vi) re-use of equipment, vii) refurbishment and upgrade.				
			Increase the lifetime of individual cars, essentially through i) digital product passport for steel components in cars, ii) design for longevity/ durability, reversible disassembly, maintenance, repair, refurbishment, re-use, and recycling, iii) modular design, iv) availability of spare parts, v) Re-use of components or spare parts, vi) re-use of cars, vii) refurbishment and upgrade.	From 12.3 years of current lifetime of cars to 15.4 years. Increased lifetime by 25% or a factor of 1.25.	Reduced **inflow of cars** in the stock by 20% or a factor of 0.8. Reduced **annual inflow of primary and secondary steel** for the production of cars by 20% or a factor of 0.8. Increased **lifetime of steel** in cars by 25% or a factor of 1.25. Increased **efficiency in the usage of steel** in cars from 583,153 passengers.km/tonne of steel/year to 728,941. An increase of 25% or a factor of 1.25.	Vehicles - cars	(World Economic Forum, 2020)
			Increase the lifetime of trucks, essentially through i) digital product passport for steel components in trucks, ii) design for longevity/ durability, reversible disassembly, maintenance, repair, refurbishment, re-use, and recycling, iii) modular design, iv) availability of spare parts, v) Re-use of components or spare parts, vi) re-use of trucks, vii) refurbishment and upgrade. Following their Circular Economy commitments, Renault offers a regeneration scheme for their trucks that has increased their lifespan by 3 years. Using this case, it is assumed that there is a potential for truck lifespan to increase by 3 years	From 14.2 years of current lifetime of trucks to 17.3 years. Increased lifetime by 21% or a factor of 1.21.	Reduced **inflow of trucks** in the stock by 17.4% or a factor of 0.826. Reduced **annual inflow of primary and secondary steel** for the production of trucks by 17.4% or a factor of 0.826. Increased **lifetime of steel** in trucks by 21% or a factor of 1.21. Increased **efficiency in the usage of steel** in trucks from 960,124 tonnes transported.km per tonne of steel per year to 1,161,750. An increase of 21% or a factor of 1.21.	Vehicles - trucks	(Renault Trucks, 2024)

Annex 2. MFA: Concordance of finished steel products categories

Table A2. Concordance of finished steel product categories from categories used in the presented MFA (based on worldsteel production statistics) to the consolidated categories defined in the draft of the Preparatory study on iron and steel

	Categories used for MFA	ESPR categories
Long	Concrete reinforcing bars	Bars for reinforcment of concrete
	Hot rolled bars	Other hot rolled bars (e.g. merchant bars)
	Wire rod	Rod
	Railway track material	Railway track material and other long products
	Heavy sections	Heavy sections and mining frames
	Light sections	Light sections
	Seamless tubes	Seamless tube
Flat	Hot rolled plate	Hot rolled plate (e.g. Quarto plate)
	Hot rolled coil, sheet and strip	Hot rolled coil + Cold rolled coil
	Electrical sheet and strip	Electrical sheet
	Tinmill products	Tinplate and tinned products
	Other metal coated sheet and strip	Galvanized coil
	Non-metallic coated sheet and strip	Organically coated and other coated products
Tubular	Welded tubes	Welded tube
Casting	Iron Cast	Cast iron products

Source: JRC elaboration

Annex 3. Steel quality grades (Dworak and Fellner, 2021)

Table A3. Quality grades from the work of Dworak and Fellner (2021)

Finished Steel Product and Sector	Quality class
HRB_for_buildings	Q4
HRB_for_infrastructure	Q4
HRB_for_cars	Q3
HRB_for_trucks	Q3
HRB_for_otherTransport	Q3
HRB_for_mechanicalEng	Q3
HRB_for_electricalEng	Q3
CRB_for_buildings	Q4
CRB_for_infrastructure	Q4
WR_for_buildings	Q3
WR_for_infrastructure	Q3
WR_for_cars	Q2
WR_for_trucks	Q2
WR_for_otherTransport	Q2
WR_for_mechanicalEng	Q2
WR_for_electricalEng	Q2
CI_for_buildings	Q0
CI_for_infrastructure	Q0
CI_for_cars	Q0
CI_for_trucks	Q0
CI_for_otherTransport	Q0
CI_for_mechanicalEng	Q0
CI_for_electricalEng	Q0
CRC_for_buildings	Q1
CRC_for_infrastructure	Q1
CRC_for_cars	Q1
CRC_for_trucks	Q1
CRC_for_metalGoods	Q1
CRC_for_mechanicalEng	Q1
CRC_for_domestics	Q1
HRC_for_buildings	Q2
HRC_for_infrastructure	Q2
HRC_for_cars	Q1
HRC_for_trucks	Q1
HRC_for_otherTransport	Q1
HRC_for_mechanicalEng	Q1
HRC_for_electricalEng	Q1
HRG_for_buildings	Q2
HRG_for_infrastructure	Q2
P_for_buildings	Q3
P_for_infrastructure	Q3
P_for_cars	Q2
P_for_trucks	Q2
P_for_otherTransport	Q2

P_for_mechanicalEng	Q2
P_for_electricalEng	Q2
TP_for_packaging	Q1
HS_for_buildings	Q4
HS_for_infrastructure	Q4
LS_for_buildings	Q4
LS_for_infrastructure	Q4
RS_for_infrastructure	Q4
ST_for_buildings	Q2
ST_for_infrastructure	Q2
ST_for_cars	Q2
ST_for_trucks	Q2
ST_for_mechanicalEng	Q2
ST_for_electricalEng	Q2
WT_for_buildings	Q2
WT_for_infrastructure	Q2
WT_for_trucks	Q2
WT_for_otherTransport	Q2
WT_for_electricalEng	Q2
HRB_for_metalGoods	Q4
WR_for_metalGoods	Q2
RS_for_mechanicalEng	Q4
ST_for_otherTransport	Q2
P_for_metalGoods	Q2
HRC_for_metalGoods	Q1
ES_for_electricalEng	Q1
CRC_for_electricalEng	Q1
WT_for_mechanicalEng	Q2
WT_for_metalGoods	Q2
CS_for_mechanicalEng	Q0
CS_for_metalGoods	Q0
CI_for_metalGoods	Q0

Source: JRC elaboration

Annex 4. Additional LCA results

Table A4. Savings relative to the Baseline (BSL50) scenario, by 2050, calculated via LCA. CTC50: Compliance to selected Circular economy Targets; ACE50: Ambitious Circular Economy; ACE50*: Ambitious Circular Economy including demand-based levers implying behavioural change

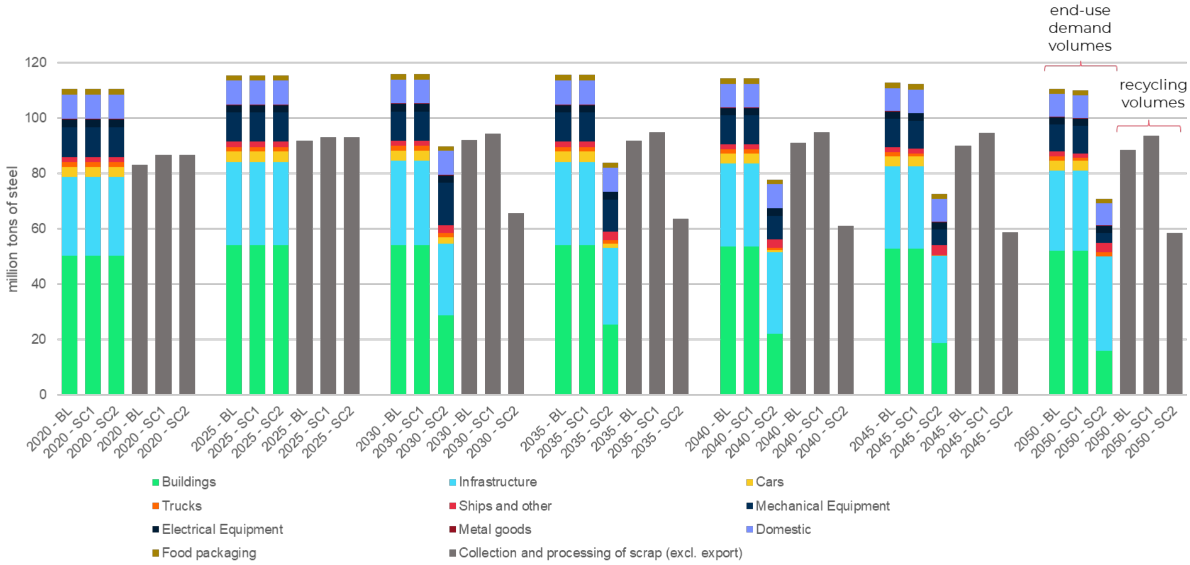
Impact category	CTC50	ACE50	ACE50*
Climate change	-3%	-54%	-66%
Ozone depletion	-3%	-49%	-60%
Human toxicity, cancer effects	-2%	-46%	-58%
Human toxicity, non-cancer effects	-3%	-56%	-69%
Particular matter	-3%	-52%	-64%
Ionising radiation	-2%	-45%	-56%
Photochemical ozone formation	-2%	-47%	-58%
Acidification, terrestrial	-2%	-47%	-58%
Eutrophication, terrestrial	-2%	-46%	-56%
Eutrophication, freshwater	-2%	-46%	-57%
Eutrophication, marine	-2%	-46%	-56%
Ecotoxicity, freshwater	-2%	-45%	-56%
Land Use	-3%	-48%	-59%
Water Use	-2%	-42%	-53%
Resource use, minerals and metals	-2%	-45%	-55%
Resource use, energy	-2%	-47%	-58%

