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Full Length Article

Circular Economy can substantially reduce EU steel supply chain emissions: A quality-focused circularity assessment

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ABSTRACT

Steel is strategically important for the European Union. Yet, the steel system majorly contributes to greenhouse gas emissions and resource use, which can potentially be mitigated through increased circularity. Circularity, however, is constrained by a growing surplus of low-quality steel scrap, contaminated with tramp elements. This study uses Material Flow Analysis and Life Cycle Assessment to investigate the potential of ambitious circularity measures and climate-compliant energy targets to cut emissions and conserve resources across the European Union's steel supply chain, while addressing steel quality challenges. Results show that circularity strategies complement each other, reducing production quantities and increasing recycled content. An ambitious circular steel supply chain combined with an energy transition can decrease greenhouse gas emissions by 69%–75% compared to 2020 and can comprise up to 94% recycled steel by 2050. The findings highlight circularity's key role in meeting global net-zero climate targets, while simultaneously increasing resource independence.

1. Introduction

Steel is central to the EU economy, underpinning key industries such as construction, automotive, energy infrastructure, and consumer goods. Moreover, Europe is the second-largest steel-producing region in the world, with the EU accounting for around 7% of global production in 2023 (Eurofer, 2024). However, the steel industry is responsible for 7%–9% of global Greenhouse Gas (GHG) emissions (IEA, 2020; Association, 2019), and emissions from iron and steel production are 'hard-to-abate' (Bataille, 2020). Multiple studies have investigated the potential for decarbonizing steel production (e.g., Kazmi et al., 2023; Bhaskar et al., 2022; Hebeda et al., 2023; Harpprecht et al., 2022) through electricity-driven, low-carbon iron production, i.e., hydrogen-based direct reduction and electrowinning of iron ore (Harpprecht et al., 2022). Yet, these steel production decarbonization efforts, as part of the energy transition, might not lower the carbon emissions of the steel supply chain at the required pace to meet global net-zero climate targets by themselves (Allwood et al., 2010, 2011; Bataille, 2020; Rissman et al., 2020).

Complementary solutions are therefore required to mitigate emissions and address other environmental pressures from the steel supply chain. Such solutions can be provided by Circular Economy (CE) (Geissdoerfer et al., 2017). CE is an economic model aimed at minimizing waste and maintaining the value of materials for as long as possible (Kirchherr et al., 2023). Strategies aimed at realizing this concept are termed circularity strategies. For instance, Bocken et al. (2016) introduced the 'narrowing', 'slowing', and 'closing' resource loops approach, depending on whether circularity strategies narrow resource flows by reducing inflows, slow resource flows by extending product lifetimes, or close resource flows by enhancing the recycling and recovery of materials. Several studies analyze the potential of CE in addition to the energy transition for decarbonizing the steel system (Garvey et al., 2022; Binet et al., 2021; Ryan et al., 2020; Bataille et al., 2023; Allwood et al., 2010; Milford et al., 2013). On a global scale, Allwood et al. (2010) found that CE measures are the most reliable for achieving 50% GHG emission reductions in the steel industry by 2050. Similar research reports reductions of 53% via CE in the United Kingdom (Garvey et al., 2022) and up to 70% in the United States (Ryan et al., 2020).

CE is promising but, among others, dependent on steel recycling (Garvey et al., 2022; Binet et al., 2021; Ryan et al., 2020; Bataille et al., 2023; Allwood et al., 2010; Milford et al., 2013). Recycled steel production conserves resources and is considerably less carbon-intensive than

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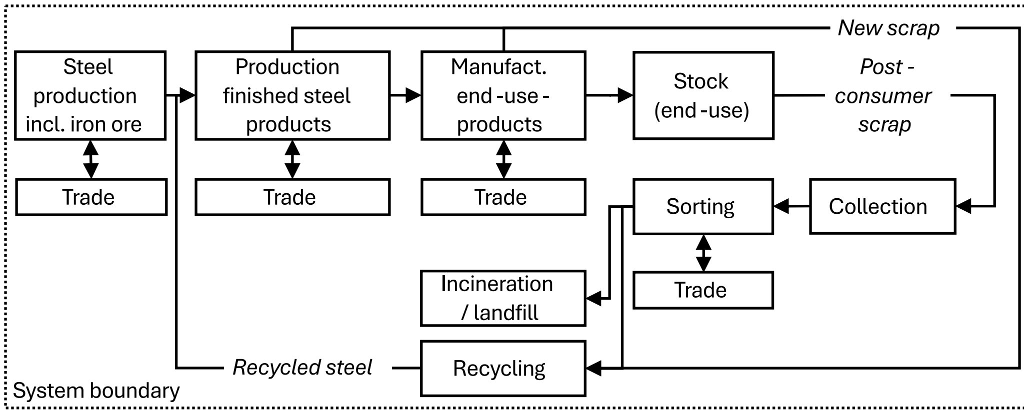

Fig. 1. MFA and LCA system boundaries. Transport between steps is included but not depicted. In some cases new steel and recycled steel need to be blended to dilute recycled steel impurities and achieve desired quality. The quantitative implications of dilution are accounted for, while new production and recycling are modeled as separate systems.

new steel, i.e., 100% ore-based or virgin steel, production (Broadbent, 2016). While steel can theoretically be recycled infinitely without losing its properties (Engh et al., 2021, p. 550), real-world recycling is constrained by the laws of thermodynamics, impurities, processing, and other limitations (Engh et al., 2021, p. 667). In the EU, the recycled content of steel products is limited more by available steel scrap quality than quantity (Dworak et al., 2022). Replacing new steel is only possible if the quality of recycled steel meets the required application standards. Most significantly, the presence of tramp elements (unwanted residual elements that accumulate in steel) poses a significant barrier to achieving high-quality recycled steel (Daehn et al., 2017; Dworak et al., 2022). These impurities, which are difficult to remove once melted into the steel, limit the recycling potential of steel products (Daehn et al., 2017, 2019; Dworak et al., 2022). For this reason, recent studies have quantified scrap flows and the distribution of tramp elements in relation to steel demand (Dworak et al., 2022; Daehn et al., 2017). They found that in the EU, the increasing surplus of low-quality scrap is expected to constrain the share of usable scrap to 55% by 2050, necessitating the dilution with new steel and the export of large quantities of scrap (Dworak et al., 2022).

