SYSTEMIQ

CIRCULAR STEEL:

A System Perspective on Recycled Content Targets

A white paper commissioned by thyssenkrupp Steel Europe

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SYSTEMIQ

ABOUT THIS WHITE PAPER

This white paper aims to inform the debate on recycled content targets, based on a quantitative model analysing the system-wide implications of different target scenarios for 2030, such as greenhouse gas (GHG) emissions of the steel industry, availability and quality of scrap, and steel production costs. It does so via two general steps:

1. **Understanding the context:** We review the current state of steel production, steel recycling, and the initiatives of steel producers, steel users, and policy makers.

2. **Analysing recycled content targets implications:** We assess the potential effects of recycled content targets via a scenario analysis leading up to 2030, and offer a generalised framework for evaluating these targets as a sustainable policy option post-2030.

This paper's scope on steel production and recycled content targets is limited to the European Union (EU). However, the analysis adopts a system-wide view in evaluating the environmental implications of such targets. The findings are supported by a quantitative model on recycled content mandates, insights from 18 expert interviews, and desktop research.

ACKNOWLEDGEMENTS

This report was commissioned and financed by thyssenkrupp Steel Europe and prepared by Systemiq. With the quantitative model at its core, and backed up by 18 expert interviews from private, public and academic stakeholders across the steel value chain, it attempts to provide an unbiased, system-level assessment of steel recycling and recycled content targets.

Systemiq core team: Canan Akgün, Laetitia de Villepin, Ben Dixon, Sophie Herrmann, Hannah Maral, Leonard von Boetticher.

thyssenkrupp Steel core team: Samuel Flückiger, Carola Funk-Tobollik, Dennis Kalveram, Dr. Helge Mees, Jasmin Niehof.

ABOUT SYSTEMIQ

Systemiq was founded in 2016 to drive the achievement of the Paris Agreement and the UN Sustainable Development Goals, by transforming markets and business models in five key systems: nature and food, materials and circularity, energy, urban areas, and sustainable finance. Systemiq's Energy and Materials Practices work extensively on decarbonisation of the "harder-to-abate" sectors and the issues that connect them. Within the iron and steel sector, Systemiq works to support private, public and philanthropic clients and through work for the Energy Transitions Commission and the Net-Zero Steel Initiative of the Mission Possible Partnership. Learn more at: systemiq.earth.

ABOUT THYSSENKRUPP STEEL EUROPE

thyssenkrupp Steel Europe is one of the leading suppliers of high-grade flat steel and stands for innovations in steel and high-quality products for demanding applications. Steel Europe has around 26,000 employees and produces about 11 million tonnes of crude steel per year – making it Germany's largest flat steel manufacturer. Its capabilities range from custom material solutions to material-related services. Visit www.thyssenkrupp-steel.com/en/ for more information.

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The European Union (EU) steel industry accounts for ~5% of EU greenhouse gas (GHG) emissions and provides a material that is central to modern economies and critical for the energy transition. With the unfolding of the European Green Deal, actors along the EU steel value chain are recalibrating their strategies to transition towards an economy that is more circular and reaches net-zero GHG emissions by mid-century. In this context, the discussion about increased usage of recycled content is gaining momentum among steel producers, policy makers, and downstream manufacturers such as automotive original equipment manufacturers (OEMs). This white paper aims to inform the debate on recycled content targets, based on a quantitative model analysing the system wide implications of different target scenarios for 2030, such as GHG emissions of the steel industry, availability and quality of scrap, and steel production costs. Its key insights are presented below.

1. The steel value chain in Europe has high collection rates for recycling of about 85%, but currently yields low quality scrap due to tramp elements like copper, especially in post-consumer scrap. This challenge is especially significant in the European steel value chain, due to its current technologically driven orientation towards premium products with low tolerance for tramp elements. As a result, 20% of EU scrap is exported and only an average 18% recycled content in ore-based production is achieved. Solving quality-concerns of scrap is thus a positive lever not just for climate reasons, but also for the resilience of the EU steel supply chain with respect to raw material supply.

2. The European Green Deal kick-started a transition that will decarbonise the steel industry and boost EU scrap demand. Alongside hydrogen-based ironmaking, increasing recycled content is emerging as a crucial strategy to reduce the carbon footprint of steel, with proactive signals from the whole value chain:

- While no binding EU-level targets for recycled content in steel currently exist, **policy makers** are considering them in the context of ongoing legislative initiatives such as the revision of the End-of-life Vehicles Directive.
- **Steel users**, particularly premium automotive OEMs, are proactively considering and/or setting ambitious recycled content targets for their suppliers.
- As **EU steel producers** transition to lower-emission production methods using direct-reduced-iron and/or scrap as feedstock, approximately 44 million tonnes per annum (Mtpa) of low-emissions steel capacity will be operational in the EU by 2030.[1] This is not only expected to significantly reduce GHG emissions but also increase demand for steel scrap, as these routes have a higher capacity to process scrap, which is cheaper than ore-based iron input.

3. Until 2030, recycled content targets would further increase demand for scrap, without resolving its limited availability and quality concerns.

a. Scrap availability is expected to be too low in the EU for recycled content targets higher than 30%, due to insufficient time for the steel recycling value chain to adapt to higher scrap demand.

b. The supply discrepancy is particularly acute for high-quality scrap; assuming that tramp element contamination issues persist within the next decade, EU steel producers would not be able to keep their current product portfolio.

4. Until 2030, ambitious targets (≥30%) entail climate and industry risks:

a. **Increase of system-level GHG emissions:** Despite their reduction effect on EU domestic steel sector emissions (-6%), recycled content targets could cause GHG emissions to increase in scrap-importing regions (+10-30% depending on the steel production technology mix), as steel producers that currently depend on EU scrap exports tend to substitute the missing steel scrap with more emission-intensive iron supplies like pig iron. Overall, this would cause system-level[1] CO_2 emissions to slightly increase by 5% (~9Mt CO_2).

b. **Risk to the EU steel value chain:** As the EU's predominant integrated production route (Blast Furnace, Basic Oxygen Furnace (BF-BOF)) today is technically limited to recycled content rates below 25%, 30-35% of the current EU production capacity could not reach ambitious recycled content targets of 30% or higher by 2030. In addition, significant post-consumer scrap quality constraints could make steel producers unable to produce their current portfolio of high-quality products. This could result in a production shift towards a higher proportion of low-quality steel products, or more likely an idling / relocation of primary / high-quality steel assets or increase in steel exports at the expense of domestic sales. This production uncertainty would come at a time when steel is needed as key input to the net-zero transformation, notably for the energy transition.

c. **Production cost increase:** There is a risk that increasing scrap prices will drive up the production cost of steel, with negative implications for steel producers, steel users, or the end customer. The risk of a cost increase is significant, as in any scenario, the cost of scrap accounts for about 41-45% of levelised crude steel production costs in 2030.

5. Until 2030, a focus on improving availability and quality of scrap in the EU is a no-regret option. EU policy makers should establish the right policy mix, with a particular focus on supply-side levers, targeting the improvement of design for recycling, scrap collection, scrap separation, scrap sorting and scrap upgrading.

6. Beyond 2030, the market dynamics of scrap demand and scrap availability might shift based on evolving market trends and circularity improvements, including demand-side material efficiency improvement, improvement of scrap collecting systems, retention of end-of-life battery electric vehicles (BEVs) in the EU, and R&D (R&D) as well as best practices for improving the quality of scrap. The model underlying this study confidently analyses market dynamics until 2030, given that infrastructure changes are well-documented and require significant time to materialise. However, beyond 2030, the level of uncertainty increases substantially, and close monitoring is required to assess whether changing industry dynamics mean that recycled content targets could have a beneficial impact on emissions reductions and EU industry competitiveness.

7. Deciding on the right policy mix requires careful consideration of shifting market dynamics in- and outside the EU. A framework is proposed to determine the desirability of recycled content targets in terms of system-level CO_2 emissions and impact on the EU steel value chain, as well as feasibility due to scrap availability and quality.

1 Emissions of Turkey and Pakistan, major importers of EU scrap. These serve as a proxy for global emissions.

INTRODUCTION

INTRODUCTION

With the unfolding of the European Green Deal, industries across the continent are recalibrating their strategies to transition towards a net-zero future. Among them is the steel industry; it accounts for ~5% of EU GHG emissions and provides a material that is central to modern economies and critical for the energy transition.[2] In light of the EU Emissions Trading System (ETS) and Carbon Border Adjustment Mechanism (CBAM), state aid conditionality,[2] and investor concerns, EU steel manufacturers are committing to decarbonising primary production and recognising the power of the circular economy as a complementary tool to reduce the carbon footprint of steel; using steel scrap instead of ore-based feedstock reduces GHG emissions by 58%.[3] Today, the use of scrap is already technologically and economically incentivised, due to lower costs of scrap-based versus ore-based metallic inputs, and its applicability as a cooling agent in the integrated steel manufacturing route. These features make steel one of the most circular materials, with about 85% of European steel collected for recycling.[4] In addition, steel products have extremely high longevity, so that about 75% of all steel ever produced is still in use today.[5]

However, recycling today does not reflect the full circularity potential of a permanent, highly recyclable material: due to current product design and end-of-life processes, steel reaching end-of-life is consistently downcycled, i.e. the quality of the recycled steel (scrap) is partly of lower quality and functionality than the original material. This is caused by so-called "tramp elements" such as copper. It means that high inputs of post-consumer scrap lead to higher concentrations of tramp elements and therefore steel that is unsuitable for applications with low tolerance for tramp elements, e.g., in many applications for the automotive industry, energy transition, and packaging materials. Applications with higher tolerance for tramp elements are typically found in the construction sector (e.g. rebar for reinforced concrete). The EU exports 20% of its scrap, especially to markets with Electric Arc-Furnace (EAF) capacity and higher demand for construction steel.