Source: JRC elaboration

Annex 5. Application of the workflows (EEMRIO) to the case of steel

The workflow starts by building upon the output of the material flow analysis: the **material flows and stocks of the material sector steel** in the year 2015 and with 5-year intervals up to 2050. Figure A1 visualises this output. It shows the amount of steel used in different end-use applications (in colours). In addition, the recycled volume of steel is shown in grey.

Figure A1. End-use demand for steel in different end-use applications (colours), and the recycling volumes of steel (grey), in million tonne of steel, 2020-2050, EU27 demand and recycling



Source: JRC elaboration

Step 1: Track the steel-related materials flows in the MRIO-tables

First, we investigate the FIGAROe3 model to track these steel-related material flows. Therefore, a matching between the steel-related material flows and stocks and the product and sector classification of FIGAROe3 is needed. The (lack of) similarities are provided in Table A5. In the last column, an indication on the quality of the exact matching is given. Note, the input-output tables (nor the supply and use tables) do not give information on stocks in the society. However, the change in stock is included in the tables.

Table A5. Similarities between the categories in the material flow analysis and the product and sector classification from FIGAROe3

Production phase	Product	Product/sector classification	Match
MFA	*MFA*	*FIGAROe3*	
Production	Iron ore	Supply of product ‘Iron ores’ (CPA_B07_B) by sector ‘Mining of iron ores’ (B07_A)	Good

Production	Crude steel	Supply of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A[56]) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B[56]) by sectors 'Manufacture of basic iron and steel and of ferro-alloys and first products thereof' (C24_A[57]) and 'Re-processing of secondary steel into new steel' C24_B[57]) *= Basic oxygen furnace + Electric arc furnace*	Good
Production	Pig iron	Not available, it is part of the production within sector 'Manufacture of basic iron and steel and of ferro-alloys and first products thereof' (C24_A) and 'Re-processing of secondary steel into new steel' C24_B)	**Poor**
Production	Direct reduction	Not available, it is part of the production within sector 'Manufacture of basic iron and steel and of ferro-alloys and first products thereof' (C24_A) and 'Re-processing of secondary steel into new steel' C24_B)	**Poor**
Steel production	Basic oxygen furnace	Not available, it is part of the production within sector 'Manufacture of basic iron and steel and of ferro-alloys and first products thereof' (C24_A) and 'Re-processing of secondary steel into new steel' C24_B)	**Poor**
Steel production	Electric arc furnace	Not available, it is part of the production within sector 'Manufacture of basic iron and steel and of ferro-alloys and first products thereof' (C24_A) and 'Re-processing of secondary steel into new steel' C24_B)	**Poor**
Recycling	Recycled scrap	Supply of product 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by sectors 'Manufacture of basic iron and steel and of ferro-alloys and first products thereof' (C24_A) and 'Reprocessing of secondary steel into new steel' C24_B)	Good
Steel demand	Buildings	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by part of the sector 'Construction' (F_A) and part of sector 'Manufacture of fabricated metal products, except machinery and equipment' (C25), specifically 25.1 (metal structures and part of structures) and 25.2 (tanks, generators, radiators and boilers)	**Poor**
Steel demand	Infrastructure	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by part of the sector 'Construction' (F_A) and part of sector 'Manufacture of fabricated metal products, except machinery and equipment' (C25), specifically 25.1 (metal structures and part of structures) and 25.2 (tanks, generators, radiators and boilers)	**Poor**
Steel demand	Cars	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by part of	**Poor**

[56] 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) include:

- Primary materials of iron and steel;
- Crude steel;
- Flat rolled products of steel (including clad, plated, or coated);
- Hot processed bars and rods of steel;
- Hot processed open sections of steel, sheet piling of steel and railway or tramway track construction material of steel;
- Tubes, pipes, hollow profiles, and related fittings of steel; and
- Other products of first processing of steel.

[57] 'Manufacture of basic iron and steel and of ferro-alloys and first products thereof' (C24_A) and 'Re-processing of secondary steel into new steel' (C24_B) are in line with NACE Rev. 2 sectors 24.1, 24.2 and 24.3 and include:

- Manufacture of basic iron and steel and of ferro-alloys;
- Manufacture of tubes, pipes, hollow profiles, and related fittings, of steel; and
- Manufacture of other products of first processing of steel.

Note that the casting of metals (NACE Rev. 2 C24.5) is not included in this sector, but is part of sector 'Casting of metals' (C24_N).

		the sector 'Manufacture of motor vehicles, trailers and semi-trailers' (C29)	
Steel demand	Trucks	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by part of the sector 'Manufacture of motor vehicles, trailers and semi-trailers' (C29)	**Poor**
Steel demand	Ships and other	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by the sector 'Manufacture of other transport equipment' (C30)	Good
Steel demand	Mechanical equipment	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by part of the sector 'Manufacture of electrical machinery and apparatus n.e.c.' (C27), (specifically 27.1 electric motors, generators, transformers), sectors 'Manufacture of machinery and equipment n.e.c.' and 'Manufacture of office machinery and computers' (C28_A and C28_B), and part of sector 'Manufacture of fabricated metal products, except machinery and equipment' (C25), specifically 25.3 (steam generators, except central heating hot water boilers)	**Poor**
Steel demand	Electrical equipment	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by the sectors 'Manufacture of radio, television and communication equipment and apparatus' (C26_A), 'Manufacture of medical, precision and optical instruments, watches and clocks' (C26_B), and part of the sector 'Manufacture of electrical machinery and apparatus n.e.c.' (C27) excluding 27.1 (electric motors, generators, transformers)	**Poor**
Steel demand	Metal goods	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by part of the sector 'Manufacture of fabricated metal products, except machinery and equipment' (C25)	**Poor**
Steel demand	Domestic	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by part of the sector 'Manufacture of fabricated metal products, except machinery and equipment' (C25), excluding 25.1, 25.2 and 25.3.	**Poor**
Steel demand	Food packaging	Use of products 'Basic iron and steel and of ferro-alloys and first products thereof' (CPA_C24_A) and 'Secondary steel for treatment, re-processing of secondary steel into new steel' (CPA_C24_B) by agriculture (A01_A till A01_Q) and the food processing industries represented by the sector C10_A till C10_J and C11	Good
Stock of steel	Buildings		No
Stock of steel	Infrastructure		No
Stock of steel	Cars		No
Stock of steel	Trucks		No
Stock of steel	Ships and other		No
Stock of steel	Mechanical equipment		No
Stock of steel	Electrical equipment		No
Stock of steel	Metal goods		No
Stock of steel	Domestic		No

Stock of steel	Food packaging		No
End of life	Buildings	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Infrastructure	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Cars	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Trucks	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Ships and other	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Mechanical equipment	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Electrical equipment	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Metal goods	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Domestic	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**
End of life	Food packaging	Steel inputs used by sector 'Recycling of waste and scrap' (E37T39_A)	**Poor**

Source: JRC elaboration

Second, we check if the quantities of these flows (in monetary values) are in line with the 2015-results from the MFA. The total EU27 supply of product CPA_C24_A (row dimension) is **152,588.4 million EUR**, mainly supplied by the EU27 sectors C24_A (91,037.6 million EUR) and C24_B (59,841.9 million EUR). Note, the supply of product CPA_C24_A by the RoW equals 1,698,726.0 million EUR. The share of secondary materials input seems to be underestimated in FIGAROe3, compared to the MFA in which in the EU27 110,297 kilotonne of recycled scrap is used compared to 27,843 kilotonne of iron ore. There is no supply of product CPA_C24_B. Both the sectors C24_A and C24_B supply the product CPA_C24_A.

From the supply tables it is derived that in the EU27 139,440.9 million EUR is supplied by the sectors C24_A and C24_B. The remainder is provided by C25 'Manufacture of fabricated metal products, except machinery and equipment' (5.427,5 million EUR) and other manufactures of metal products. The high concentration (>91%) of product CPA_C24_A shows that the production of intermediate steel products is well represented by the output of sectors C24_A and C24_B.