Research to date has not yet quantified the combined potential of the energy transition and CE in the EU steel supply chain, particularly under constraints from tramp element contamination. This study addresses that gap by quantitatively assessing how ambitious circularity measures could influence environmental impacts and resource consumption of the projected 2050 EU steel supply chain, while accounting for steel quality. To capture a range of CE dynamics, five bottom-up circularity strategies, namely Reduce (Technical and Behavioral), Reuse, and Recover (Collection and Quality), are evaluated across end-use sectors.

2. Methods

This study integrates Material Flow Analysis (MFA) to quantify steel flows with Life Cycle Assessment (LCA) to determine environmental impacts. The method is specified in the following sections and the overall workflow is shown in supplementary material Figure H.

2.1. Material flow analysis

The MFA builds upon a dynamic MFA conducted by Rostek et al. (2022) for the year 2020. The MFA system boundaries cover the entire steel supply chain, from iron ore extraction, steel production, and end-use product manufacturing to the collection, processing, and recycling of steel scrap, including the trade associated with the fulfillment of the demands of the EU manufacturing sector (see Fig. 1). Steel is produced via the Blast Furnace-Basic Oxygen Furnace (BF-BOF) and the Electric Arc Furnace (EAF) routes, the latter using either Direct Reduced Iron (DRI) or steel scrap. The resulting crude steel is used to produce finished steel products, which are used for manufacturing of products for various end-use sectors. For each sector, product lifetime distributions from Rostek et al. (2022) define when products reach their end-of-life. For further 2020 MFA detail, see supplementary material, II.ii.

The material flows in the 2050 baseline are based on the 2050 MFA reported by Wagner et al. (2025), which tracks in-use steel stocks and flows year-by-year until 2050. This MFA integrates an exogenous projection for relatively constant crude steel demand until 2050 into the 2020 MFA model (supplementary material, II.ii). Steel production routes follow projections of Keramidas et al. (2023) to ensure consistency with energy transition assumptions (see Section 2.2). This transition includes a shift in the energy mix toward renewable sources, increased Carbon Capture and Storage (CCS), and significant electrification of steel production. As a result, the share of new steel produced via the BF-BOF route is expected to decline from 56% to 23% by 2050, giving way to DRI-EAF steel (supplementary material, II.ii).

To enable integration with LCA, the MFA by Rostek et al. (2022) and Wagner et al. (2025) was refined to offer greater detail at the end-of-life stage. This encompasses the inclusion of a Deposit Return System (DRS) reflecting current EU collection practices for steel food packaging, such as cans, waste collection according to sector and waste-stream-specific rates, and centralized sorting before recycling (supplementary material, II.ii). On average, 75% of total steel scrap is recovered and available for recycling, consistent with Rostek et al. (2022).

Recyclable scrap is either processed within the EU or exported, with an export share of 17.5% in the 2020 MFA, which is maintained across all 2050 scenarios. This assumption is made due to the uncertainty over future trade trends, as changes in scrap quality could plausibly drive either higher domestic use or greater international demand. To address this uncertainty, the study additionally assesses the impacts of retaining up to 100% of scrap in the EU, illustrating the maximum potential recycled steel contribution to EU demand.

Recycling occurs via the EAF route, assuming a technical yield of 88.4%, based on data from ecoinvent 3.9. The technical yield is reflected in reported recycled steel and yield-adjusted scrap values. Steel recycled within the EU is employed to fulfill EU steel demands. To quantify the substitution of new steel by recycled steel without double-counting recycled content, all steel entering the system is intially modeled as new steel. Substituted ('excess') new steel is then subtracted from the system, while still accounting for dilution requirements of recycled steel (see Fig. 1 and the approach to multifunctionality in supplementary material, II.iii). Steel scrap that is not collected or cannot be recycled is sent to disposal, in line with current EU practices extrapolated to 2050 (supplementary material II.ii).

Steel quality. Steel flows were complemented with steel quality data from Dworak and Fellner (2021) to determine recycled steel qualities and the quality requirements of steel demands. Quality is determined through the concentration of tramp elements Cu, Ni, Mo, Cr, and Sn in steel (Dworak et al., 2022). On this basis, quality is distinguished into grades Q1, Q2, Q3, Q4, and Q0. Q1 represents the highest quality (lowest average tramp element content of 0.13%), whereas Q4 represents the lowest quality (average tramp element content of 0.4%). Q0 is an additional cast product category for which quality is not considered.

While it is assumed that the quality of steel employed in each end-use sector is primarily determined by the technical requirements of the finished steel products contained in that sector, in the absence of improved sorting techniques, further contamination with tramp elements is expected at end-of-life. Thus, quality grades are assigned to the recycled steel based on the end-use sector-dependent scrap quality, which results from sector-specific recovery practices (Dworak and Fellner, 2021). For instance, all recycled steel from the construction sector is classified as Q4 due to high contamination with tramp elements during the recovery process (Dworak and Fellner, 2021). Only in scenarios where sorting practices are improved, scrap quality is instead determined by the quality of the finished steel products contained in end-use sectors. For further details, see supplementary material, II.v.

2.2. Life cycle assessment

Goal and scope. The LCA was conducted according to ISO 14040/14044 standards (ISO, 2006a,b). The goal of the LCA is to evaluate the environmental impacts of the EU-27 steel supply chain and changes arising from CE scenarios (see Section 2.3). The functional unit is defined as the fulfillment of the EU-27 steel demand for the production of end-use goods for a given year, including the management of the resulting waste. The system boundaries are analogous to the MFA. The assessed impacts encompass scope 1, 2, and 3 (supplementary material, II.iii).

Life cycle inventory. Life cycle inventory data are obtained from the ecoinvent v3.9 database, using the 'allocation at the point of substitution' system model (Wernet et al., 2016) and complemented with scholarly references. This section provides descriptions of selected inventories. For a comprehensive account of inventories employed for each steel supply chain stage, see supplementary material, II.iii.