Market players and policy makers are strongly focused on the prospect of recycled content targets. Understanding the system-level implications of such recycled content targets is critical to harmonising stakeholder viewpoints across the value chain. This white paper aims to inform the debate on potential recycled content targets based on a quantitative model analysing the implications of different target scenarios by 2030, such as GHG emissions of the steel industry, availability and quality of scrap, and steel production costs. To reach this objective, it covers the following sections:

1. **The status quo:** EU steel features high collection rates for recycling, but currently yields low quality scrap.
2. **The steel momentum:** The European Green Deal kick-started a transition that will decarbonise the steel industry and boost EU scrap demand.
3. **Recycled content target implications:** Until 2030, recycled content targets of 30% or higher entail climate and industry risks.
4. **Enabling high-quality recycling systems:** The right policy mix is required to increase high quality recycling in the EU. This paper proposes a framework to assess the feasibility and desirability of recycled content targets in the EU.

2 State aid under certain – in this case environmental – conditions.

1. THE STATUS QUO:

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The steel industry is key for the EU economy

The EU steel industry has significant consequences for the EU economy, in terms of growth, employment, and trade impact. In 2022, the industry produced about 125 million tons of hot rolled steel, equating to approximately €143 billion of gross value added[3] and supporting about 2.5 million jobs.[4] The consumers of EU steel span various sectors, with construction taking the lead at 37%, followed by automotive at 17%, and mechanical engineering at 15%.[6] Some of these sectors are closely tied to the capacity of the EU steel industry to meet their steel demands, while playing a critical role for key priorities such as:

- **The energy transition:** Electrical steel is critical for transformers, wind turbine generators, and other energy technology.[7] As a result, reduced competitiveness of EU steel would make it harder to scale up renewable energy and establish a stable electricity grid.

- **The transition to electric mobility:** Millions of new electric vehicles will be required, as well as a significant scale-up of public transport systems. This transition relies on steel; for example, high-quality steel plays a vital role in the chassis, car bodies, engines, and charging stations.[8]

- **Food security:** Steel is an integral part of secure food packaging. It preserves nutritional value extremely well, offers the longest shelf-life of any packaging material, and offers high protection from damage.[9] It is also used for lids of various glass containers. As a result, the food supply chain of fruits, vegetables, ready-made-meals, baby foods, and drinks is closely tied to packaging steel production.

Despite its importance, the EU steel industry lost 26 million tons of permanent steel capacity production, and 80,000 direct jobs – one in four of its workforce – between 2009 and 2020. At the same time, the EU shifted from being a net steel exporter to becoming a major net importer, losing 30 million tons of sales.[10] This is explained by a steel overcapacity in the global market, and the fact that European producers face higher costs for raw material, energy and labour compared to other regions.[11] As a result in 2022, 14% of the world's steel was produced in the EU, compared to China's 54%.[12]

Actions to increase recycling – by EU policy makers and players throughout the steel value chain – can impact the competitiveness of EU steel production. Promoting domestic scrap supply makes the industry less dependent on importing raw materials, while scrap's cost and low-emission qualities make it a pivotal part of cost-effectiveness and the ability to reduce product carbon footprint for the EU steel industry.

Scrap recovery rates are high, driven by its cost benefits and recyclability

Steel is one of the most recycled materials worldwide, due to three general attributes:

3 Includes both direct and indirect gross value added (GVA).
4 306,000 jobs, with an additional 2,270,000 indirect and induced jobs.

Firstly, steel is highly recyclable; steel is a permanent material, meaning it is theoretically 100% recyclable[5].[13] Secondly, scrap allows steel producers to avoid a lengthy ironmaking chain, realising savings of roughly 1400 kg of iron ore, 740 kg of coal, and 120 kg of limestone per ton of 100% scrap-based steel.[14] These material savings form the basis of the value of scrap steel. Thirdly, the ferromagnetic properties of typical steel grades make post-consumer scrap easy to separate from other waste, which yields a cheap and efficient recovery process.

As a result, global steel recovery rates[6] are high at:

- 85% for construction,
- 90% for automotive, reaching close to 100% in the US,
- 90% for machinery,
- 50% for electrical and domestic appliances.[15]

In addition, in the EU, scrap usage is incentivised by GHG emissions benefits; scrap-based production is 58% less emissions intensive than ore-based production.[16]

Recycling is characterised by significant scrap contamination with tramp elements

Despite the high recovery rates of steel, a significant challenge persists in the form of downcycling, i.e., the recycling of waste where the recycled material is of lower quality and functionality than the original material. This is especially true for post-consumer scrap, which represents about 50% of global scrap feedstock, compared to 20% and 30% for 'home scrap'[7] and 'prompt scrap'[8] respectively.[17] The presence of tramp elements such as copper in recycled steel leads to quality degradation of the end-product, specifically causing surface cracking in steel sheets, a phenomenon known as 'hot shortness'.

Several factors contribute to this tramp element contamination, including current product design, end-of-life processes, the economics of scrap upgrading, and limited availability of product information: Firstly, the steel itself often becomes contaminated with coatings or alloying elements. Secondly, current product dismantling or shredding processes contaminate steel scrap with other materials, such as copper and plastics in vehicles. While many tramp elements can be managed or removed during processing relatively easy, copper, molybdenum, and nickel stand out as a particular concern. While steel itself could be recycled over-and-over, the concentration of tramp elements builds up with every recycling cycle, gradually exacerbating quality concerns.[18] Current removal technologies for tramp elements – such as physical separation, vacuum distillation, slagging, and solid scrap pre-treatments – are capable of reducing copper concentration to 0.1 weight percentage. However, physical removal – possible only prior to scrap entering a molten state – and especially chemical removal, are still under development and not commercially available today, entailing high costs.[19]

5 In practice, 100% recyclability is not reachable due to 1% losses from corrosion, wear and tear.

6 The percentage of materials that are recovered from the waste stream and sent for recycling, composting, or energy recovery. It considers all materials that are diverted from landfilling or incineration and are instead used as a resource.

7 Home scrap: Also known as internal scrap, is the scrap generated within the steel mill during the production process (comes from trimming, cut-offs, etc.).

8 Prompt scrap: also known as industrial scrap, originates from manufacturing facilities outside the steel mill, such as automobile manufacturers.

The EU is predominantly a premium steel market, requiring high-quality scrap

In the global steel landscape, EU production is characterised by high-quality steel production. This is evident as 60% of the 125 million tons of hot-rolled steel produced in 2022 was premium flat steel.[20] This high quality is currently ensured by the integrated production route (BF-BOF), which currently accounts for about 60% of the EU's total capacity. However, this production route is technically limited to scrap input no higher than 15-25% as a cooling agent, beyond which scrap excessively cools the reaction.[9] As a result, producers predominantly rely on high-quality scrap from their own production waste to uphold quality standards, sidelining lower-quality post-consumer scrap. In contrast, the EAF route – representing the remaining 40% of EU steel production capacity – enables up to 100% of scrap input but is currently predominantly used for lower-quality, long-steel products such as rebar due to tramp element contamination.

20% of EU scrap is exported, likely driven by trade prices and a surplus of low-quality scrap

The EU currently exports around 20% of its steel scrap and imports a mass of scrap equivalent to only 4% of total EU scrap supply (domestic and imports), thus establishing itself as a net-exporter of scrap. This dynamic is not dictated by a shortfall in domestic scrap processing capacity; in fact, this study's quantitative analysis shows that, in 2022, the existing capacity surpassed the volume of all available scrap in Europe (domestic, imported, and exported) by 21%. For a detailed view on current and future production capacity by technology, please refer to the technical appendix, section 2.1.

This net export rate is determined by exported scrap fetching higher prices internationally, EU power prices yielding a comparative cost disadvantage for scrap use within the EU compared to other regions, or scrap not meeting the quality standards required by European steel producers. While export data is scarce, interviews with industry experts confirmed that the majority of exported scrap is of lower quality. Conversely, the 4% of scrap that is imported tends to be of higher grade. This is consistent with the fact that over 60% of the EU's steel scrap is being shipped to Turkey.[21] In Turkey, long-steel products suitable for construction are predominantly produced through the EAF production route. These long-products have a higher tolerance for contamination, making them suitable for the lower-quality scrap exported from the EU. Resolving the quality limitation of scrap would strengthen the position of the EU steel industry in the global steel market; especially due to an increase in supply-chain resilience, as dependencies on imports of iron ore and scrap decrease.

9 Pre-melting could increase this percentage. However, this technology requires high investments, which are unlikely to happen in light of the need to retire the BF-BOF route for decarbonisation in the years to come.

2. THE STEEL MOMENTUM:

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The European Green Deal is reshaping the core of the EU steel industry. One of its key pillars is increasing circularity via the levers of reduce, reuse, recycling, and redesign. For steel, a focus of policy makers is especially on shifting EU primary steel production towards low-emission, direct reduced iron (DRI) routes in combination with either Melt-BOF or EAF production processes:

- **DRI-Melter-Basic Oxygen Furnace (BOF):** This process uses DRI as a metallic input, which is melted in an electric melting unit, before going to the BOF to produce steel. DRI replaces coal as a reducing agent with natural gas or hydrogen in a shaft furnace rather than a blast furnace.

- **(DRI) Electric Arc Furnace (EAF):** This approach melts DRI, combined with scrap metallic input in an EAF to produce steel. If 100% scrap is used, this route is simply labelled "EAF".[22]

However, the role of increasing recycled content for resource efficiency and as an auxiliary strategy to reduce the product carbon footprint is beginning to move into focus.

Policy makers increasingly consider mandatory recycled content targets to drive the circularity and decarbonisation agenda

The EU steel industry is set for potential transformation with new or revised legislations at EU level. These impending changes aim to enhance the industry's circularity. One of the policy options being considered is the establishment of recycled content targets. While currently no binding targets for steel recycled content exist at EU level, several legislative initiatives could set recycled content benchmarks directly for steel production or indirectly by regulating products that contain steel. A further option would be to link financing for steel production investments to recycled content targets.

Specifically, five pieces of legislation will be revised or introduced in the next four years, with potential implications for setting recycled content targets for steel:

- **Revision of the End-of-Life Vehicles Directive (ELV Directive):** Suggests establishing a recycled content target on the basis of a feasibility study. The impact assessment accompanying the legislative proposal considers a 30% recycled content target for post-consumer steel in vehicles, with a 15% minimum threshold of product-closed-loop steel.

- **Revision of the Ecodesign for Sustainable Products Regulation (ESPR):** The forthcoming revision introduces the possibility of setting recycled content targets. Specific requirements could be set for both intermediary products such as steel, and end-products.