Looking into detail into the use tables focusses on two dimensions. The row-dimension shows the use of product CPA_C24_A across the different industries, while the column dimension shows the input structure of sectors C24_A and C24_B.

The total use of the EU27 product CPA_C24_A is **152,586.7 million euro** (almost) equalling the total EU27 supply of this product. 119,592.1 million euro (78%) is used by EU27-industries, 1,346.4 million euro (1%) by EU27 final demand, and the remainder, 31,648.2 million euro (21%) is exported. In addition, the EU27 imports 23,047.1 million euro of product CPA_C24_A from the RoW. The total EU27 use of product CPA_C24_A (EU27 + RoW) is **143,985.6 million euro**. The products CPA_C24_A is used by different manufacturing industries: The EU27 sectors using the largest shares of product CPA_C24_A are:

- 'Manufacture of basic metals' (C24): 27.4%
- 'Manufacture of fabricated metal products, except machinery and equipment' (C25): 25.1%
- 'Manufacture of computer, electronic and optical products' (C26): 0.8%
- 'Manufacture of electrical equipment' (C27): 5.6%
- 'Manufacture of machinery and equipment n.e.c.' (C28): 10.2%
- 'Manufacture of motor vehicles, trailers and semi-trailers' (C29): 11.2%
- 'Manufacture of other transport equipment' (C30): 2.0%
- 'Construction' (F_A): 6.1%
- 'Manufacture of food products and beverages (C10-11): 0.1%

Together, these sectors use 88.7% of the product CPA_C24_A. Although the identified steel demand sectors (see Table A5), the distribution is not in line with the results from the MFA.

The column dimension shows the input structure of the sectors C24_A and C24_B. The total use by the EU27 sectors C24_A and C24_B (almost) equal the total supply of both sectors: 91,037.6 million euro and 59,841.9 million euro respectively. Per euro output, both sectors create, respectively, 0.27 and 0.22 euro value added (incl. compensation of employees, consumption of fixed capital, and net operating surplus). The use of metal ores is only 0.01 euro for sector C24_A. Also, both use energy products (including coal, electricity, and gas) of, respectively, 0.08 and 0.12 euro. A large intersectoral loop exist expressed by a use of product CPA_C24 of, respectively, 0.26 and 0.27 euro and waste management services of, respectively, 0.07 and 0.09 euro. Other use includes mainly trade, transport and supporting (e.g. legal and accounting) services.

The input structure of the RoW sector C24_A is different, with a smaller share of value added (only 0.11 euro) and much higher inputs costs for metal ores (0.07 euro), energy products (0.11 euro), and the use of CPA_C24 (0.41 euro).

Based on the above assessment, several misalignments with the MFA-results arise:

- There is no disaggregation in FIGAROe3 available to distinguish between iron production and steel production.
- There is no disaggregation in FIGAROe3 available to distinguish between blast furnaces and direct reduction (for iron production) and between basic oxygen furnaces and electric arc furnaces (for steel production).
- A disaggregation between primary and secondary production is provided, but it is unclear as there is no disaggregation between iron and steel production an no disaggregation between the main production routes.
- No disaggregation available for construction to distinguish between buildings and infra-structure.
- No disaggregation is available to allow a distinction between the production of metal goods and the production of domestic goods.
- No disaggregation between waste categories (CD, MSW, WEEE, ELV, IEW, NEW, dissipative, and non-collectable steel).

Step 2 and Step 3 are performed in R.

Step 4: Product and sector disaggregation

A disaggregation of the sector related to steel 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 i) to make the sum of the existing sectors 'Manufacture of basic iron and steel and of ferro-alloys and first products thereof' (C24_A) and 'Re-processing of secondary steel into new steel' C24_B), and ii) to disaggregate into:

- (C24_AB1) Manufacture of **pig iron** (blast furnace)
- (C24_AB2) Manufacture of **direct reduced iron** (direct reduction)
- (C24_AB3) Manufacture of **liquid stee**l via oxygen blow furnace
- (C24_AB4) Manufacture of **liquid steel** via electric furnace
- (C24_AB5) Manufacture of **cast steel** (liquid steel -> steel product casting)

- (C24_AB6) Manufacture of **cast iron** (pig iron -> iron foundry casting)
- (C24_AB7) Manufacture of **electrical sheet and cold rolled coil** (liquid steel -> slab -> hot strip mill -> cold rolling mill)
- (C24_AB8) Manufacture of **tin plated** (liquid steel -> slab -> hot strip mill -> cold rolling mill -> tin mill)
- (C24_AB9) Manufacture of **plate** (liquid steel -> slab -> plate mill)
- (C24_AB10) Manufacture of **cold rolled coil galvanized or coated** (liquid steel -> slab -> hot strip mill -> cold rolling mill -> galv. plant)
- (C24_AB11) Manufacture of **hot rolled galvanized** (liquid steel -> slab -> hot strip mill -> galv. plant)
- (C24_AB12) Manufacture of **hot rolled narrow strip and coil** (liquid steel -> slab -> hot strip mill)
- (C24_AB13) Manufacture of **welded tube** (liquid steel -> slab -> hot strip mill -> forming)
- (C24_AB14) Manufacture of **seamless tube** (liquid steel -> billet -> rod and bar mill -> extrusion)
- (C24_AB15) Manufacture of **wire rod, reinforcing bar and hot rolled bar** (liquid steel -> billet -> rod and bar mill)
- (C24_AB16) Manufacture of **heavy, light, and rail section** (liquid steel -> bloom -> section mill)
- (C24_AB17) Collection and processing of **steel scrap** (end of life scrap)
- (C24_AB18) Collection and processing of **steel scrap** (production scrap)
- *(C24_AB19) C24 others*

The ‘C24 others’ is added to keep the balance in the supply and use tables.

The product disaggregation includes the disaggregation of products ‘Basic iron and steel and of ferro-alloys and first products thereof’ (CPA_C24_A) and ‘Secondary steel for treatment, reprocessing of secondary steel into new steel’ (CPA_C24_B) into:

- (CPA_C24_AB1) **Pig iron**: input to the oxygen blow furnace (92.4%), electric furnace (5.0%), or iron foundry casting (2.6%)
- (CPA_C24_AB2) **Direct reduced iron**: input to electric furnace (100.0%)
- (CPA_C24_AB3) **Liquid steel** via oxygen blow furnace into cast steel (0.7%), electrical sheet and cold rolled coil (16.6%), tin plated (1.4%), plate (13.4%), cold rolled coil galvanized or coated (13.2%), hot rolled galvanized (1.2%), hot rolled narrow strip and coil (20.7%), welded rube (7.5%), seamless tube (1.8%), wire rod, reinforcing bar and hot rolled bar (19.7%), and heavy, light, and rail section (3.8%).
- (CPA_C24_AB4) **Liquid steel** via electric furnace into cast steel (1.1%), electrical sheet and cold rolled coil (2.1%), tin plated (0.2%), plate (0.1%), cold rolled coil galvanized or coated (1.6%), hot rolled galvanized (0.1%), hot rolled narrow strip and coil (2.6%), welded rube (0.7%), seamless tube (4.9%), wire rod, reinforcing bar and hot rolled bar (69.9%), and heavy, light, and rail section (16.7%).
- (CPA_C24_AB5) **Cast steel** into mechanical engineering (50.0%) and other metal goods (50.0%).