Energy The electricity and heat production mixes for 2020 and 2050 are modeled using the European Commission Joint Research Centre's Global Energy and Climate Outlook (GECO) 2023 update (Keramidas et al., 2023). To integrate these projections, the employed (background) ecoinvent inventories are modified by isolating and replacing their original energy mixes with those from GECO 2023. The Nationally Determined Contribution (NDC) and Long-Term Strategies (LTS) (NDC-LTS) is implemented as default energy scenario for 2050 (Keramidas et al., 2023). NDC-LTS reflects GHG emission reduction commitments under the United Nations Framework Convention on Climate Change (UNFCCC). For the EU, this means net-zero emissions by 2050 on average across economic sectors (Keramidas et al., 2023), which is reflected in high shares of renewables in electricity and heat production and as a result of CCS (supplementary material, II.iii). To study the effects of CE without an energy transition, the GECO 2023 Reference energy scenario was additionally employed, reflecting energy and GHG policies legislated before June 2023 (Keramidas et al., 2023).

Steel production and recycling Steel production is modeled through production routes defined in Section 2.1, using life cycle inventory data from ecoinvent, adapted to include CCS (supplementary material, II.iii). The substitution of new steel with recycled steel is credited with negative impacts at end-of-life. Available recycled steel is allocated to EU steel demands, while taking into account steel quality (see allocation algorithm in supplementary material, II.vi). Since steel entering the system is modeled as new steel (see Section 2.1), this corrects the net impacts of the system. Thus, steel production impacts are composed of new steel production, recycling, and substitution.

If recycled steel cannot be allocated to EU demands, it is defined as 'surplus'. 'Surplus beyond default export' describes any surplus exceeding default exports (17.5% of scrap) and is not expected to serve any substitution purposes. In the following, default exports are referred to as 'optional export', if they can theoretically be allocated to EU demands. The potential recycling impacts of exported scrap are reported separately. They are not included in the study's net results, since this activity does not displace steel within the assessed EU steel supply chain.

Life cycle impact assessment. The environmental impacts are quantified following the Environmental Footprint Life Cycle Impact Assessment method (EF, v3.1, Andreasi Bassi et al. (2023)). The employed LCA software, EASETECH v.3.6.0, was used to assign material flows with life cycle inventories and for life cycle impact assessment (Astrup et al., 2012; Clavreul et al., 2014).

2.3. Scenarios

This study focuses on the EU-27 steel supply chain for the years 2020 and 2050 under a business-as-usual scenario and three CE scenarios, which modify the material flows provided in the 2050 MFA (see Section 2.1). The studied systems are thus: 2020 Status-Quo (SQ2020), 2050 Baseline (BASE), 2050 Compliance (COMP), 2050 Circularity (CIRC), and 2050 Maximum Circularity (MAXCIRC).

COMP contains a selection of EU policies contained in the Circular Economy Action Plans 1&2 affecting steel material flows (European Commission, 2020). We only consider policies with a clearly defined implementation, limited to reuse/recycling targets across different sectors (supplementary material, II.iv).

The CE strategies, which make up CIRC and MAXCIRC, are clustered in accordance with the framework by Bocken et al. (2016). CIRC consists of four strategies: Reuse, Reduce-Technical, Recover-Collection, and Recover-Quality. The strategy Reuse slows resource flows by increasing lifetime. Reduce-Technical narrows resource flows through more efficient product use and manufacturing. Recover closes material loops from a waste management perspective. While Recover-Collection does this through maximum steel scrap collection, Recover-Quality relies on enhanced sorting to improve scrap quality. MAXCIRC consists of CIRC and the additional strategy Reduce-Behavioral. Reduce-Behavioral narrows resource flows by relying on behavioral change in the population, including shifts to sharing systems or alternative products. While Reuse and Reduce strategies impact demand, production quantity, and scrap outflows of end-use sectors, Recover strategies affect the magnitude and destination of the end-of-life flows. For CE strategies, trade-offs were addressed where possible, such as additional energy use for Recover strategies, whereas uncertain product-level impacts for Reduce and Reuse were excluded to avoid speculative estimates. See Table 1 for an overview of the scenarios, including individual strategies, and related changes in material flows.

3. Results

3.1. Material flows by scenario

Material flows in the EU steel industry take markedly different paths under different scenarios and strategies (Table 1). Steel demand

Table 1
Scenarios and Strategies. Annual material flows in Mt according to Scenario or Strategy. [1] of which 4.6% imported. [2] recycling yield-adjusted scrap outflows before subtracting exports, i.e., 17.5% outside the EU per default. Abbreviations for waste stream categories: Municipal Solid Waste (MSW), Waste Electric and Electronic Equipment (WEEE), End-of-Life Vehicles (ELV), Industrial Electronic Waste (IEW), Industrial Non-Electronic Waste (INEW). See supplementary material, II.iv for assumptions, caclulations, and references regarding each strategy.

Scenario/ Strategy	Description	CE impact per end-use-product sector	Steel demand[1]	vs BASE	Scrap (yield-adj.)[2]	vs BASE
CE Scenarios:						
SQ2020	Based on 2020 MFA	–	145	−6%	96	−5%
BASE	Based on 2050 MFA	–	155	–	102	–
COMP	BASE + EU circularity policy	Waste collection separation efficiency increase to: 71% (MSW); 92% (ELV cars, WEEE)	155	±0%	103	+1%
CIRC	BASE + Reduce-Technical, Reuse, Recover (-Collection, -Quality)	see strategies	109	−29%	105	+3%
MAXCIRC	CIRC + Reduce-Behavioral	see strategies	96	−38%	102	±0%
CE Strategies:						
Reuse	Extend building steel structure lifetime through renovation and reuse; Extend lifetimes of cars, trucks, electrical, and mechanical equipment	Demand reduction: 16% (Buildings); 20% (Cars); 17% (Trucks); 15% (Electrical Equipment, Mechanical Equipment)	140	−10%	90	−12%
Reduce-Technical	Reduce building steel beam mass; Reduce car mass; Intelligent transport systems to increase road and rail capacity; Reduce distance traveled by empty trucks; Efficient food packaging	Demand reduction: 36% (Buildings); 31% (Cars); 13% (Infrastructure); 6% (Trucks); 20% (Food packaging)	121	−22%	95	−6%
Recover-Collection	Waste collection separation efficiency increase, i.e., more waste undergoes centralized sorting (similar to COMP but more extensive)	Waste collection separation efficiency increase to: 92% (MSW, WEEE, ELV, IEW, INEW); Steel packaging DRS	155	±0%	125	+23%
Recover-Quality	Separate scrap by end-use sector and implement enhanced shredding and magnetic separation (Daehn et al., 2019)	Scrap separated by sector and no additional tramp element contamination	155	±0%	102	±0%
Reduce-Behavioral	Reduce demand for office spaces; Reduce private living space; Car sharing; Reduce Car ownership; Reduce SUV-shares	Demand reduction: 33% (Buildings); 68% (Cars)	130	−16%	96	−5%