- **Revision of the Packaging and Packaging Waste Directive (PPWD):** Potential changes might include minimum recycled content targets, including for steel.

- **Revision of the Construction Products Regulation (CPR):** To address the sustainability performance of construction products, it is proposed that minimum recycled content obligations are respected. These are however not further specified.

- **Introduction of the EU Taxonomy Regulation:** Proposals are in place to correlate sustainability funding for EAFs with a minimum recycled content.

Legislative proposals for recycled content targets such as in the revision of the ELV Directive often focus on post-consumer scrap. This indirect exclusion of home and prompt scrap can be explained by the fact that these scrap types are significantly less contaminated than post-consumer scrap already today, therefore lessening the need for regulatory intervention, and that scrap quality issues are mainly evident for post-consumer scrap up to date. However, when defining thresholds for recycled content targets, home and prompt scrap need to be considered to not disincentivise their use.

Steel users are increasingly setting voluntary recycled content targets

While policy makers explore the introduction of legislative or mandatory recycled content targets, some manufacturers, specifically premium automotive original equipment manufacturers (OEMs), are already setting voluntary recycled content targets which impact their suppliers. This proactive move is both a means of differentiation in an increasingly environmentally conscious market and a response to the regulatory drive to reduce emissions throughout the value chain. With the swift transition towards BEVs in the automotive sector, the focus shifts from tailpipe emissions to the environmental impact of vehicle materials. Steel, accounting for an average of 900 kg per vehicle and representing around 16% of BEV material GHG emissions in production,[23] becomes pivotal for reducing the product carbon footprint. As a result, Volvo has pledged to incorporate 25% recycled steel by 2025,[24] BMW intends all vehicles to be made of 50% recycled and reused materials by 2030,[25] and Mercedes-Benz has ambitions to increase the use of secondary materials by 40% by the end of the decade.[26] In light of the high ambition for recycled content in steel, and requirements on batteries and plastic, OEMs are likely to show a growing interest in staying close to materials in vehicles. This is a positive factor in increasing the circular economy of the sector.

Besides the automotive sector, the electrical and white-goods sectors also use high-quality steel from EU producers. While these sectors have not yet set specific recycled content targets for steel, interviews with steel users and sustainability announcements reveal a strong commitment to increasing the use of secondary steel.[27] However, given the important role that steel typically plays in creating end-products, steel quality and price remain paramount.

EU steel producers are likely to demand more scrap, especially high-quality scrap

Currently, the integrated BF-BOF process dominates the production of high-quality steel products. However, over the next four to seven years, a notable shift is anticipated as the EU moves towards lower-emission steel production methods, notably DRI-EAF or DRI-Melt-BOF, fuelled either by natural gas or low-emissions hydrogen (H2). By 2030, it is expected that around 44 Mtpa of primary low-emission iron and steel capacity will be operational, out of the 200 Mtpa total projected capacity.[28],[29] The likely shift to these routes is explained both by the 90%[10] reduction in emissions intensity and a cost reduction as detailed in Figure 1. For a detailed view on emission intensity by technology, and grid emission intensity by region, please refer to the technical appendix, section 2.2.

10 Assuming 100% green hydrogen is used and 2030 grid electricity. Steel is modelled as crude steel.

Figure 1: EU steel producers shift to lower-emissions routes, enabling a higher percentage scrap uptake

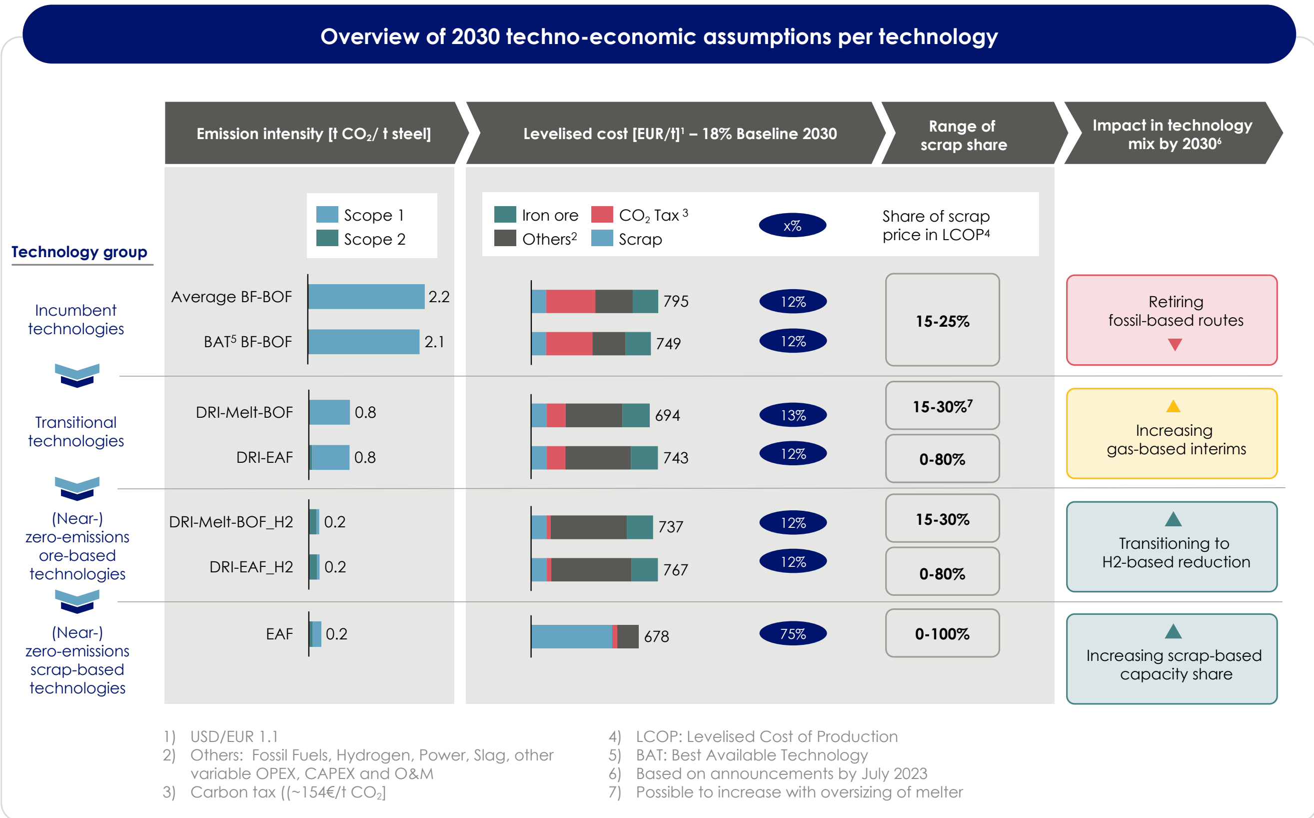

Table 1: Commodity price assumptions

Commodity	Current price (in EUR/t)[11]
Scrap	474
Iron ore	117
Gas-based DRI	409
H2-based DRI	591

11 Assumed as constant to 2030 by model, given the high volatility of scrap prices and a lack of reliable data on scrap price developments. A sensitivity analysis was conducted to analyse the impact of scrap price increases of 20% (see box 2 of section 3). USD/EUR conversion rate 1.1.

In addition to the emissions and cost decrease of new production routes, the range of possible scrap share uptake also increases. Given the benefits of scrap previously described, scrap demand is likely to increase.

However, this scrap demand increase is predicated on the sufficiency of scrap quality. The demand for high-quality scrap is expected to additionally intensify due to two features of increasing scrap share:

- Producing high-quality steel with increased recycled content requires higher-quality scrap, given the decreased dilution effect from uncontaminated primary material.

- Low-quality scrap causes significantly higher energy consumption: specific electricity demand is up to 45% higher for low-quality scrap than for high-quality scrap.[30]

Given the impending competition for scrap, steel producers are starting to enter the scrap market to secure their supply.

In light of the momentum of policy makers and steel users towards setting targets, and steel producers shifting to decarbonised ore-based production routes, the implications of recycled content targets are of significant interest.

The impact of recycled content targets on steel circularity, GHG emissions, and the state of the EU steel value chain until 2030 are explored in the next section.

3. RECYCLED CONTENT TARGET IMPLICATIONS:

Until 2030, recycled content targets of 30% or higher entail climate and industry risks

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European policy makers and industry leaders are aiming to decarbonise EU steel and make it more resource efficient, while bolstering its competitiveness. The current focus of the discussion on recycled content targets raises complex questions about scrap availability, scrap quality, and GHG emissions implications and constraints. To provide a fact-base for future discussions, the authors have built a quantitative model that analyses the implications of different recycled content target scenarios in 2030, specifically investigating:

- scrap availability and quality,
- the impact on EU and system-level[12] GHG emissions, and
- the implications for the EU steel industry and value chain.

BOX 1: THE QUANTITATIVE MODEL UNDERLYING THIS ANALYSIS

The quantitative underlying this analysis model distinguishes three scenarios for 2030, including a **baseline scenario with 18% recycled content, a highly ambitious regulation scenario with 30% recycled content** and an **extreme customer requirements scenario with 50% recycled content:**

- 2030 was selected as a timeframe - firstly, because of its relevance to the ongoing policy discussions
- significant changes are expected beyond 2030 both in technological infrastructure as well as the energy mix making scenarios more hypothetical;
- this timeframe can be projected with a relatively high degree of confidence, so altering recycled content scenarios allows for clearer reasoning.

Any model results on steel refer to crude steel. Model logic description and assumptions are detailed in the technical appendix.

The quantitative analysis reveals that ambitious recycled content targets of 30% or more by 2030 would have negative impacts: a projected shortage of scrap (especially high-quality scrap) would slightly increase steel industry GHG emissions at a system-level, and could negatively affect the EU steel industry and value chain. These impacts are discussed in the following sections.