- (CPA_C24_AB6) **Cast iron** into buildings (4.0%), infrastructure (36.4%), cars (19.2%), trucks (4.0%), other transport (1.0%), mechanical engineering (13.1%), electrical engineering (9.1%), and other metal goods (13.1%).
- (CPA_C24_AB7) **Electrical sheet and cold rolled coil** into buildings (15.1%), infrastructure (2.5%), cars (12.6%), trucks (2.5%), mechanical engineering (12.6%), electrical engineering (18.6%), other metal goods (21.8%), and domestic appliances (14.3%).
- (CPA_C24_AB8) **Tin plated** into packaging (100.0%).
- (CPA_C24_AB9) **Plate** into buildings (18.0%), infrastructure (17.0%), cars (1.0%), other transport (17.0%), mechanical engineering (17.0%), electrical engineering (3.0%), and other metal goods (27.0%).
- (CPA_C24_AB10) **Cold rolled coil galvanized or coated** into buildings (23.4%), infrastructure (4.7%), cars (43.0%), trucks (4.4%), mechanical engineering (2.8%), electrical engineering (3.0%), other metal goods (13.9%), and domestic appliances (4.8%).
- (CPA_C24_AB11) **Hot rolled galvanized** into buildings (80.0%) and infrastructure (20.0%).
- (CPA_C24_AB12) **Hot rolled narrow strip and coil** into buildings (45.1%), infrastructure (15.5%), cars (9.3%), trucks (2.4%), other transport equipment (1.0%), mechanical engineering (16.1%), electrical engineering (1.9%), and other metal goods (8.6%).
- (CPA_C24_AB13) **Welded tube** into buildings (21.8%), infrastructure (39.6%), trucks (2.0%), other transport (2.0%), mechanical engineering (26.7%), electrical engineering (5.9%), and other metal goods (2.0%).
- (CPA_C24_AB14) **Seamless tube** into buildings (45.5%), infrastructure (13.9%), cars (17.8%), trucks (4.0%), other transport (4.0%), mechanical engineering (10.9%), and electrical engineering (4.0%).
- (CPA_C24_AB15) **Wire rod, reinforcing bar and hot rolled bar** into buildings (29.6%), infrastructure (25.5%), cars (4.6%), trucks (2.1%), other transport (0.7%), mechanical engineering (9.7%), electrical engineering (3.3%), and other metal goods (24.3%).
- (CPA_C24_AB16) **Heavy, light, and rail section** into buildings (63.3%), infrastructure (34.9%), and mechanical engineering (1.8%).
- (CPA_C24_AB17) **Steel scrap** (end of life scrap): input to electric furnace (61.7%), oxygen blow furnace (36.2%) and iron foundry casting (2.0%)
- (CPA_C24_AB18) **Steel scrap** (production scrap): input to electric furnace (61.7%), oxygen blow furnace (36.2%) and iron foundry casting (2.0%)
- *(CPA_C24_AB19) CPA_C24 others*

All shares are based on Cullen et al. (2012) [58]. The 'CPA_C24 others' is added to keep the balance in the supply and use tables.

[58] Shares from Cullen J., Allwood J., Bambach M. (2012). Mapping of Global Flow of Steel: From Steelmaking to End-Use Goods. Environmental Science & Technology, 46, 13048-13055. https://doi.org/10.1021/es302433p

First, the total production output of the intermediate products is estimated for EU27 in 2015. Table C2 in the SI of Dworak and Fellner (2021)[59] details the use of steel intermediate products in end-use applications. In combination with a production volume of intermediary steel products of the EU27 and the UK[60] a first rough estimate is derived. The totals from Rostek et al. (2022) are entered in the last column of the table (see Figure A2). Based on the shares from Dworak and Fellner (2021), the middle of the table is filled in. As a last step, the column totals are added.

Figure A2. Estimate of the use of intermediate products linked to end-use applications, 2019-estimate for EU27 + UK. Own estimate based on Dworak and Fellner (2021) and Rostek et al. (2022)

No.	Intermediate products	Construction		Transport			Industrial Equip.		Metal goods			Total
		Buildings	Infra-structure	Cars	Trucks	Other Transport	Mechanical Engineering	Electrical Engineering	Other Metal Goods	Domestic appliances	Packaging	*kton*
7	Cast Steel	0,0	0,0	0,0	0,0	0,0	99,0	0,0	99,0	0,0	0,0	**198,0**
8	Cast Iron	366,8	3.301,5	1.742,4	366,8	91,7	1.192,2	825,4	1.192,2	0,0	0,0	**9.079,0**
9	Electrical Strip	0,0	0,0	0,0	0,0	0,0	0,0	1.377,0	0,0	0,0	0,0	**1.377,0**
10	Tin plated	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3.845,0	**3.845,0**
11	Plate	*1.987,6*	*1.877,1*	*110,4*	0,0	*1.877,1*	*1.877,1*	*331,3*	*2.981,3*	0,0	0,0	**11.042,0**
12	Cold Rolled Coil galvanized	*3.362,8*	*896,8*	*11.209,5*	*1.120,9*	*0,0*	*672,6*	*672,6*	*3.587,0*	*1.120,9*	0,0	**22.643,1**
13	Cold Rolled Coil coated	*2.873,8*	*359,2*	*239,5*	*39,9*	*0,0*	*79,8*	*119,7*	*119,7*	*159,7*	0,0	**3.991,4**
14	Cold Rolled Coil	*1.295,7*	*216,0*	*1.079,8*	*216,0*	*0,0*	*1.079,8*	*216,0*	*1.871,6*	*1.223,7*	0,0	**7.198,5**
15	Hot Rolled galvanized	2.084,5	521,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**2.605,7**
16	Hot Rolled Narrow Strip	*314,9*	*175,0*	*647,4*	*175,0*	*17,5*	*52,5*	*17,5*	*384,9*	0,0	0,0	**1.784,6**
17	Hot Rolled Coil	*15.954,3*	*5.431,2*	*2.715,6*	*678,9*	*339,5*	*5.770,7*	*678,9*	*2.715,6*	0,0	0,0	**34.284,7**
18	Welded Tube	181,4	329,9	0,0	16,5	16,5	222,7	49,5	16,5	0,0	0,0	**833,0**
19	Seamless Tube	419,5	127,7	164,1	36,5	36,5	100,3	36,5	0,0	0,0	0,0	**921,0**
20	Wire Rod	6.065,6	5.438,2	627,5	627,5	209,2	209,2	1.045,8	6.693,1	0,0	0,0	**20.916,0**
21	Reinforcing Bar	6.766,0	6.000,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**12.766,0**
22	Hot Rolled Bar	566,8	113,4	1.473,7	340,1	113,4	4.194,4	453,5	4.307,8	0,0	0,0	**11.563,0**
23	Heavy Section	7.359,7	2.198,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**9.558,0**
24	Light Section	70,7	22,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	**93,0**
25	Rail Section	0,0	1.883,7	0,0	0,0	0,0	209,3	0,0	0,0	0,0	0,0	**2.093,0**
		49.670,2	**28.891,3**	**20.009,9**	**3.618,1**	**2.701,3**	**15.759,6**	**5.823,5**	**23.968,9**	**2.504,3**	**3.845,0**	**156.792,0**

Source: JRC elaboration

Starting from the data in Figure A2, several steps will be implemented to bring the result in line with EU27 and the year 2015:

- Aggregation of the intermediate product groups in line with the defined sector/products groups in the new supply and use tables. Intermediate products 9 and 14 are aggregated into AB7 electrical sheet and CR coil. Intermediate products 12 and 13 are aggregated into AB10 CR coil galvanized or coated. Intermediate products 16 and 17 are aggregated into AB12 HR narrow strip and coil. Intermediate products 20, 21 and 22 are aggregated into AB15 wire rod, reinforcing bar and HR bar. Intermediate products 23, 24 and 25 are aggregated into AB16 heavy, light, and rail section.
- The column totals are corrected based on the MFA-results for 2015. For example, the steel use in buildings (part of construction) is corrected to 59,314.0 kiloton.
- Based on the new column totals, the use of intermediate products per end-use application is recalculated keeping the input shares of intermediate products per end-use applications constant.
- New row totals are calculated per intermediate product AB5 to AB16.

[59] Dworak S. & Fellner J. (2021). Steel scrap generation in the EU-28 since 1946 – Sources and composition. Resources, Conservation and Recycling, 173, 105692, https://doi.org/10.1016/j.resconrec.2021.105692

[60] Rostek L., Lotz M., Wittig S., Herbst A., Loibl A., Espinoza L. (2022). A dynamic material flow model for the European cycle. No. S07/2022

Figure A3. Improved estimate of the use of intermediate products linked to end-use applications, 2015-estimate for EU27