increases by 7% from SQ2020 to BASE. Scenario COMP includes unchanging demands but leads to a slight 1% increase in steel scrap availability due to EU scrap collection regulation. A larger 23% increase is achieved with strategy Recover-Collection, which assumes significantly higher waste collection effectiveness across several waste streams (see Table 1).

Substantial reductions in production occur under CIRC (29%) and MAXCIRC (38%), driven by strategies Reduce and Reuse. Examples for these reductions are actions such as the reduction of steel beam mass for buildings, which results in 36% steel demand reduction for steel in buildings as part of Reduce-Technical and extension of building lifetime, resulting in 16% steel demand reduction for buildings as part of Reuse (supplementary material, II.iv). Scrap outflows do not decrease under the CIRC (+ 3%) and MAXCIRC scenarios (±0%), since increased waste collection and long product lifetimes counteract and delay outflow reductions caused by decreased inflows beyond the projected timeframe. Notably, the Recover-Quality strategy does not show any changes in production or end-of-life flows compared to BASE since it exclusively affects the quality of flows.

3.2. Steel demand and supply quality

As shown in Fig. 2, steel demand is characterized by a need for high-quality steel (Q1 and Q2), whereas under SQ2020 and BASE, yield-adjusted scrap supply is primarily composed of lower-quality grades (Q3 and Q4). For example, in the BASE scenario, 65% of demand is for Q1 and Q2 steel, whereas only 12% of yield-adjusted scrap is of this quality. While the strategies Reuse and Reduce-Technical lower the demand for steel effectively and, therefore, nearly balance scrap supply and demand quantities, they do not change this quality imbalance. Only Recover-Quality substantially improves the quality of scrap. The combination of CE strategies in CIRC and MAXCIRC better balance the supply and demand qualities, showing a higher overlap between the two than under BASE (65% demand for Q1 and Q2 and ca. 30% recycled steel supply of Q1 and Q2 under CIRC and MAXCIRC).

3.3. Recycled steel flows

The relationship between steel demand and recycled steel supply affects the possibilities of its utilization in the EU (Fig. 3). BASE requires considerable dilution of scrap steel and exports to enable its use. Implementing Reuse has nearly no effect aside from decreasing available scrap quantities. Implementing Reduce-Technical additionally creates a considerable surplus of low-quality scrap. This mostly eliminates the possibility of retaining the expected exports (17.5%) in the EU (see ‘optional exports’ vs. ‘surplus’). Recover-Collection exacerbates the mismatch on the supply side by increasing steel scrap availability, particularly in low-quality grades, leading to a 22 Mt surplus of yield-adjusted scrap, 7 Mt of which goes beyond the default scrap export (i.e., scrap export is unable to balance the quality mismatch). Subsequently implementing Recover-Quality reduces the quantity of low-quality steel scrap and reduces the need for dilution while enabling most scrap designated for export to potentially be retained in the EU.

3.4. Demand side effects

The dynamics related to changes in steel flow quantities and qualities are also evident on the demand side (Fig. 4). Depending on export assumptions, SQ2020, BASE, and COMP require 36%–46%, i.e., 56–72 Mt, of new steel to fulfill demands, whereas CIRC and

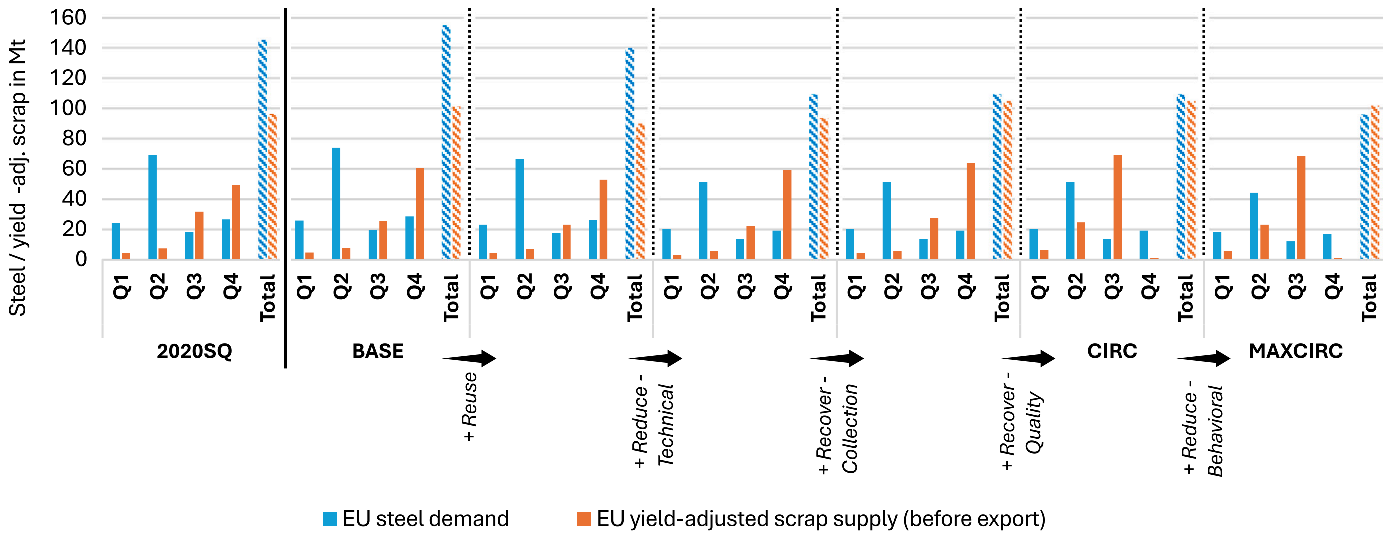

Fig. 2. EU steel demand and EU yield-adjusted scrap supply (prior to scrap exports and dilution) per scenario. Quantities are shown by quality grades Q1, Q2, Q3, and Q4. Quality grade Q0 is not shown but is part of the total. Arrows indicate the implementation sequence of each strategy. See data table B in supplementary material.