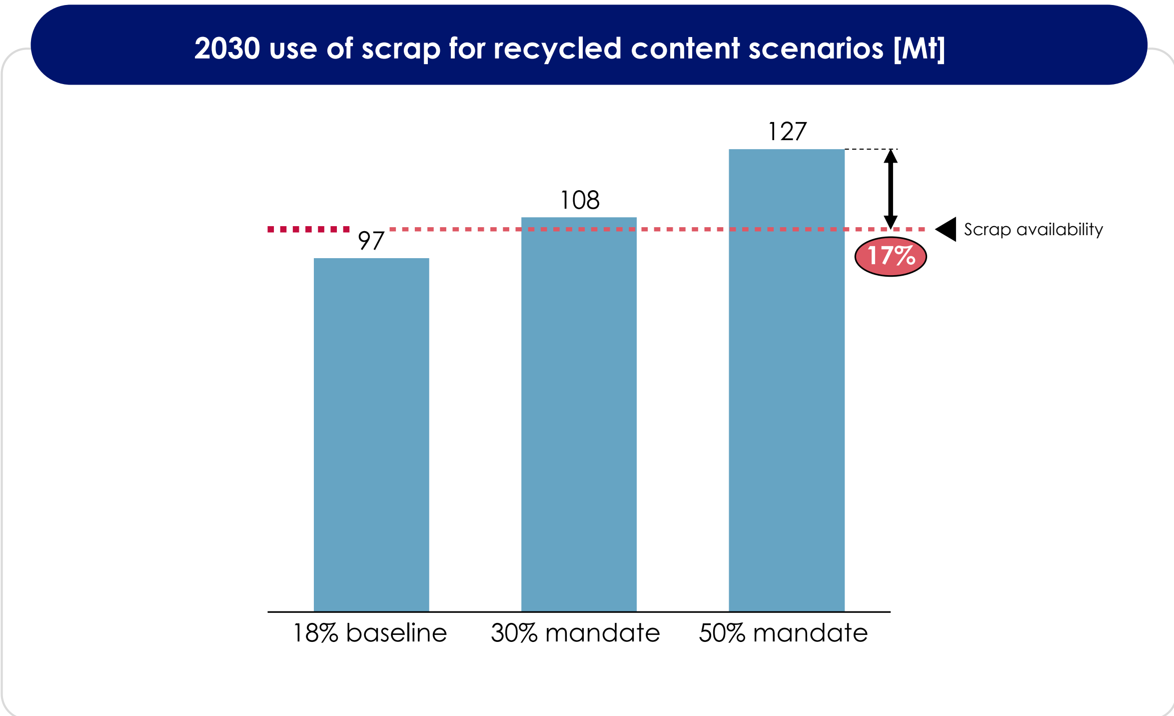
By 2030, recycled content targets are projected to increase the scrap demand-supply discrepancy

Ambitious recycled content targets of 30% or more by 2030 are expected to lead to EU scrap demand outgrowing the supply. The modelling shows that under a 30% recycled content scenario, mandated use of scrap nearly matches scrap available,

12 "System-level" considers the aggregated impact of >70% of EU steel scrap export regions.

i.e., all scrap collected in the EU, as shown in Figure 2[13]. Thus, a 30% target would not allow for scrap exports. Under a 50% recycled content scenario, mandated use of scrap surpasses availability by 17% compared to the baseline. A sensitivity analysis shows that if extensive circularity levers for steel are pulled – such as improving reuse and recovery, increasing the utilisation and lifetime of steel in use, and further increasing material efficiency – sufficient scrap could be available for both a 30% and a 50% recycled content target. However, this "high circularity scenario" is not likely to be reached within the next decade because of inertia in implementing effective measures for increasing productivity of use[14] and material efficiency[15]. Nevertheless, further research needs to be pursued on the

Figure 2: EU scrap availability will roughly match mandated scrap consumption under a 30% scenario and undershoot required scrap for a 50% recycled content scenario



combined effect of circularity levers and a 30% recycled content target by 2030. Note: the model derives scrap availability by applying the 2030 growth rate for continental Europe from the Mission Possible Partnership (MPP) scrap availability data set onto EU scrap supply from 2022. For more details, see section 2.1 in the technical appendix.

The anticipated mismatch between required scrap consumption and available supply in 2030 stems mainly from the expectation that recycled content targets will not, in themselves, translate heightened demand into an increase in supply. Advances in collection, separation and sorting technologies, and infrastructure are unlikely to yield significant enough results within this timeframe. For a detailed view of projected scrap supply and crude steel demand for 2030, please refer to the technical appendix (see section 2.1).

13 Assuming all ore-based technologies use exactly as much scrap as mandated, which is surpassing the technological limits of BF-BOF and DRI-Melt-BOF as of today.

14 Such as shared mobility systems, shared buildings, and increased product lifetime.

15 Such as vehicle lightweighting, material substitution, and better product design.

Scrap quality is a major roadblock to increasing recycled content

In addition to the challenge of insufficient scrap supply, the limited availability of high-quality scrap poses a major concern. Literature on scrap quality requirements indicates that the quality of scrap, especially in terms of copper contamination, is insufficient for high-quality products; shredded end-of-life scrap typically contains a 0.4 weight percentage of copper, which is tolerated in reinforcing bar, but not in flat steel products, which require less than a 0.1 weight percentage of copper.[31] Today, this is a barrier to increasing recycled content in sectors that have a low tolerance for tramp element contamination, such as the automotive, packaging and electric steel sectors. For example, non-grain-oriented electrical steel is limited to a maximum recycled content due to its extremely high sensitivity to copper, chromium, nickel, and especially nitrogen, and can only be commercially produced through the integrated production route today.[16]

The limitation of scrap quality causes current primary and secondary steel producers to generally serve different markets. However, this strategy will face significant issues in the future: studies of the global steel cycle estimate that the copper content in scrap may render part of its stock useless unless better control methods are implemented.[32]

Some of these control methods were described in the previous section: better collection, sorting, and separation would not just increase scrap availability but also quality. For example, if packaging steel is collected separately, it avoids incineration with other municipal waste and the resulting contamination with ash. However, according to expert interviews, improvements to these systems are unlikely to scale up fast enough to establish sufficient scrap quality for recycled content targets of 30% or more by 2030.

Another significant method to improve scrap quality is to foster design for recycling, which is capable of reducing tramp element contamination at its origin. However, recycled content targets on their own are unlikely to significantly incentivise design for recycling. In addition, greater design for recycling would have no significant impact before 2030 because the long average lifespan of steel products would delay impact by around 10 years.[33]

If scrap contamination cannot be avoided, scrap upgrading – in the form of tramp element removal – offers a potential solution. While this technology is not commercially available today, R&D is beginning to show potential; a study revealed that improved physical separation, vacuum distillation, slagging, and solid scrap pre-treatments can reduce copper concentration to 0.1 weight percentage while adding only 5-20% to the melting energy of the EAF route.[34] However, this technology is still at an early stage, with a significant cost. While these removal technologies are not yet commercialised, mechanical upgrading by diluting scrap with cleaner sources is available. However, to upgrade the required amount of scrap to meet a 30% target via dilution would cost €1.2 billion, assuming an upgrading cost of ~€60/t scrap. This represents about 1% of total steel production OPEX costs, which is significant in light of the margins of the steel industry.

A final option to increase recycled content is to use more home and prompt scrap. These are derived as waste directly during steelmaking and the manufacture of steel

16 Information based on expert interviews.

products, are the least contaminated form of scrap, and like post-consumer scrap yield emissions benefits. However, these sources of scrap are also unable to meet the increased demand for high-quality feedstock due to:

- existing production scrap stock from steel producers already being utilised,[17]
- the incentive to reduce production scrap as a key lever to reducing GHG emissions from steel production, and the risk that over-reliance on home and prompt scrap weakens the incentives to reduce waste in these industrial processes.

The lack of scrap availability, especially of high-quality scrap, is a main driver of the climate risk and risk to the competitiveness and ability of EU steel producers to meet market demands. These are discussed in the next two sections.

Recycled content targets slightly reduce EU emissions but slightly raise system-level ones by 2030

Given the substantial impact of steel production on global GHG emissions – representing about 8%[35] – decarbonising steel is a top-priority for decision-makers. The EU may be ambitious in decarbonising its own steel industry, but the globalised nature of the steel and scrap market requires a system-level assessment of GHG emissions, as provided by this analysis. To derive "system level" emissions, this model aggregates emissions of the EU, Turkey, and Pakistan. The latter two countries were selected as they represent the majority of EU scrap imports (>70%), and different production routes (Turkey mainly EAF based, Pakistan mainly BF-BOF based). As a result, they serve as a proxy to estimate impacts on global emissions.

There are two complementary measures to decarbonise steel production: decarbonising primary production of steel, and increasing the use of scrap in steel production. Our analysis shows that while ambitious recycled content targets of 30% by 2030 reduce EU specific steel production CO_2 emissions by 6% (~7 Mt CO_2) compared to baseline, the impacts at a system-level are more ambiguous.

Given the limited availability of scrap as described in the previous section, an increased use of scrap in the EU would lead to lower scrap export rates. As 'scrap protectionism' is observed in major players such as China[36], it is assumed that countries that are currently highly dependent on EU scrap exports from Europe are assumed to substitute the missing steel scrap with pig iron. This is a likely scenario in light of the predominance of BF-BOF capacity, which incentivises the use of pig iron if scrap availability decreases.[37] Increased pig iron use would result in an increase in steel CO_2 emissions for importing countries of between 10% and 33%.[18] At a system-level,[19] this would imply an increase of total steel CO_2 emissions by 5% (~9Mt CO_2) (Figure 3: Aggregated (system-level) CO_2 emissions slightly increase, as emissions shift to EU-scrap-importing countries). This is further explained by the projection that decarbonisation of the primary steel production routes will be further advanced in the EU than in most current export regions: in the baseline 2030 scenario[20] on a weighted average, the EU emits 0.7 tons of CO_2 per ton of crude steel, compared to 1.15 tons of CO_2 per ton of crude steel[21] in Turkey, which