No.	Intermediate products	Construction		Transport			Industrial Equip.		Metal goods			Total	
		Buildings	Infra-structure	Cars	Trucks	Other Transport	Mechanical Engineering	Electrical Engineering	Other Metal Goods	Domestic appliances	Packaging	*kton, calculated*	*kton, from MFA*
AB5	Cast Steel	0,0	0,0	0,0	0,0	0,0	76,8	0,0	40,9	0,0	0,0	**117,7**	**117,7**
AB6	Cast Iron	438,1	3.689,8	366,4	187,6	72,5	925,1	411,6	492,7	0,0	0,0	**6.583,8**	**6.583,8**
AB7	Electrical sheet and CR coil	1.547,3	241,4	227,1	110,4	0,0	837,9	794,4	773,5	65,5	0,0	**4.597,5**	**4.597,5**
AB8	Tin plated	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2.580,0	**2.580,0**	**2.580,0**
AB9	Plate	*2.373,5*	*2.098,0*	*23,2*	*0,0*	*1.485,0*	*1.456,6*	*165,2*	*1.232,1*	*0,0*	*0,0*	**8.833,6**	**8.833,6**
AB10	CR coil galvanized or coated	*7.447,5*	*1.403,7*	*2.407,7*	*593,6*	*0,0*	*583,8*	*395,1*	*1.532,0*	*68,6*	*0,0*	**14.432,0**	**14.432,0**
AB11	HR galvanized	*2.489,3*	*582,4*	*0,0*	*0,0*	*0,0*	*0,0*	*0,0*	*0,0*	*0,0*	*0,0*	**3.071,7**	**3.071,7**
AB12	HR narrow strip and coil	*19.428,0*	*6.265,7*	*707,2*	*436,6*	*282,4*	*4.518,6*	*347,3*	*1.281,4*	*0,0*	*0,0*	**33.267,2**	**33.267,2**
AB13	Welded Tube	216,7	368,7	0,0	8,4	13,0	172,8	24,7	6,8	0,0	0,0	**811,2**	**811,2**
AB14	Seamless tube	*500,9*	*142,7*	*34,5*	*18,7*	*28,9*	*77,8*	*18,2*	*0,0*	*0,0*	*0,0*	**821,6**	**821,6**
AB15	Wire rod, reinforcing bar and HR bar	*15.999,8*	*12.910,4*	*441,9*	*494,7*	*255,1*	*3.417,1*	*747,6*	*4.546,5*	*0,0*	*0,0*	**38.813,2**	**38.813,2**
AB16	Heavy, light, and rail section	8.873,0	4.587,2	0,0	0,0	0,0	162,4	0,0	0,0	0,0	0,0	**13.622,6**	**13.622,6**
		59.314,0	**32.290,0**	**4.208,0**	**1.850,0**	**2.137,0**	**12.229,0**	**2.904,0**	**9.906,0**	**134,1**	**2.580,0**	**127.552,1**	**127.552,1**
											127.552,1		

Source: JRC elaboration

In addition, a market price (2015, in EUR per kilogram intermediate product) is estimated to allow for a conversion into monetary units. The classification codes (HS-nomenclature) per intermediate product are taken from Table B1 from the SI of Dworak and Fellner (2021). The estimate is based on Eurostat trade data (extra EU-trade of EU27_2020 in HS6-classification for 2015) by dividing the import value with the import quantity. For AB1 to AB4 and AB17 and AB18 Dworak and Fellner (2021) did not provide a list of classification codes, therefor an own estimate is made. Only for AB11 HR galvanized no data could be found. Therefore, the value from AB12 HR narrow strip and coil is taken as an approximate value (Figure A4).

Figure A4. Estimated market price for intermediate products, 2015, EU27. Own estimate based on Eurostat trade data

Intermediate products	Classification code (estimate)	Estimated market price (2015, EUR/kg)
Pig Iron	24.10.11.00	0,290
Direct reduced iron	24.10.13.00	0,196
Liquid steel (from BOF)	24.10.21	0,320
Liquid steel (from EF)	24.10.21	0,320
Cast Steel	based on trade statistics, Eurostat, 2015, extra-EU trade, in HS6, classification from Dworak (2020) - SI section B1	0,422
Cast Iron		4,592
Electrical sheet and CR coil		1,313
Tin plated		0,955
Plate		0,937
CR coil galvanized or coated		0,636
HR galvanized		0,837
HR narrow strip and coil		0,837
Welded Tube		0,634
Seamless tube		1,740
Wire rod, reinforcing bar and HR bar		1,160
Heavy, light, and rail section		0,731
Steel scrap (EoL)	24.10.14.20	0,264
Steel scrap (Production)	24.10.14.20	0,264

Source: JRC elaboration

Next, the production routes per intermediate product are described in order to have a full overview of the steel flows. The most common production route (including input and output data and information on loss, scrap and internal recycling rates) is taken from Cullen et al. (2012)[61]. Import, export, and the derived net import data from Trade Statistics database from Eurostat.

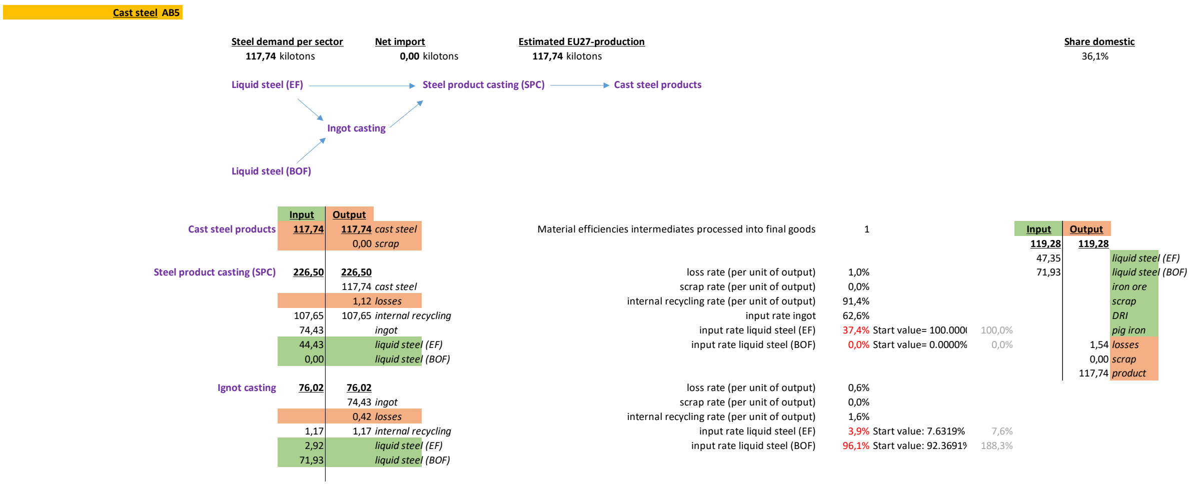
[61] Cullen J., Allwood J., Bambach M. (2012). Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods. Environ. Sci. Technol. 2012, 46, 24, 13048–13055. https://doi.org/10.1021/es302433p

Example on AB5: cast steel

Cast steel products are produced via the steel products casting process. This process uses liquid steel (from electric furnace) and ingot castings. The ingot casting is produced using liquid steel (from electric furnace and oxygen blown converter).

Starting from a demand of cast steel products in EU27 end-use applications of 117.7 kiloton and no net export results in an estimated production volume of **117.7 kiloton**. The details of the steel product casting and ingot casting processes are shown in Figure A5. A summary of the total inputs and outputs is given on the right. The input shares, loss rate, scrap rate, and internal recycling rate are taken from Cullen et al. (2012). Input to this production route is indicated in green, output is indicated in red. Intermediary flows are not highlighted (so shown in white).

Figure A5. Production route of cast steel products, EU27, 2015. Data in kiloton. Own estimate based on Cullen at al. (2012)



Source: JRC elaboration

In addition, the share of export and domestic use are estimated which are used later step. The export share shows the share of domestic production being exported. The domestic share shows the share of domestic use in total domestic production.

For the processes **AB6 to AB18** the same methodology is applied. In AB9, AB15 and AB16 we deviate from the original input rates for liquid steel mentioned in Cullen et al. (2020) to improve the alignment with the MFA-results from Task 1.3. The deviations are indicated in red. The corrections in AB9, AB15 and AB16 are selected as these intermediate products could be produced in lower qualities (Q3 and Q4).

Based on the results from AB5 to AB18, also the production volumes of the intermediate products AB1 to AB4 are estimated as these products are an input to (some of) the production routes of AB5 to AB18. Also, in AB3 and AB4 modifications are applied to the input shares of pig iron and scrap to improve the alignment with the MFA results from Task 1.3. In AB3 the total input is compared to and aligned with the total output of steel scrap (both End-of-Life and production scrap). See blue table in the Excel-file.

A summary of the production volumes and production values is provided in Figure A6. These production values are used as the totals in both the supply and use table for both the totals for industries and products.

Figure A6. Summary of the production volumes and values of AB1 to AB18, 2015, EU27.

No.	Intermediate products	Production volume EU27	Production value
		kton	mEUR
AB1	Pig Iron	33.986,18	9.858,58
AB2	Direct reduced iron	9.555,40	1.868,77
AB3	Liquid steel (from BOF)	99.909,80	31.976,84
AB4	Liquid steel (from EF)	58.959,67	18.870,46
AB5	Cast Steel	117,74	49,67
AB6	Cast Iron	6.583,83	30.233,18
AB7	Electrical sheet and CR coil	4.597,45	6.037,99
AB8	Tin plated	2.580,00	2.464,28
AB9	Plate	8.833,60	8.276,72
AB10	CR coil galvanized or coated	14.431,98	9.183,41
AB11	HR galvanized	3.071,69	2.570,29
AB12	HR narrow strip and coil	33.267,22	27.836,95
AB13	Welded Tube	811,16	514,05
AB14	Seamless tube	821,64	1.429,69
AB15	Wire rod, reinforcing bar and HR bar	38.813,24	45.030,95
AB16	Heavy, light, and rail section	13.622,59	9.956,94
AB17	Steel scrap (EoL)	110.297,00	29.102,91
AB18	Steel scrap (Production)	35.213,52	9.291,42

Source: JRC elaboration

Next, the end-use of products is linked to the sector-classification of FIGAROe3. The demand of intermediary steel products per end-use sector is divided across one or multiple sectors. The share depends on the demand to sector C24 of each end-use sector in the original FIGAROe3 use table in combination with the goal to avoid excess demand (i.e. the newly estimated demand to intermediary steel products is higher than the original demand for product CPA_C24). In case of excess demand, the excess demand will be subtracted from the use of product CPA_C25.