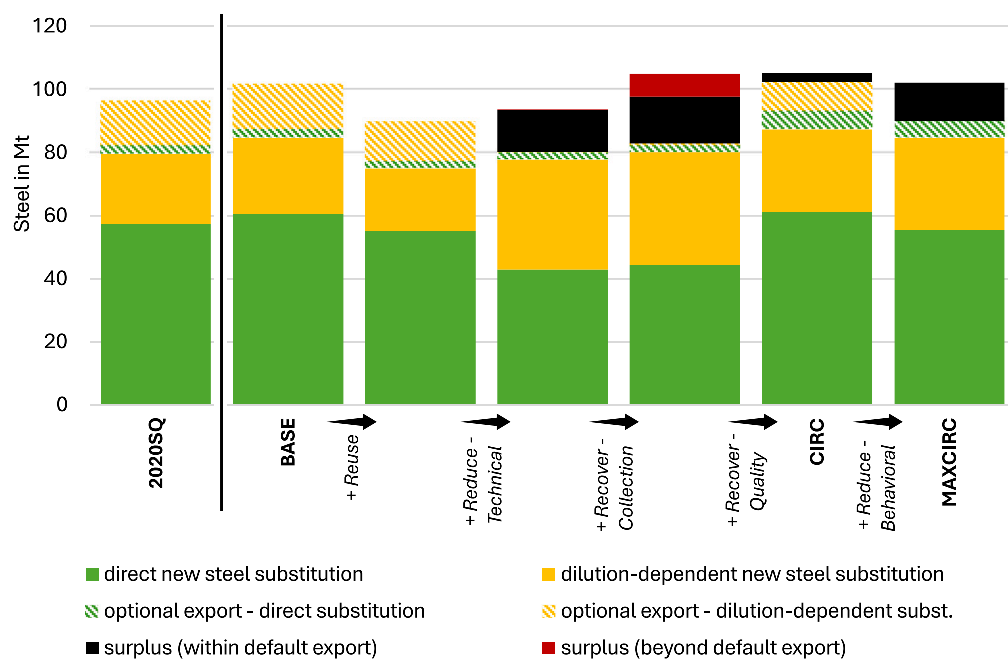

Fig. 3. Recycled steel flows and allocation to EU demands and export per scenario. Only recycled steel is shown, the associated quantity of dilution agent (new steel) is omitted from the Figure. Arrows indicate the implementation sequence of each strategy. Colors denote the utilization of recycled steel. 'Optional export' refers to default scrap exports (17.5% of scrap), which may alternatively be allocated to EU demand with varying utilization. 'Surplus' denotes default exports that cannot be alternatively allocated to EU demands. 'Surplus beyond default export' captures any remaining surplus in excess of default export flows (i.e., without substitution credits in the LCA). Recycled steel flows under different export assumptions are provided in supplementary material, I.v. See data table C in supplementary material.

MAXCIRC decrease this number to 6%–21%. The implementation of Reuse, Reduce-Technical, and Recover-Collection lowers the new steel required to 26 Mt, mostly by reducing total demand. Without improvements in scrap quality, retaining more scrap within the EU has little effect on new steel demand, as shown by the minimal difference between new steel demand in the default and minimized scrap export scenarios prior to implementing the Recover-Quality strategy. The additional introduction of Recover-Quality as part of CIRC can reduce the new steel demand to 22 Mt, with the potential to reduce it further to 7 Mt if steel scrap export is minimized. Under MAXCIRC, the share of new steel can be reduced even further, reaching just 6 Mt.