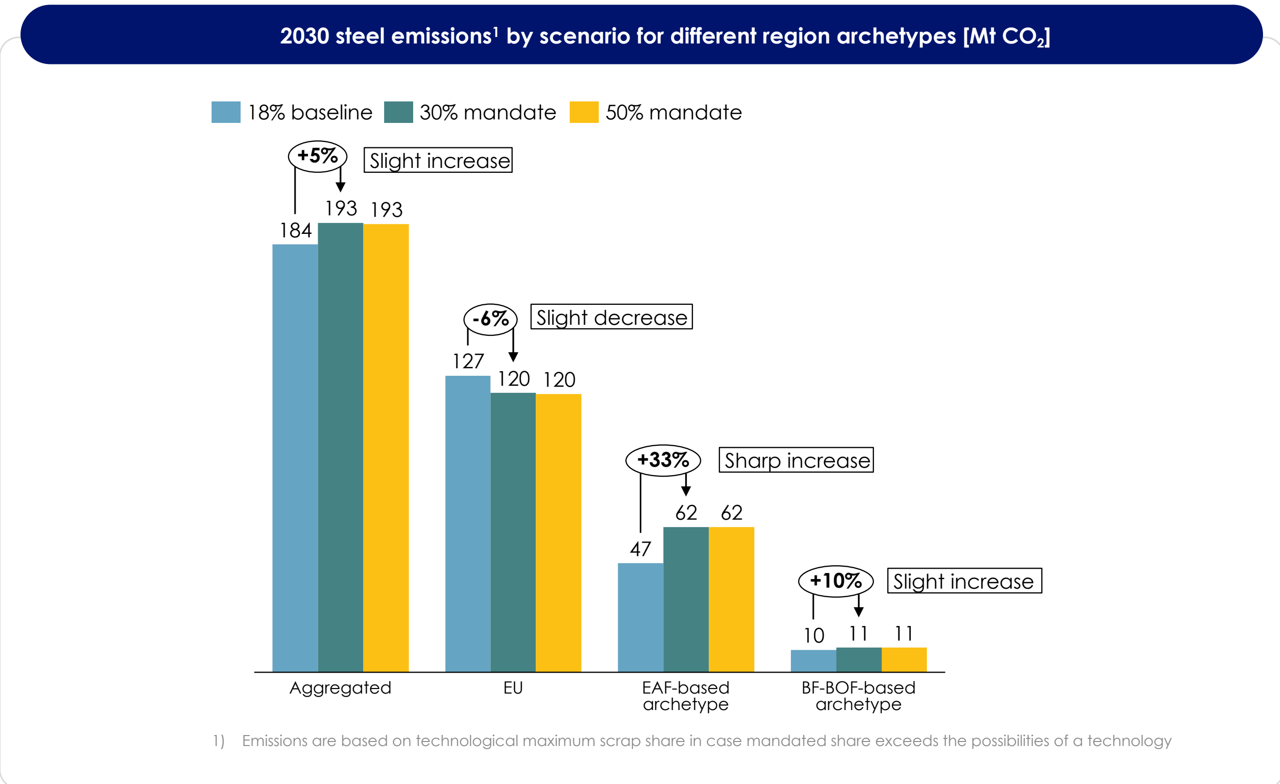
17 Information based on expert interviews.
18 32% for an archetype region that is predominantly producing steel via EAF (80% EAF, 20% BF-BOF), e.g., Turkey, and 10% for an archetype region that is predominantly producing steel via BF-BOF (80% BF-BOF, 20% EAF), e.g., Pakistan.
19 System-level emissions: GHG emissions by the EU, Turkey, and Pakistan. This acts as a proxy for the effect of recycled content targets on global emissions, but does not provide a full representation of global emissions impact.
20 Baseline scenario assumes 18% scrap share.

represents the largest importer of EU scrap and is an EAF-based archetype.

For a 50% mandate, aggregated CO_2 emissions remain constant. This can be explained by two mechanisms: Firstly, in the EU, CO_2 emissions do not further decline, as most ore-based technologies already hit their technological scrap share limit in the 30% mandate scenario, therefore being unable to meet an even higher target. Therefore, only DRI-EAF production effectively increases its scrap share to 50%. Since DRI-EAF is assumed to run on green hydrogen and on a significantly decarbonised electricity grid by 2030, the CO_2 emissions decrease associated with a higher scrap share is limited. Secondly, for regions outside the EU, CO_2 emissions do not change because the EU already hits its limit of scrap supply at a 30% mandate. This means that for both a 30% and 50% recycled content scenario, there is no scrap available for export, resulting in no difference in CO_2 emissions between a 30% and a 50% scenario.

Note: CO_2 emissions (scope 1 and 2) were calculated by multiplying energy and feedstock consumption for each technology with the respective emission factors for each commodity (scope 1) and by multiplying net electricity consumption per technology with the grid emission intensity of each region respectively. For additional information, visit section 2.2 of the technical appendix.

Figure 3: Aggregated (system-level) CO_2 emissions slightly increase, as emissions shift to EU-scrap-importing countries



21 Scope 1 and 2 weighted average emission intensities. Note: these emissions include the substitution of missing scrap with pig iron in the archetypes.

These findings show that, in light of the ultimate goal to reduce global GHG emissions, instead of setting targets, the EU might be better off concentrating its short-term efforts on decarbonising primary steel production and on targeted measures that increase availability and quality of scrap in the EU. Due to the shift in CO_2 emissions to EU-scrap-importing countries described above, from a climate point of view reducing exports should not be targeted by policy.[22] It is important to note that this picture may change beyond 2030, depending on the speed at which current EU scrap export regions decarbonise primary steel production and/or increase the availability and quality of their own scrap.

Recycled content targets of 30% or more by 2030 pose a risk to the EU steel value chain

Besides the ambiguity of system-level GHG emissions impacts, ambitious recycled content targets of 30% or more by 2030 pose two major risks to the steel industry and value chain. These risks must be avoided also due to the negative impacts they may have on the sectors that rely on EU steel production. Especially sectors that rely on high-quality steel products, such as the automotive, packaging, and energy sectors, rely significantly on competitive EU steel supply, and in turn play an important role for the shift to electric mobility, the energy transition, and food security. The reactions of steel producers to the two risks cannot be foreseen with certainty.

Risk 1: Premium steel producers are unable to meet ambitious recycled content targets, affecting the ability of the EU steel value chain to meet market demand

If targets are ambitious, such as in the modelled 30% or even 50% recycled content by 2030 scenarios, manufacturers of high-end steel products will likely struggle to meet them. This could be caused by two limiting factors:

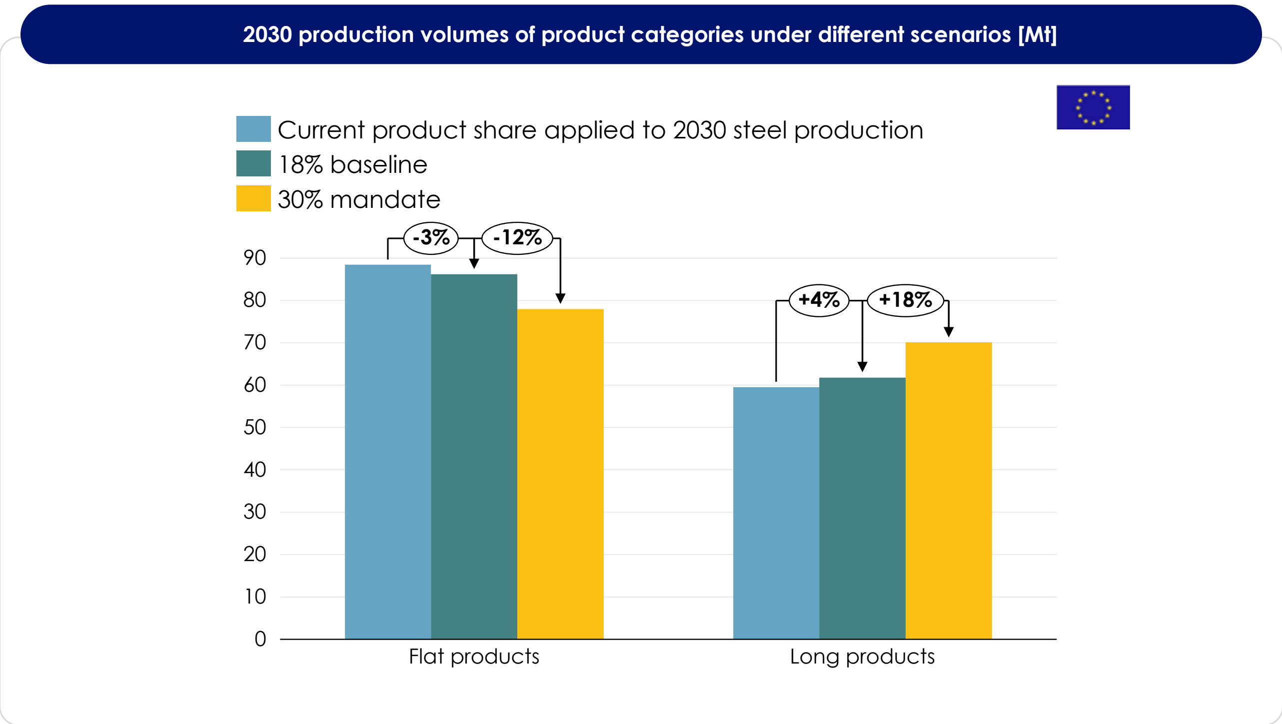
- First, the integrated BF-BOF route is limited to a maximum processing level of 25% scrap, and DRI-Melter-BOF to 30%.[23] Based on current project announcements and their technological scrap processing capacity, setting a target of 30% by 2030 could put up to 31% of EU steel production capacity at risk, increasing to 34% if targets are set at 50%. Without costly upgrades to these capacities, then, depending on how targets are set (e.g., border mechanisms and to whom targets apply), producers may attempt to shift production or sales to outside the EU, or to idle or retire EU assets. This would have negative socio-economic implications for the EU, and affect the EU's capacity to produce steel that meets market demands.

- Second, scrap quality poses another limitation. Assuming product design, collection, sorting, separation and upgrading practices do not sufficiently improve by 2030, producers could shift their product portfolio to lower quality products. These have a higher tolerance to tramp elements and thus allow for higher recycled content. The model reveals that the more moderate 30% recycled content scenario already yields a ~12% decrease in high-quality flat product volumes, relative to the current 60:40% flat- to long-product share applied to 2030

22 It is important to note that these emission projections operate under the assumption that the quality of scrap is sufficient to meet the stipulated recycled content targets.

23 Theoretically limits could be further increased, but this would result in a significant increase in energy, GHG emissions and associated costs.