- **Buildings** (construction) are covered by sectors C25 'Manufacture of fabricated metal products, except machinery and equipment' (36.2%) and F_A 'Construction' (63.8%).
- **Infrastructure** (construction) is covered by sectors C25 'Manufacture of fabricated metal products, except machinery and equipment' (36.2%) and F_A 'Construction' (63.8%).
- **Cars** (transport) are covered by sector C29 'Manufacture of motor vehicles, trailers and semi-trailers'.
- **Trucks** (transport) are covered by sector C29 'Manufacture of motor vehicles, trailers and semi-trailers'.
- **Other transport** (transport) is covered by sector C30 'Manufacture of other transport equipment'.
- **Mechanical engineering** (industrial equipment) is covered by sectors C25 'Manufacture of fabricated metal products, except machinery and equipment' (1.9%), C27 'Manufacture of electrical machinery and apparatus n.e.c.' (2.0%), C28_A 'Manufacture of machinery and equipment n.e.c.' (95.2%), and C28_B 'Manufacture of office machinery and computers' (1.0%).
- **Electrical engineering** (industrial equipment) is covered by sectors C26_A 'Manufacture of radio, television and communication equipment and apparatus' (23.5%), C26_B 'Manufacture of medical, precision and optical instruments, watches and clocks' (13.6%), and C27 'Manufacture of electrical machinery and apparatus n.e.c.' (62.9%).
- **Other metal goods** (metal goods) are covered by sector C25 'Manufacture of fabricated metal products, except machinery and equipment'.
- **Domestic appliances** (metal goods) are covered by sector C25 'Manufacture of fabricated metal products, except machinery and equipment' (67.0%), C26_A 'Manufacture of radio,

television and communication equipment and apparatus' (23.5%), and C26_B 'Manufacture of medical, precision and optical instruments, watches and clocks' (10.0%).

- **Packaging** (metal goods) is covered by sectors A01 'Agriculture' (A01_A till A01_Q), and C10 'food manufacturing' (C10_A till C10_J).

Finally, the use of steel intermediary products per end-use application (and per sector) are derived (see Figure A7-A8). A distinction is made between the use of domestic (i.e. EU27 products) or imported products.

Figure A7. Estimated use (in million euro) of steel intermediary products per sector and per end-use application, EU27, 2015 (part 1)

		Buildings		Infrastructure		Cars	Trucks	Other transport	Mechanical engineering			
		C25	F_A	C25	F_A	C29	C29	C30	C25	C27	C28_A	C28_B
EU27_AB1	Pig Iron	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB2	Direct reduced iron	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB3	Liquid steel (from BOF)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB4	Liquid steel (from EF)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB5	Cast Steel	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,2	0,2	11,1	0,1
EU27_AB6	Cast Iron	630,7	1.109,4	5.312,9	9.344,7	1.455,6	745,1	288,2	68,1	73,5	3.498,2	35,2
EU27_AB7	Electrical sheet and CR coil	106,4	187,1	16,6	29,2	43,1	20,9	0,0	2,9	3,2	151,3	1,5
EU27_AB8	Tin plated	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB9	Plate	513,2	902,7	453,6	797,9	13,9	0,0	885,9	16,1	17,4	827,1	8,3
EU27_AB10	CR coil galvanized or coated	1.328,9	2.337,3	250,5	440,5	1.185,2	292,2	0,0	5,3	5,7	273,6	2,8
EU27_AB11	HR galvanized	755,0	1.327,9	176,7	310,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB12	HR narrow strip and coil	5.180,8	9.112,3	1.670,8	2.938,8	520,3	321,2	207,7	61,6	66,5	3.164,4	31,8
EU27_AB13	Welded Tube	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB14	Seamless tube	9,7	17,0	2,8	4,8	1,8	1,0	1,5	0,1	0,1	3,9	0,0
EU27_AB15	Wire rod, reinforcing bar and HR bar	5.328,2	9.371,6	4.299,4	7.562,0	406,0	454,5	234,4	58,2	62,8	2.988,4	30,1
EU27_AB16	Heavy, light, and rail section	1.897,7	3.337,8	981,1	1.725,6	0,0	0,0	0,0	1,8	1,9	91,2	0,9
EU27_AB17	Steel scrap (EoL)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB18	Steel scrap (Production)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB1	Pig Iron	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB2	Direct reduced iron	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB3	Liquid steel (from BOF)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB4	Liquid steel (from EF)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB5	Cast Steel	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,4	0,4	19,7	0,2
RoW_AB6	Cast Iron	98,4	173,0	828,7	1.457,6	227,0	116,2	45,0	10,6	11,5	545,6	5,5
RoW_AB7	Electrical sheet and CR coil	630,2	1.108,4	98,3	172,9	255,1	124,1	0,0	17,4	18,8	896,2	9,0
RoW_AB8	Tin plated	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB9	Plate	292,9	515,1	258,9	455,3	7,9	0,0	505,5	9,2	9,9	472,0	4,7
RoW_AB10	CR coil galvanized or coated	388,9	684,0	73,3	128,9	346,8	85,5	0,0	1,6	1,7	80,1	0,8
RoW_AB11	HR galvanized	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB12	HR narrow strip and coil	711,8	1.251,9	229,5	403,7	71,5	44,1	28,5	8,5	9,1	434,7	4,4
RoW_AB13	Welded Tube	49,8	87,5	84,7	149,0	0,0	5,3	8,3	2,0	2,2	104,2	1,0
RoW_AB14	Seamless tube	306,3	538,7	87,2	153,4	58,2	31,5	48,7	2,4	2,6	125,0	1,3
RoW_AB15	Wire rod, reinforcing bar and HR bar	1.400,3	2.462,9	1.129,9	1.987,3	106,7	119,5	61,6	15,3	16,5	785,4	7,9
RoW_AB16	Heavy, light, and rail section	453,1	796,9	234,2	412,0	0,0	0,0	0,0	0,4	0,5	21,8	0,2
RoW_AB17	Steel scrap (EoL)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB18	Steel scrap (Production)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	sum	**20.081,9**	**35.321,5**	**16.189,0**	**28.474,4**	**4.699,2**	**2.361,2**	**2.315,3**	**282,1**	**304,5**	**14.494,1**	**145,8**
EU27_CPA_C25	correction	-4.771,2	-28.252,4	-3.846,3	-22.775,6	0,0	0,0	0,0	-67,0	0,0	0,0	0,0
RoW_CPA_C25	correction	-292,2	-2.184,2	-235,5	-1.760,8	0,0	0,0	0,0	-4,1	0,0	0,0	0,0

Source: JRC elaboration

Figure A8. Estimated use (in million euro) of steel intermediary products per sector and per end-use application, EU27, 2015 (part 2)