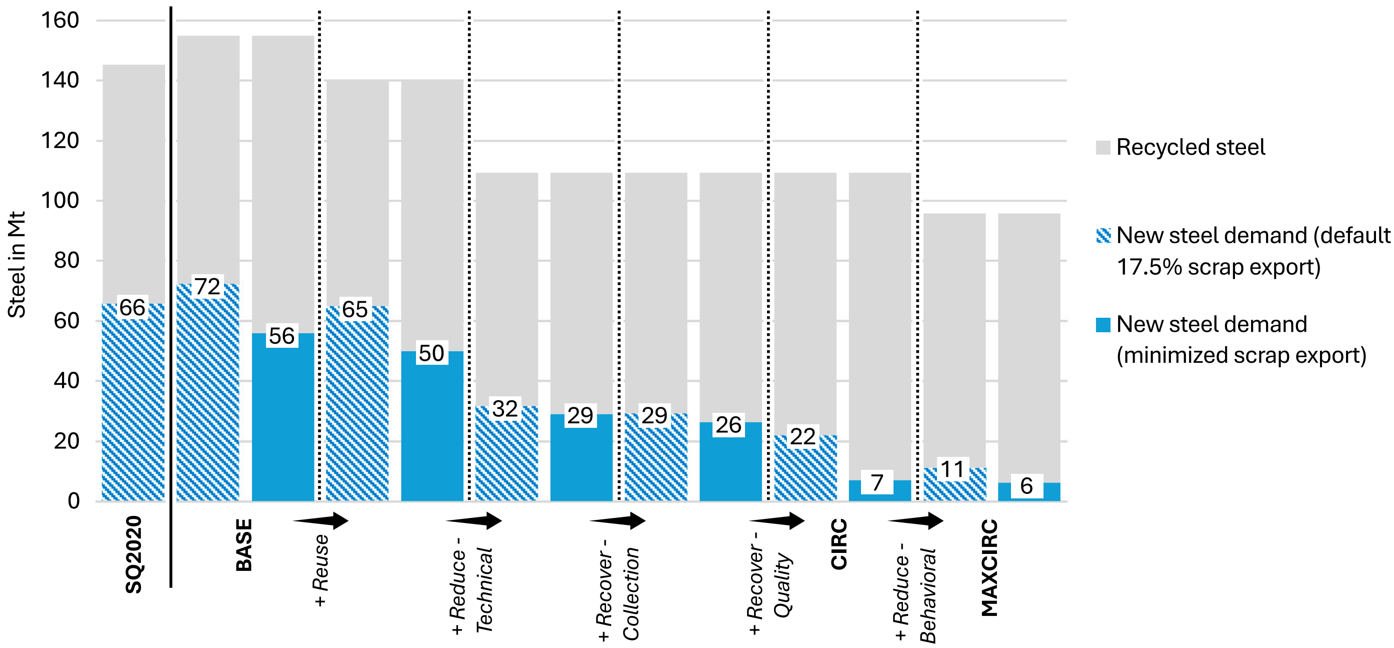

Fig. 4. EU new steel production necessary to fulfill demands per scenario. The quantities of dilution agent required for recycling are included. Arrows indicate the implementation sequence of each strategy. Due to the impact of varying scrap availability, results are shown with the default, i.e., after scrap export of 17.5% and before export (minimized scrap export). See data table D in supplementary material.

3.5. Greenhouse gas emissions

GHG emissions decrease with CE implementation (Fig. 5a). Despite an increase in steel production, BASE reduces GHG emissions by 44%, driven by the assumed energy transition. Scenario COMP results in an additional reduction of only 1%, reflecting the minimal effect of the 1% increase in scrap availability. The CIRC scenario yields a more substantial GHG emissions reduction of 45% compared to the baseline BASE, further increased to 56% in the MAXCIRC scenario. Net impacts of the system further decrease in minimized scrap export scenarios, due to higher recycling shares in EU steel (see supplementary material, I.v). An additional breakdown of GHG emissions by scope 1, 2, and 3, can be found in supplementary material, I.iv.

Among the indivudial circularity strategies, Reduce-Technical leads to the most significant reductions in GHG emissions, lowering them by an additional 33% when implemented after Reuse and 28% when implemented individually (Fig. 5b and for individual results per strategy, see supplementary material, I.i). Second-most effective is Reduce-Behavioral, which achieves 20% emission reductions both combined with other strategies and individually. Most strategies produce similar reductions in GHG emissions when applied individually or in combination with other strategies, but there are diminishing returns with subsequent applications of strategies. Thus, the sequence of implementation influences the results but mostly does not change the relative importance of each strategy. One exception is Recover-Quality, which achieves 8% additional GHG emission reductions as part of CIRC but shows no emission reduction potential when employed individually. This is because in the BASE scenario, recycled steel supply and demand can be balanced through dilution and export. Under these conditions, improved quality sorting has little impact on emission savings from new steel substitution. Instead, its effect is only significant when demand decreases and/or scrap surplus increases.

4. Discussion

4.1. Key findings

Quantity of steel flows. When implementing CE strategies, we see that steel demand can be reduced by 29% (CIRC) and 38% (MAXCIRC) compared to BASE. This is achieved through CE strategies focused on demand reduction (Reuse and Reduce), which lower demand and scrap flows (with a time delay). In contrast, end-of-life focused strategies, such as Recover-Collection, increase scrap flows through intensified collection efforts. Overall, the opposing effects of CE strategies, combined in CIRC and MAXCIRC, balance each other, leaving scrap flows similar to those of BASE.

Greenhouse gas emissions of the steel industry. From a GHG emission perspective, circularity contributes to large emissions reductions, complementing the energy transition by achieving between 45% (CIRC) and 56% (MAXCIRC) of additional reduction to BASE. These reductions also affect other impact categories, such as energy use, water use, and particulate matter emissions on a similar scale (supplementary material, I.vi).

The results for GHG emissions are generally consistent with previous studies, which also find that the adoption of material efficiency and circularity in the steel industry can significantly reduce steel system emissions (e.g., Allwood et al., 2010; Allwood and Cullen, 2012; Milford et al., 2013; Ryan et al., 2020; Bataille et al., 2023). Specifically, Garvey et al. (2022) report 50% emission reduction potential in the United Kingdom by 2050 between a circularity scenario (including decarbonization and 38% demand reduction) and a decarbonization scenario without demand reduction, which aligns with the emission reduction we achieve with CIRC compared to BASE. However, our results are not fully comparable to the aforementioned studies, since they focus on the steel-producing sector individually, whereas we analyze the impacts of the entire EU steel supply chain (see Fig. 1).

The proportional contributions of Reuse, Reduce, and Recover strategies to emission reduction (Fig. 5b) are consistent with previous works, which repeatedly showed that demand reduction is the most impactful strategy individually (Allwood et al., 2010; Allwood and Cullen, 2012; Ryan et al., 2020; Binet et al., 2021; Bataille et al., 2023). Previous studies generally assume fixed recycling rates in their baselines and implement higher recycling rates under circularity, which leads to additional GHG emission reductions (e.g., Milford et al., 2013; Ryan et al., 2020; Binet et al., 2021; Garvey et al., 2022; Bataille et al., 2023). Since these studies do not consider steel quality, they