Figure 4: Production volumes would need to shift from flat to long products in order to meet targets



steel production (see Figure 4). The graph further reveals that to achieve even the current 18% recycled content target in 2030, scrap quality would be insufficient to maintain the 60:40% flat- to long-product split the EU has today.

Note: production volumes in Figure 4 are derived by comparing the weighted average copper tolerance of the current production portfolio (projected to 2030) with the weighted average copper contamination of all iron feedstock sources (iron ore and scrap), shifting production from flat to long products until tolerance levels of the "adjusted" portfolio matches contamination levels of feedstock sources. For more details, please refer to section 2.4 of the technical appendix.

Given the value proposition of European steel producers based on customer demand and the existing market dynamics, a portfolio shift is unlikely. Projections suggest that the necessary portfolio shift in the 30% mandate scenario could decrease revenue in the EU market by approximately 2% as a result of decreasing production of high-quality products. For a detailed view on assumed copper tolerances, and contamination of iron feedstock sources, please refer to section 2.2 in the technical appendix.

Alternatively to a portfolio shift, EU steel producers could idle production capacity in the EU, and/or shift it to outside of the EU, with negative implications on jobs and the economy. If targets apply to EU steel users, e.g. automotive OEMs, EU producers could also attempt to increase exports, i.e. shift sales to regions with no recycled content targets.

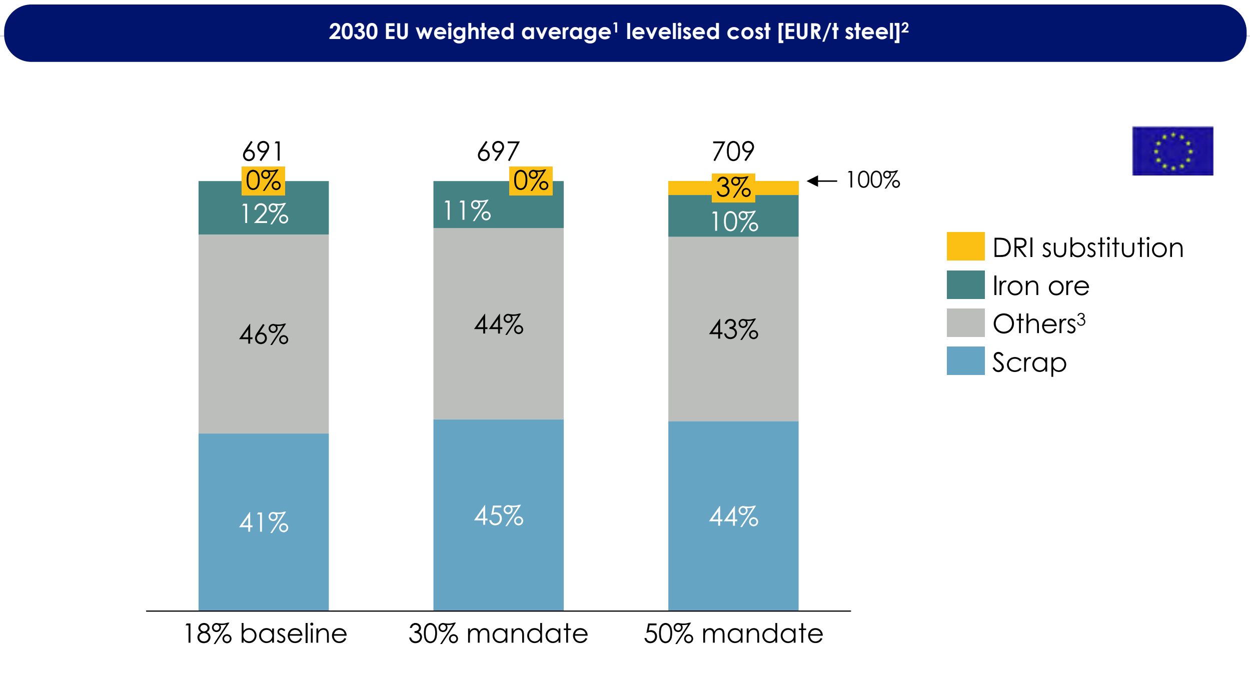
It is important to note that capacity cuts are an extreme – albeit possible – reaction to recycled content targets, which would occur only if producers are financially unable to make the required investments to meet targets. However, the likely production cost increase poses its own risk, as described below.

Risk 2: The cost of steel production is highly sensitive to scrap prices, with scrap costs accounting for over 40% of overall production costs

Modelling results show that the levelised cost of production in the 2030 baseline scenario represents 41% of total production[24] costs (these costs are calculated as weighted averages across steel production routes). This increases to ~45% if recycled content targets are set (see Figure 5).

While higher scrap prices directly translate into higher incentives for collection, sorting, separation, and upgrading of scrap, they also pose a risk; if the cost increase cannot be passed down the value chain, this poses a serious concern to producers. This risk is accentuated given the already soaring energy prices and the considerable expense associated with transitioning to climate-friendly steel production. For a detailed view on assumed commodity prices, please refer to section 2.3 in the technical appendix.

Figure 5: Production costs increase slightly across different recycled content scenarios.



1) USD/EUR 1.1
2) Weighted average over all technologies with respective production share as weight
3) Others: Fossil Fuels, Hydrogen, Power, Slag, Carbon tax (~154€/t CO_2), other variable OPEX, CAPEX and O&M

24 Levelised cost: average net present cost of production over asset lifetime.

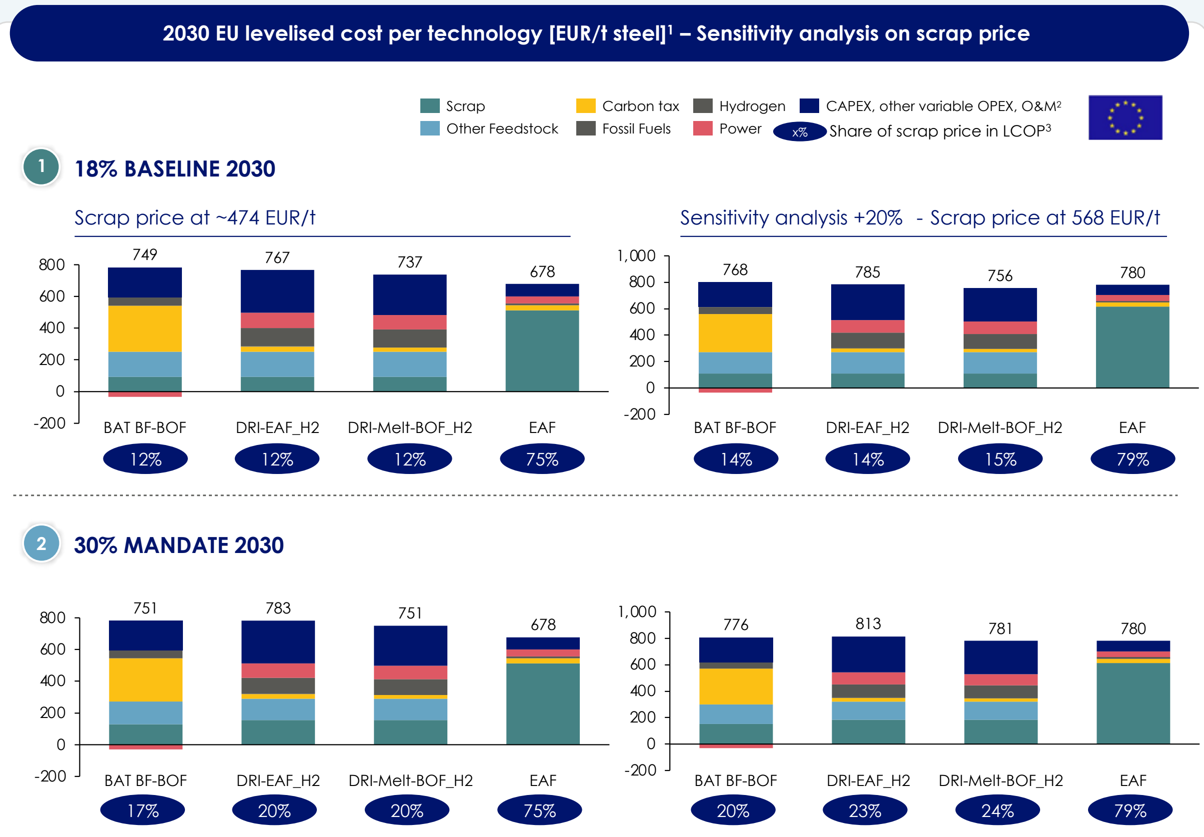
BOX 2: SENSITIVITY ANALYSIS OF SCRAP PRICES

Due to uncertainties associated with future commodity price developments and market dynamics, scrap price assumptions are static over time.

To investigate the impact of future scrap price increases on levelised cost of production (LCOP), a sensitivity analysis with a 20% price increase for 2030 resulted in a roughly 10% increase in weighted average levelised production cost across the scenarios.

Notably EAF levelised costs are more sensitive to scrap prices than other near-zero emissions technologies. Total LCOP increase from scrap price increase due to scrap share differences **ranges between ~2% for the BAT BF-BOF route and ~4% for the EAF route.**

In the 30% mandate scenario, even with higher scrap prices, ore-based near-zero emissions routes are still more cost-competitive than fossil-fuel based incumbent routes. This is mainly driven by the carbon tax (assumed carbon price ~€154/t CO_2).



1) USD/EUR 1.1
2) CAPEX (Capital Expenditure), OPEX (Operational Expenditure), O&M (Operation and Maintenance)
3) LCOP: Levelized Cost of Production
4) BAT: Best Available Technology

A set of trends might change market dynamics after 2030

The quantitative analysis of this paper models the impact of recycled content targets to 2030. Beyond 2030, trends might change the market dynamics, and therefore the impact such targets. would have. Three central trends should be closely followed in considering targets beyond 2030:

1. Steel demand: To what extent will steel be mitigated by proactive demand-side efficiency measures and progress in the EU?

Recycled content describes how much scrap is used in proportion to the amount of overall steel consumed, i.e. steel demand. Put simply, if steel demand is 100 times higher than scrap availability in the EU, the average recycled content will be a maximum of 1%.