		Electrical Engineering			Other metal goods	Domestic appliances			Packaging	
		C26_A	C26_B	C27	C25	C25	C26_A	C26_B	A01	C10
EU27_AB1	Pig Iron	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB2	Direct reduced iron	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB3	Liquid steel (from BOF)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB4	Liquid steel (from EF)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB5	Cast Steel	0,0	0,0	0,0	6,2	0,0	0,0	0,0	0,0	0,0
EU27_AB6	Cast Iron	383,5	223,1	1.028,4	1.957,3	0,0	0,0	0,0	0,0	0,0
EU27_AB7	Electrical sheet and CR coil	35,3	20,6	94,8	146,7	8,3	2,9	1,2	0,0	0,0
EU27_AB8	Tin plated	0,0	0,0	0,0	0,0	0,0	0,0	0,0	431,1	1.293,2
EU27_AB9	Plate	23,1	13,4	62,0	735,0	0,0	0,0	0,0	0,0	0,0
EU27_AB10	CR coil galvanized or coated	45,6	26,5	122,3	754,1	22,5	7,9	3,4	0,0	0,0
EU27_AB11	HR galvanized	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB12	HR narrow strip and coil	59,9	34,9	160,7	942,7	0,0	0,0	0,0	0,0	0,0
EU27_AB13	Welded Tube	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB14	Seamless tube	0,2	0,1	0,6	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB15	Wire rod, reinforcing bar and HR bar	161,1	93,7	432,0	4.177,1	0,0	0,0	0,0	0,0	0,0
EU27_AB16	Heavy, light, and rail section	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB17	Steel scrap (EoL)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
EU27_AB18	Steel scrap (Production)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB1	Pig Iron	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB2	Direct reduced iron	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB3	Liquid steel (from BOF)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB4	Liquid steel (from EF)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB5	Cast Steel	0,0	0,0	0,0	11,0	0,0	0,0	0,0	0,0	0,0
RoW_AB6	Cast Iron	59,8	34,8	160,4	305,3	0,0	0,0	0,0	0,0	0,0
RoW_AB7	Electrical sheet and CR coil	209,4	121,8	561,4	869,1	49,0	17,3	7,4	0,0	0,0
RoW_AB8	Tin plated	0,0	0,0	0,0	0,0	0,0	0,0	0,0	185,0	555,0
RoW_AB9	Plate	13,2	7,7	35,4	419,4	0,0	0,0	0,0	0,0	0,0
RoW_AB10	CR coil galvanized or coated	13,4	7,8	35,8	220,7	6,6	2,3	1,0	0,0	0,0
RoW_AB11	HR galvanized	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB12	HR narrow strip and coil	8,2	4,8	22,1	129,5	0,0	0,0	0,0	0,0	0,0
RoW_AB13	Welded Tube	3,7	2,1	9,8	4,3	0,0	0,0	0,0	0,0	0,0
RoW_AB14	Seamless tube	7,2	4,2	19,3	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB15	Wire rod, reinforcing bar and HR bar	42,3	24,6	113,5	1.097,8	0,0	0,0	0,0	0,0	0,0
RoW_AB16	Heavy, light, and rail section	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB17	Steel scrap (EoL)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RoW_AB18	Steel scrap (Production)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	sum	**1.066,0**	**620,1**	**2.858,6**	**11.776,4**	**86,3**	**30,4**	**13,0**	**616,1**	**1.848,2**
EU27_CPA_C25	correction	-311,9	0,0	0,0	-2.797,9	-20,5	-8,9	0,0	-457,70	-1.498,83
RoW_CPA_C25	correction	-33,7	0,0	0,0	-171,3	-1,3	-1,0	0,0	-59,23	-208,41

Source: JRC elaboration

Based on the above calculations, the supply and use of steel products can be entered into the disaggregated supply and use tables. In the supply table, the total monetary supply (in million euro) of the products AB1 to AB18 by sectors AB1 to AB18 are entered. The values from Figure A6 are copied to the main diagonal of the disaggregated supply table, meaning the newly added sectors only supply one product each. To balance the supply table with the original version, the sector C24_AB19 is used. It contains all other supplies by sector C24_A an C24_B. The product CPA_C24_AB19 is used to gather all the supplies of the original products CPA_C24_A and CPA_C24_B by all other sectors than C24_A or C24_B.

Entering the flows of steel products in the use table is more complex and included multiple steps:

- **Use of iron ores**. Both sectors AB1 and AB2 use iron ore into their production process. The use by AB1 of 34,235.11 iron ore is converted into 1,980.6 million EUR (assuming an average iron ore price of 0.058 EUR per kilogram[62]). This value is split across the consumption

[62] Eurostat trade data, code 2601 (HS-nomenclature), extra EU27 trade by EU27_2020, year 2015, calculated via the import value divided by the import quantity.

of iron ores from EU27 and from RoW. In FIGAROe3 the use of iron ores by sectors C24_A and C24_B equals 599.6 million euro of which 17.5% from EU27. Therefor 17.5% of 1,980.6 million EUR, or 345.7 million EUR, is allocated to EU27_CPA_B07_B 'iron ore' and the remaining part, 1,634.9 million EUR, to RoW_CPA_B07_B. The same reasoning is applied to the use of iron ores by AB2.

- **Use of intermediary steel products by AB1 to AB18**. Based on the detailed production processes per sector the use of pig iron, direct reduced iron, liquid steel and scrap is allocated to the sectors. Volumes are first converted into monetary values using the unit prices from Figure A4.
- **Use of intermediary steel products by end-use sectors**. The data from Figure A7 and Figure A8 is directly included in the disaggregated use table. Note that a correction is applied to CPA_C25 (both in EU27 and RoW) in case Figure A7 and Figure A8 show negative values in the two bottom rows (to cover the excess demand).
- **Export of intermediary steel products**. From the detailed production processes per sector also the trade flows are estimated. The export of intermediary steel products is included in the use table. The export is allocated to all RoW-sectors based on the original shares of CPA_C24_A exports. To balance the use table, these exports are subtracted from EU27_CPA_C24_AB19. To avoid negative values in this subtraction, RoW_CPA_C24_A is used as an alternative in case necessary.

Next to the steel inputs, the newly added sectors have other (non-steel) inputs which need to be included in the use table to complete the 'production recipe'. The input structure for sectors AB1 to AB18 is based on data based on life cycle inventories. Each sector is linked to one or multiple LCI-processes.

- **AB1 pig iron**: pig iron production from blast furnace at plant.
- **AB2 direct reduced iron**: no process available.
- **AB3 liquid steel (from BOF)**: steel production, converter, 2 records: unalloyed, low-alloyed.
- **AB4 liquid steel (from EF)**: steel production, electric, 2 records: un- and low alloyed, chromium steel.
- **AB5 cast steel**: no process available.
- **AB6 cast iron**: cast iron production (already includes EAF).
- **AB7 electrical sheet and CR coil**: hot rolling steel + sheet rolling.
- **AB8 tin plated**: hot rolling steel + sheet rolling + tin plating.
- **AB9 plate**: hot rolling steel.
- **AB10 CR coil galvanized or coated**: hot rolling steel + sheet rolling + zinc coat + powder coat steel.
- **AB11 HR galvanized**: hot rolling steel + sheet rolling + zinc coat (coils).
- **AB12 HR narrow strip and coil**: hot rolling steel.
- **AB13 welded tube**: hot rolling steel + sheet rolling.
- **AB14 seamless tube**: drawing of pipe.
- **AB15 wire rod, reinforcing bar and HR bar**: wire drawing.
- **AB16 heavy, light and rail section**: section bar rolling.

- **AB17 steel scrap (EoL)**: iron scrap
- **AB18 steel scrap (production)**: iron scrap

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. The data is included in the Excel-file in black.

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_A and C24_B are used and spread across all sectors (AB1 to AB18) based on the monetary output shares. The data is included in the Excel-file in grey.

The CPA-codes related to steel flows are left empty.

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.

<u>Step 5: Balancing the supply and use tables using the RAS-method</u>

This step generates for all other scenarios RAS balanced EU27-RoW level supply and use tables.

The total output per sector and the total output per products in both the supply and use tables are calculated. As a **balanced model** is strived for, the difference at both product and sector level should be negligible. As multiple changes are applied to the both the supply and use table, it is likely to have an unbalanced model.

To restore both the sector and product balance between the supply and use table, a RAS-method is applied. The RAS method is an iterative procedure that bi-proportionally scales a table to be consistent with given row and column sums and is as closely as possible to the composition of the starting matrix.

As the supply table is directly in line with the MFA-results, we choose to apply the RAS-method to the use table (and keep the supply table as is). The product and sector totals of the supply table are used as an input to the RAS-method, together with the (unbalanced) use table. After applying the RAS-method, a balanced use table is derived.

<u>Step 6: Estimate prospective IO tables</u>:

This step estimates the prospective IO tables for all scenarios except for 2015 based on GECO 2023 (see 7.1.3.7 Prospective input-output tables). It is implemented in Excel.

<u>Step 7</u>: **<u>Balancing prospective EU27-RoW supply and use tables using RAS method</u>**

This step generates for all other scenarios RAS balanced EU27-RoW level prospective supply and use tables for 2050 scenarios. It is implemented in R.

<u>Step 8: Regional disaggregation of the supply and use tables, original FIAGROe3 layout</u>

The result is a supply and a use table with disaggregation of the steel related sectors and products. The result shows only two regions: EU27 and RoW. In this step, the original country resolution is restored.

<u>Step 9: Extension tables for the newly added sectors</u>

This step creates new extension tables in preparation of the IO-analysis using Excel. The same disaggregation of the monetary tables is applied to the extension tables. The disaggregation implies that all the stressors of the extension table are disaggregated in line with the sector disaggregation of step 2.

A starting point is created by summing all stressors of the individual EU27 MS sectors C24_A and C24_B. This shows the total value of each stressor of the original C24 sector in FIGAROe3. The stressors combine extension data from FIGAROe3, EXIOBASE, and Air Emission Accounts.