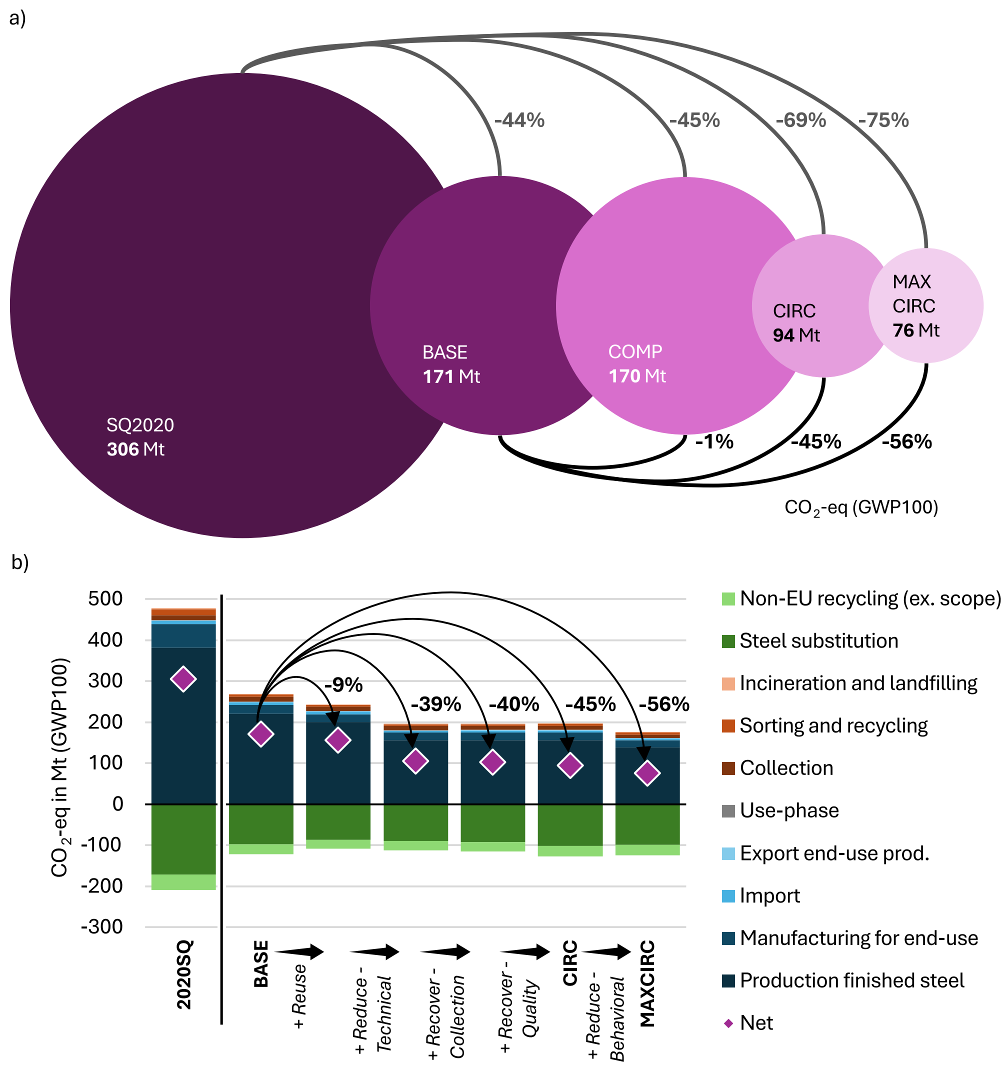

Fig. 5. (a) Net GHG emissions per scenario and change versus SQ2020 (top value) and BASE (bottom value). (b) GHG emissions per scenario by life-cycle stages. Arrows indicate the implementation sequence of each strategy. EU steel production impacts are comprised of new steel production, recycling, and substitution. Non-EU recycling impacts are depicted but excluded from net emissions. Use-phase emissions are zero, since the functional unit focuses on material provision. See data table F in supplementary material.

offer no understanding of how and even whether the targeted recycling rates can be achieved. In contrast, our results provide more detailed insights into the individual impact and combination of CE strategies. In particular, we can show the benefit of combining quality improvements with demand reduction (Fig. 3). This demonstrates that sorting-based strategies, although less effective individually (because high steel demands enable the dilution of impurities), are a crucial part of CE.

Quality of steel flows. Under business-as-usual practices, recycled steel flows tend to be of low quality (60% Q4/lowest-quality flows in BASE), but including a sorting-based strategy, i.e., Recover-Quality, substantially improves quality (1% Q4/lowest-quality flows in CIRC). This improvement allows a close (quality-wise) fit between steel demand and recycled steel supply, which, coupled with demand reductions, enables meeting EU steel demands largely from recycled sources (Fig. 4). These results are consistent with previous studies, which find that the mismatch of scrap supply and steel demand increases when tramp element contamination is not curbed, leading to lower recycled content in steel (Daehn et al., 2017; Cooper et al., 2020; Dworak et al., 2022, 2023). Compared to our results, Dworak et al. (2022) report an even higher low-quality scrap surplus when analyzing EU steel scrap flows in 2050, reaching a surplus of 62 Mt, due to the exclusion of scrap dilution and export, whereas we find none under BASE.

While our findings suggest the importance of sorting, we believe that the GHG emission reductions from Recover-Quality may likely still be underestimated for several reasons. First, demand for low-quality scrap may be overestimated under BASE, as we assume stable export demand irrespective of scrap quality, whereas future saturation of global steel markets may reduce this demand buffer for low-quality scrap (Pauliuk et al., 2013; Dworak et al., 2022). Second, BASE assumes ideal allocation of recycled steel to demands by quality, which in reality is limited because scrap quality is not known to processors before melting in the absence of quality sorting (Daehn et al., 2019; Compañero et al., 2021, 2023). Sorting provides the necessary information to enable efficient allocation of recycled scrap to demand. Third, all scenarios rely on dilution of low-quality scrap, which may be unfeasible due to economic and logistical limitations linked to missing information on scrap quality. We see that when dilution-dependent new steel substitution is unfeasible, strategy Recover (Quality) is essential for enabling emission reductions (supplementary material, I.ii).

4.2. Limitations and future research

A limitation of this study is the simplification of background changes in 2050. For example, transport decarbonization was not modeled, likely causing a slight overestimation of transport-related emissions (4% in SQ2020 vs. 8% in BASE). Additionally, steel decarbonization was represented through electrification (EAF) and CCS, while hydrogen-based routes were excluded due to uncertainties in their CO_2 footprint (Suer et al., 2022; Hauschild et al., 2025). However, a sensitivity analysis with a less decarbonized energy mix was conducted to cover plausible futures, with results suggesting that the relative impacts of CE strategies are robust across energy scenarios (supplementary material, I.iii).