To reach climate goals, it may be that demand-side efficiency measures are achieved that reduce the demand for steel. These consist of:

- Productivity-of-use strategies that increase the utilisation of steel in use. This includes shared, service-oriented, mobility system and shared buildings or more durable product design to extend product lifetimes.
- Material efficiency strategies that reduce the amount of steel needed. In particular, vehicle lightweighting, increased efficiency in building construction, and designing products and processes to minimise production scrap could play a role.[38]

While such efficiency measures are important to contribute to decarbonising steel production, it is uncertain whether they can compensate the expected demand growth of steel in light of its central role in modern economies and enabling function for multiple transitions such as the energy transition or shift to electric mobility. While such efficiency measures can make important contributions to decarbonising steel production, it is uncertain whether they can compensate for the expected demand growth of steel, as it is central to modern economies and to multiple transitions such as the energy transition or shift to electric mobility.

2. Scrap availability: Will changes in scrap availability and/or quality inside the EU and/or in scrap-importing countries lead to an increase in the availability of high-quality scrap in the EU?

While scrap demand may grow, so will scrap supply: global scrap availability is projected to increase by 30% between 2030 and 2050, driven especially by changes in Chinese scrap availability as large volumes of Chinese steel capacity are projected to reach end-of-life. However, the availability of such scrap for EU production is unlikely, as the Chinese government is targeting a significant scale up of scrap-EAF production and pursues a strategy of 'scrap protectionism'.[39]

In addition, export changes in light of the electric vehicle transition could increase scrap supply. BEVs are much less likely to be exported to outside of Europe at their end-of-life than their combustion engine counterparts, because the battery represents a component of high interest for reuse and recycling in Europe. As a result, the steel of these retained vehicles could boost European scrap availability. However, given the current pace of BEV uptake and the projected lifespan of BEVs in Europe, this effect is unlikely to materialise before 2035. The Energy Transitions Commission estimates that only 0.5 million BEVs will come to end-of-life in 2030. By 2040 that number increases to

5.4 million BEVs.[40] Assuming 0.7 t steel/BEV, this translates to a potential recovery of 3.8 Mt of scrap in 2040.

3. Scrap quality: Will scrap quality improve, solving the issue of tramp elements contamination?

A central constraint for increasing recycled content in high-quality products by 2030 is the excessive contamination of post-consumer scrap. Beyond 2030, this may change due to two developments:

Firstly, the expected high-quality scrap deficiency in the next decade could cause competition that encourages practices to improve scrap quality, further strengthened by existing legislation. Design for recycling could increase (e.g., due to the impact of eco-design requirements), collection, sorting, and separation practices might be built out, and better differentiation of scrap streams could reduce downcycling.

Secondly, technology improvements could alleviate the quality constraint. For example, contaminant removal technologies could scale. First companies are starting to overcome scrap quality limitations, employing high scrap rates to deliver high-quality steel products to automotive companies.[41] While technological limitations still hinder a significant scale-up of such solutions, their development could be catalysed with R&D support and make EU scrap a competitive resource for all quality grades beyond 2030.

4. ENABLING HIGH-QUALITY RECYCLING SYSTEMS:

Finding the appropriate policy mix

4. ENABLING HIGH-QUALITY RECYCLING SYSTEMS:

Finding the appropriate policy mix

Proactive supply-side measures to increase the availability and quality of scrap in the EU are a no-regret option

As seen above, scrap availability and quality are key roadblocks limiting the increase of recycled content. Well-known supply side measures can alleviate these constraints by increasing scrap availability and offer a solution to the quality challenge. Implementing them from now on is a no-regret measure to improve the system readiness for closing the circularity loop.

Improving design for recycling: As a first step, better product design will result in more high-quality 'clean' post-consumer scrap. This includes minimising materials that are problematic for recycling, minimising complex material compositions, and designing products to facilitate efficient disassembly. This can be supported by measures such as minimum product circularity requirements, such as those observed in the proposal for the revision of the ELV Directive. As the availability of steel scrap might be boosted by a significant decrease in, or even a ban of, exports of BEVs at end-of-life after 2030, this is of particular importance for the automotive industry.

Improving scrap collection: Global collection rates for recycling of steel scrap are high at 85%[42], but there is still room for improvement. An example is the automotive sector, where about one third of all end-of-life vehicles – 3-4.5 million annually – are lost to uncontrolled dismantling or exports.[43] This could be improved by increasing controls and oversight on the EU's end-of-life vehicles system.

Improving separation of scrap: This involves separating materials at a higher granularity than today to physically remove tramp elements. This could involve manual disassembly and/or a range of advanced sensor-based technologies. Several technologies to remove tramp elements from scrap steel are market ready and can be deployed, leveraging a wide range of techniques such as artificial intelligence (AI), sorting based on metal colour, near-infrared sorting based on molecular composition of materials, X-ray sorting based on varying radiations reflected by different materials, and float-sink technology based on densities of different materials.

Improving the sorting of scrap grades: This involves automated sorting technologies that facilitate efficient analysis of scrap composition and contamination, such as near-infrared technology, X-ray fluorescence, and hyperspectral imaging.

Facilitating scrap upgrading: At this stage, the focus is on processes to extract tramp elements. However, these are often very expensive and need to be further developed and scaled to bring down the costs of copper management post-mixing.[44] To further speed up the development of these crucial technologies, effective measures could be incentives such as R&D grants for pilot projects, government guarantees for larger investments, or export credits. In addition, EU-wide joint ventures of steel producers who invest in these technologies could be an effective approach to scale this technology.

Increased scrap collection, separation, sorting, and upgrading causes scrap costs to rise. This can either be carried by the steel producers, users, and end customers (e.g., car buyers paying a premium for more circular products) and/or be provided with public support. As these processes scale, costs are likely to reduce over time.

A cross-cutting enabler of increasing steel circularity, is to close current data gaps, e.g. on scrap quality, scrap trade and recycling rates. This would not only help avoid mixing high- and low-quality scrap and thus enable higher quality scrap availability, but support key stakeholders in making informed decisions.

Further research is recommended to investigate how exactly these measures can be supported by EU legislation and industry action and how they can be supported by cross-cutting market enablers, such as digital product passports, and product certifications.

A framework for assessing the relevance of targets to increase circularity and recycling rates of EU steel

Recycled content targets are a known policy instrument to promote more circular end-of-life practices, increasing scrap demand, promoting off-take agreements and thereby incentivising/de-risking circular economy investments by increasing and stabilising the price of recyclates. However, in light of high scrap demand and limited scrap availability, as well as the already high recycling rate of steel, the authors' analysis concludes that recycled content targets of 30% or more by 2030 would entail negative impacts on system-level[25] GHG emissions and the ability of EU steel producers to meet the demands of European steel users.

In light of changing market dynamics beyond 2030, the below framework (see Figure 6) proposes a set of criteria to determine whether policy instruments can support steering market dynamics in a way that they contribute to desired decarbonisation and circularity outcomes, while being feasible to implement and not distorting the playing field in an undesired way:

A. Desirability of recycled content targets

1. Would increasing recycled content of EU steel within the EU (vs. outside the EU) via targets **translate into system-level decarbonisation?**

Until at least 2030, the analysis shows this would not be the case until at least 2030, because recycled content targets would reduce scrap exports and thereby shift GHG emissions to countries currently importing EU scrap. Beyond 2030, this could potentially change, depending on the speed at which scrap-importing countries decarbonise their grid and steel production or become independent of EU scrap supply.

2. Would increasing recycled content of EU steel within the EU (vs. outside the EU) via targets **translate into higher system-level recycling rates and use of recycled steel?**

Currently, around 85% of scrap is already recovered for recycling, of which 20% is exported. By 2030, increased recycled content in the EU would likely come at the expense of reducing scrap exports, i.e., reducing recycled content outside of the EU with no significant benefit to system-level recycling rates. Beyond 2030, this may change, depending on how scrap supply increases relative to scrap demand in the EU.

3. Would recycled content targets for EU steel within the EU (vs. outside the EU) **enable EU steel producers to meet EU market demand?**

By 2030, increasing recycled content could have the opposite effect: EU steel

25 System-level emissions: GHG emissions by the EU, Turkey, Pakistan. This acts as a proxy for the effect of recycled content targets on global emissions, but does not provide a full representation of global emissions impact.

producers unable to meet targets would face risks of increased cost, relocating production, increasing exports of products at the cost of domestic sales, or losing out to international competitors that do not face targets.

4. Would increasing recycled content of EU steel within the EU (vs. outside the EU) via targets **reduce raw material supply-chain dependency on non-EU countries?**

By 2030, increasing recycled content could positively impact raw material supply-security. However, scrap quality requirements mean that imports of virgin ores are still needed to meet most of the EU steel demand. In the long-term beyond 2030, if post-consumer scrap quality and availability improves in the EU, the EU value chain could benefit significantly from a more independent supply chain.

B. Feasibility of increased recycled content

1. Is there **sufficient available scrap inside the EU** to allow for higher recycled content?

Yes, to some degree in total volume terms; the EU is a net exporter of scrap. However, the quality of exported scrap is partly incompatible with current production. In addition, if steel demand grows faster than scrap availability, it will not be possible to increase recycled content.

2. Is the **quality of post-consumer scrap high enough** to allow EU steel producers to serve their customers?

Current post-consumer scrap quality is not high enough for use in high-quality products due to tramp element contamination. This is expected to persist to 2030.

The feasibility could change significantly beyond 2030, driven by demand-side policy measures, an increase in end-of-life vehicle availability, and technological developments (see chapter 3 for detail).

C. Enablers: are targets the right tool to increase recycled content?

1. Are recycled content targets **necessary to increase circularity of EU steel** within the EU?

The existing high demand and limited availability of scrap already acts as a strong driver to incentivise high scrap usage, which is projected to increase. However, recycled content targets could incentivise better quality of post-consumer scrap and reduce downcycling, as uncontaminated post-consumer scrap would be needed to achieve higher recycled content in high-quality products.

2. Are recycled content targets **the most effective instrument to increase circularity and lower the product carbon footprint of steel?**

Recycled content target effectiveness should be compared to other policies, or as part of a broader policy mix, and evaluated based on the answers to the previous questions of this framework. Further research is proposed to clarify this in the context of circularity, decarbonisation, and socio-economic implications.