The total value of each stressor is divided by the newly estimated output value from C24_AB1 to C24_AB19: 264,361.4 million euro (see Figure A6 plus the estimated output of C24_AB19). The result is an average coefficient per stressor for EU27 for sector C24. As a first step, this coefficient is copied to each sector C24_AB1 to C24_AB19.

In a next step, additional (external) information is used to improve the quality of individual stressors. The stressors from EXIOBASE are often linked to specific activities. For example, the non-combustion emissions from arsenic are detailed across 8 activities (see Figure A9). The activities agglomeration plant (both pellets and sinter) is only linked to C24_AB1 and CPA_AB2. A coefficient is calculated via dividing the total value of the stressor, 16,418.4 kg and 18,635.3 kg in the example, by the output of sectors C24_AB1 and C24_AB2, 11,727.35 million euro, resulting in a coefficient of, respectively, 1.40 kg and 1.59 kg per million euro output. The coefficients of the other sectors (C24_AB3 to AB24_AB19) are set to zero.

Figure A9. Example of stressors of Arsenic non-combustion emissions in EXIOBASE. Source: EXIOBASE v3.8.2

As - non combustion - Agglomeration plant - pellets - air	kg	16.418,4
As - non combustion - Agglomeration plant - sinter - air	kg	18.635,3
As - non combustion - Glass production - air	kg	0,0
As - non combustion - Production of coke oven coke - air	kg	124,9
As - non combustion - Production of gascoke - air	kg	0,0
As - non combustion - Steel production: basic oxygen furnace - air	kg	219.252,5
As - non combustion - Steel production: electric arc furnace - air	kg	10.093,5
As - non combustion - Steel production: open hearth furnace - air	kg	480.733,9

Source: JRC elaboration

The same methodology is applied to the stressors of steel production (basic oxygen furnace) linked to C24_AB3 and steel production (electric arc furnace) to C24_AB4. The coefficients of steel production (open hearth furnace) are set to zero. The other stressors are left untouched.

The activities of pig iron production (blast furnace) are linked to C24_AB1 and C24_AB2. The activity cast iron production is linked to C24_AB6.

The data from the LCI in step 4 is used here to improve the stressors. The data from the processes in the LCI-data show emissions to air per unit of output. This information is used to improve data on carbon dioxide, carbon monoxide, lead, nickel, nitrogen oxides, PM2.5, PM10, sulphur dioxide, chromium, cupper, PAH, cadmium, mercury, PCB, zinc, sulphate, ammonia, arsenic, and sodium.

The result is an extension table for sectors C24_AB1 to C24_AB19. Some of the stressors for which specific data is available are differentiated across the sectors, while others have an equal coefficient for all subsectors.

Annex 6. Additional EEIOA results

Table A6. Savings relative to the Baseline (BSL50) scenario, by 2050, calculated via EEIOA. CTC50: Compliance to selected Circular economy Targets; ACE50: Ambitious Circular Economy; ACE50*: Ambitious Circular Economy including demand-based levers implying behavioural change

Impact category	CTC50	ACE50	ACE50*
Climate change	-0.03%	-0.24%	-0.27%
Ozone depletion	0.00%	-27%	-38%
Photochemical ozone formation	-0.06%	-0.44%	-0.50%
Particulate Matter	-0.11%	-0.81%	-1.1%
Acidification	-0.03%	-0.24%	-0.26%
Land use	0.00%	-0.01%	-0.01%
Water use	0.00%	-0.03%	-0.04%

Source: JRC elaboration

Annex 7. Environmental Footprint method: Impact categories

- **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.

The 16 impact categories can be normalized and weighted into a single weighted score[63] (Table A7). Normalization means that all impact indicators are multiplied by normalization factors that represent the overall impact of a reference unit (e.g. a whole country or an average citizen). Normalized 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 A7. 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
Resource Use, minerals, and metals	kg Sb eq	0.0636226	0.0755

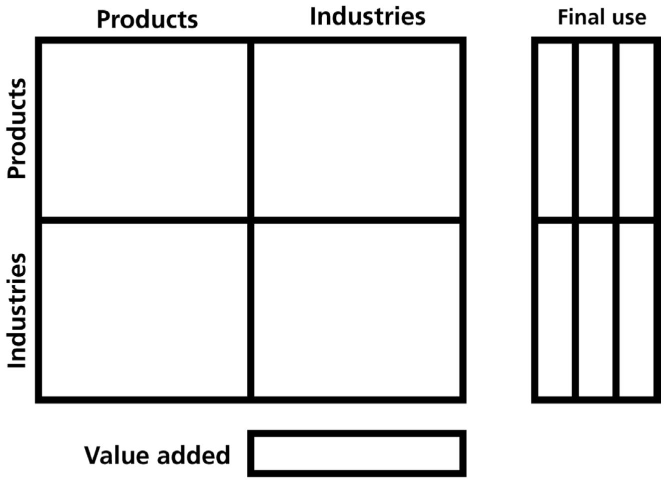
Source: JRC elaboration

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

Annex 8. Description of the FIDELIO modules

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 A10.

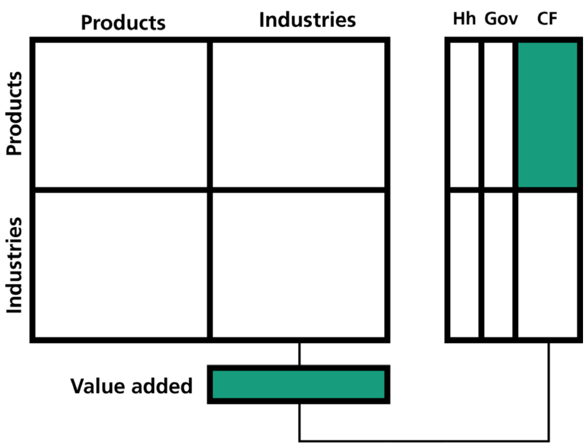
Figure A10. First module of FIDELO: Static Supply-module



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 A11.

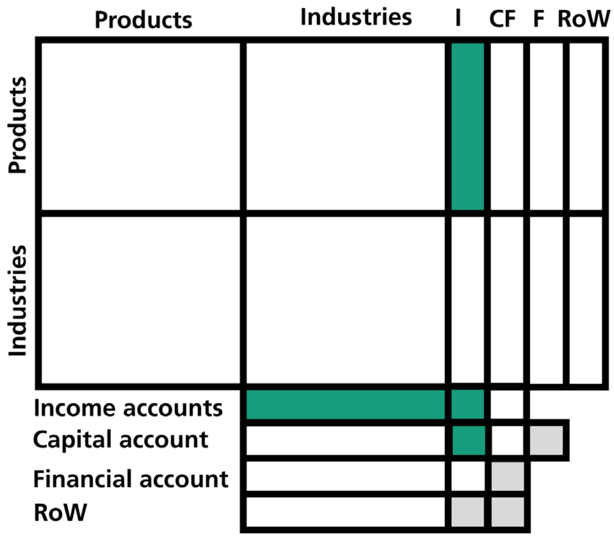
Figure A11. Second module of FIDELIO: Investment dynamics. CF: Capital account; Gov: Government; Hh: Household



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 and is displayed in Figure A12. Household consumption is divided into quintiles, allowing the impact on different parts of the income spectrum to be assessed. Changes in household disposable income lead 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.

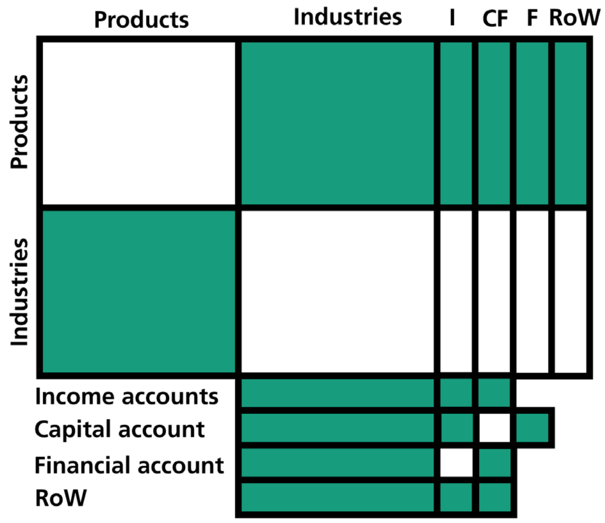
Figure A12. Third module of FIDELIO: Consumption dynamics. CF: Capital account; F: Financial account; I: Income account; RoW: Rest-of-the-World



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 takes into account 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 A13.

Figure A13. Fourth module of FIDELIO: Full model with price dynamics. CF: Capital account; F: Financial account; I: Income account; RoW: Rest-of-the-World



Source: JRC elaboration

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