Uncertainty remains in other areas, such as scrap quality. This study applied enhanced shredding and magnetic separation as a feasible, energy-efficient option to reduce contamination, but other interventions, such as chemical tramp element removal (Daehn et al., 2019), could alter outcomes and should be studied. Furthermore, scrap quality was deduced from the MFA data rather than tracked dynamically across multiple life cycles, assuming that technical requirements that determine steel quality and contamination patterns remain unchanged without targeted interventions. While this is a simplification, it captures the most relevant drivers. Additionally, variations in alloy composition, which could affect recycling feasibility, were not explicitly modeled. Their implications are likely to be similar to those of quality considerations.

The analysis concludes in 2050, while long lifetimes in the building and infrastructure sectors delay reductions in scrap outflows caused by CE strategies. This delay pushes some impacts beyond the 2050 time frame, which warrants further research. Finally, the process-based LCA approach of this study enables a detailed and comparable physical flow analysis, but limits insight into market-driven effects such as price shifts or recycling incentives. Future studies should include economic modeling to capture such effects on the uptake of CE strategies.

4.3. Implications

Prioritization. The results show important synergies among CE strategies, achieving greater GHG emission reductions when implemented in combination. However, existing CE legislation does not yet leverage this sufficiently. Current EU CE policy focuses on increasing waste collection (Table 1), which we show to be primarily effective when combined with improved steel scrap quality.

Demand reduction strategies like Reuse and Reduce should be prioritized in the long-term, since they are most effective in delivering emission reductions, but they require significant technological advancements and systemic shifts (Table 1). Conversely, Recover strategies can probably be implemented more swiftly in the short term (Bataille, 2020). In our model, 17.5% (i.e., the share of scrap assumed to be exported) of steel substitution savings happen outside the EU, which could be partially internalized if higher quality scrap were supplied and could help achieve climate targets (supplementary material, I.v), whilst simultaneously reducing steel and iron imports. This is backed by evidence from historical data, which confirms that increased recycling rates reduce metal imports, increasing resource independence (Dussaux and Glachant, 2019).

Policy recommendations. Several policy measures could support the diffusion of Recover strategies. A key issue is the lack of economic incentives for scrap processors to reduce contamination (Daehn et al., 2019; Compañero et al., 2021, 2023). In principle, scrap dealers could improve quality through manual disassembly of steel products or through technical measures such as enhanced shredding and magnetic separation, the latter of which is applied in this study with negligible additional energy demand (supplementary material, II.iv). However, scrap pricing does not currently reflect tramp element concentration, impeding better sorting and quality control (Daehn et al., 2019; Compañero et al., 2021, 2023). A first step could be consistent labeling of steel products and scrap based on composition (Dworak et al., 2022; Compañero et al., 2023), enabling more efficient dilution of existing scrap flows. Our results indicate that, at present, most high-quality scrap is used in EU production, whereas low-quality scrap needs to be exported. Thus, incentivizing higher recycled steel content in EU products could drive improvements in scrap quality. Additionally, financial measures supporting scrap processing and mitigation of risks associated with fluctuating scrap prices could encourage investment in domestic scrap sorting and recycling (Dworak et al., 2022, 2023). Since our CE scenarios entail no increase in scrap outflow and steel demands, the additional capacity to process this scrap within the EU would be limited. As the EU industry is particularly reliant on high-quality steel (scrap) for its applications, this need should be considered in product design, facilitating disassembly and sorting. Such approaches can be combined with more efficient and forward-looking product design, which is part of Reduce and Reuse strategies.

Demand-reduction strategies require end-use sector-specific measures (Table 1). Reduce-Technical, found here to be the most effective CE strategy, could be supported through material efficiency policies such as revising building codes to limit overspecification, implementing intelligent transport systems to optimize existing road and rail capacity, and improving logistics efficiency (supplementary material, II.iv). Lifetime extension as part of Reuse could be achieved through building renovations and 'Right to Repair' legislation (Svensson et al., 2018). While Reduce-Behavioral represents an optimistic strategy requiring societal transformations that are unlikely to be fully realizable, it is the second-most effective strategy according to our results. Thus, behavioral shifts towards a sharing economy and smaller housing should be encouraged, while simultaneously preventing increased social inequalities. For example, policy intervention could enable more flexible use of existing housing stock and support for downsizing (Lehner et al., 2024).

While these results provide aggregated EU-level priorities, differences in industrial structure and policy approaches across member states mean that the most effective implementation of strategies may vary by country. Future research at the member-state level is essential to identify tailored approaches that align with both national circumstances and EU circularity goals.

5. Conclusion

This paper quantified the future environmental impact of Circular Economy strategies on the EU-27 steel supply chain in 2050, demonstrating that ambitious circularity can significantly lower steel demand and achieve major GHG emission reductions. The presented circularity strategies decrease total steel demand by 38% compared with the 2050 baseline and limit the need for new steel demand to just 6% of total demand. In addition, they enable a 66% reduction in GHG emissions in addition to what can be achieved through the energy transition alone.

Our findings highlight the essential role of demand reduction and steel scrap quality enhancement in reducing GHG emissions, minimizing resource extraction, and EU resource dependence. Policymakers and industry stakeholders should promote more efficient material use and the extension of product lifetimes. Additionally, there needs to be a focus on driving higher steel scrap quality through policy. GHG emission reductions depend on achieving higher recycling rates, which, in turn, hinge on improving scrap quality. Without these improvements, tramp element contamination will cap the amount of scrap that can be used in the EU, forcing reliance on new steel, even when steel scrap supply is theoretically sufficient.

CRediT authorship contribution statement

Aymara Wagner: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **José M. Mogollón:** Writing – review & editing, Supervision, Funding acquisition. **Paola Federica Albizzati:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Anna Walker:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Arnold Tukker:** Writing – review & editing, Supervision, Funding acquisition. **Davide Tonini:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Disclaimer

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resconrec.2026.108825.

Data availability

Data will be made available on request.

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