Figure 6: Framework to assess recycled content targets

<table>
<tr><th></th><th></th><th>In the short term
Until 2030</th><th>In the medium to long term
Beyond 2030</th></tr>
<tr><td rowspan="4">Desirability</td><td>Would increasing recycling content of EU steel within the EU (vs. outside the EU) via targets translate into system level decarbonisation?</td><td>No (exporting emissions to currently scrap importing countries).</td><td>Potentially. If scrap importing countries decarbonise grid and steel production or identify other sources of scrap.</td></tr>
<tr><td>Would increasing recycling content of EU steel within the EU (vs. outside the EU) via targets translate into higher system-level recycling rates and use of scrap?</td><td>No, scrap is being traded and used in markets inside and outside EU. Increasing EU scrap use, would initially decrease scrap use elsewhere.</td><td>Potentially. If scrap availability increases and simultaneous steel demand flattens.</td></tr>
<tr><td>Would increasing recycling content of EU steel within the EU (vs. outside the EU) via targets enable EU steel producers to meet EU market demand?</td><td>Potential opposite effects if producers cannot serve customers as they cannot reach targets or delocalise production.</td><td rowspan="4">Potentially. If scrap quality and quantity improves (e.g., quantity effect of BEVs staying in EU at end-of-life or technological progress enabling post-consumer scrap upgrading).</td></tr>
<tr><td>Would increasing recycled content of EU steel within the EU (vs. outside the EU) via targets reduce supply-chain dependency on imported raw materials?</td><td>Limited effect – scrap quality requirements mean that imports of virgin ores still needed to meet most EU steel demand.</td></tr>
<tr><td rowspan="2">Feasibility</td><td>Is there sufficient available scrap inside the EU to increase the share of scrap in EU production?</td><td>Yes, to some degree in total volumes as EU is a net exporter of scrap</td></tr>
<tr><td>Is the available scrap high-quality enough to allow EU steel producers to serve their customers?</td><td>No, tramp element contamination does not allow the production of high-quality steel (needed by multiple EU customer segments).</td></tr>
<tr><td rowspan="2">Enablers</td><td>Are recycled content targets necessary to increase circularity of EU steel within the EU?</td><td>Scrap demand already higher than scrap supply. However, could incentivize improving post-consumer scrap quality.</td><td>Monitor scrap demand vs supply developments.</td></tr>
<tr><td>Are recycled content targets the most effective instrument to increase circularity and lower product carbon footprint of steel?</td><td>Supply-side measures increase circularity while mitigating risks to EU steel value chain.</td><td>To be investigated among other instruments.</td></tr>
</table>

The above framework indicates the complex implications that need to be weighed up when assessing recycled content targets. This paper attempts to provide a fact-based analysis of the desirability and feasibility of recycled content targets until 2030. However, especially in light of long-term market trends, the questions and dynamics of the above framework should be monitored to assess the potential of recycled content targets as a policy that increases circularity, reduces GHG emissions, and enables the ability of the domestic steel value chain to economically drive its green transition.

TECHNICAL APPENDIX

1. Introduction

This technical appendix accompanies the white paper "Circular Steel: A system perspective on recycled content targets", commissioned by thyssenkrupp Steel Europe and authored by Systemiq. Inputs and assumptions, to a large degree, are based on the steel sector transition strategy published by the MPP in 2022: "Making net-zero steel possible – an industry-backed, 1.5°C-aligned transition strategy".[45]

Within this context, the model quantifies the demand and supply side of scrap and the impact on GHG emissions and levelised cost of steel making of different recycled content mandates, with a primary focus on the EU from 2023 to 2030.

The selection of the year 2030 as the timeframe is driven by several considerations. Firstly, it aligns with ongoing policy discussions, providing relevance to current developments. Secondly, the period beyond 2030 is expected to have significant changes in technological infrastructure and energy mix, introducing more uncertainties. Lastly, the timeframe of 2030 allows for projections with a relatively high degree of confidence, facilitating a clearer and reasoned modelling of recycled content scenarios. Like all models, this approach is an imperfect reflection of the intricate trade dynamics and decision-making processes in the iron and steel value chain. The model does not predict the future but offers various conceivable scenarios. It is designed as a flexible tool for users to explore the effects of recycled content mandates on steel within a simplified framework.

Given the uncertainties tied to model inputs such as future commodity prices, feedstock availability, steel demand, technological advancements, and regulatory decisions, it is crucial to note that the model's outputs are contingent on a specific set of techno-economic assumptions. To interpret and comprehend the model results effectively, understanding these foundational assumptions is essential.

Critically, the model is not a full market or environmental impact assessment model. The following presents a simplified overview of the different modules, key inputs and underlying assumption.

1.1. Regional archetypes

An approach using regional archetypes is chosen in order to explore the impact of changing scrap exports on other regions, that currently depend on EU scrap as a feedstock for domestic steel production.

Unlike the alternative global stock and flow model, this method enables us to extract insights for a specific archetype and extrapolate conclusions to the majority of trade partners. Despite its simplicity, this approach effectively encapsulates a broad and dynamic array of trade partners, given the potential rapid shifts in trade dynamics.

The following table outlines the characteristics of the two regional archetypes and maps all regions currently dependent on EU scrap imports to either of these archetypes. Notably, this excludes interregional trade partners within the EU.

Subsequent sections will focus on relevant input assumptions for Turkey and Pakistan, together accounting for more than 70% of EU scrap exports.[46]

Table 2: Export regions archetype mapping

Regional archetype	Archetype description	Mapping of EU scrap import regions[26]
EAF-based	Majority of production capacity is scrap-based EAFs.	Turkey
		Egypt
		USA
		Moldova
		Switzerland
BF-BOF-based	Majority of production capacity is the ore-based integrated route.	Pakistan
		India

1.2. Technological archetypes

The model considers four overarching production processes (see Table 3) and their respective variations, which are represented as technological archetypes. Due to the unique setup of each steel plant, shaped by its technological, regulatory, and regional frameworks, such a simplified approach is necessary to best describe production processes in techno-economic terms.

Each technological archetype's business case is based on the MPP sector transition strategy, tested and validated by the industry in 2022. They consider feedstock, fuel, and energy consumption, associated GHG emissions, and operating and capital expenditures from publicly available data source.

To be able to explore the impact of various recycled content mandates for steel, a linear relationship of scrap versus iron ore consumption and all related commodities was is commodities was established. This allows the model to quantify the shift of material consumption when varying the scrap share.

Table 3: Technology archetype mapping

Classification/Feedstock type	Production process	Technology archetype[27]
Ore-based production	Integrated route	Average BF-BOF
		BAT BF-BOF
	Direct reduction -EAF	Gas-based DRI-EAF
		H2-based DRI-EAF
	Direct reduction-BOF	Gas-based DRI-melt-BOF
		H2-based DRI-melt-BOF
Scrap-based production	EAF	EAF

26 BIR global facts and figures 13th edition.
27 For a more detailed description of the different technologies, please refer to the MPP steel sector transition strategy.

2. Model components

The following section gives a brief description of the four main model components and their relevant inputs respectively. Each component explores a different aspect of quantifying the impact of introducing recycled content targets for steel.

2.1. Scrap balance

The scrap balance module investigates and quantifies the impact of mandated scrap shares for ore-based production on the consumption of scrap within the EU, and compares is to projected scrap supply and consequently determines resulting export quantities for 2023 and 2030. The following gives a detailed overview of all relevant inputs and underlying assumptions.

Table 4: Steel production capacity by region and technology (2023,2030)

Technology	Production capacity 2023[Mt]			Production capacity 2030[Mt]			Source
	EU	Turkey	Pakistan	EU	Turkey	Pakistan	
Avg BF-BOF	n/a	14.4	4.1[29]	n/a	14.4	4.1[27]	GEM[47]
BAT BF-BOF	110.7	n/a	n/a	61.7	n/a	n/a	ibid.
EAF	79.5	37.7	1.5[27]	92.2	45.7	1.5[27]	ibid.
DRI-EAF	1.9	n/a	n/a	n/a	n/a	n/a	ibid.
DRI-EAF_H2	n/a	n/a	n/a	39.1	n/a	n/a	ibid.
DRI-Melt-BOF_H2	n/a	n/a	n/a	7.0	n/a	n/a	ibid.

Table 5: EU total scrap supply in 2023, 2030

Year	Scrap supply[Mt]	Source
2023	97.1	EUROFER[48]
2030 – Business-as-Usual scenario	106.5[31]	MPP STS[49]
2030 – High -circularity scenario	115.2[28]	ibid.

Table 6: Crude steel production in 2023, 2030 by region

Year	Crude steel production[Mt]			Source
	EU	Turkey	Pakistan	
2023	136.3	35.1	5.3	WSA[50]
2030 – Business-as-Usual scenario	161.0	36.5[32]	5.3[1]	IDDRI[51]
2030 – High -circularity scenario	126.5[33]			MPP STS[52]

28 Average Blast Furnace – Basic Oxygen Furnace, refer to glossary for explanation.
29 Adjusted Pakistan capacity to match WSA production data.
30 Best available technology Blast Furnace – Basic Oxygen Furnace, refer to glossary for explanation.
31 Applied growth rate for continental Europe onto EU scrap supply from 2022.
32 Applied IDDRI growth rate to 2022 production.
33 Applied MPP High Circularity growth rate to 2022 values.

2.2. CO_2 emissions

The emissions module investigates and quantifies the impact of mandated scrap shares for ore-based production on overall aggregated emissions. This section provides a detailed overview of all relevant inputs to obtain scope 1 and 2 emissions for each technological archetype with respect to a varying scrap share over the modelled timeline and for each regional archetype.

The following also provides the resulting scope 1 emissions intensity per technology for the baseline scenario with 18% scrap share for reference. Please note scope 2 emissions vary, since power grids are expected to decarbonise over time (see Table 7).

Table 7: Grid emission intensity per region 2023 – 2050 [t CO_2 /MWh]

Region	2023	2030	Applied region	Source
EU	0.19	0.11	EU	MPP STS – grid decarbonisation scenario[53]
Turkey	0.58	0.38	Asia	ibid.
Pakistan	0.6	0.33	India	ibid.

Table 8: Emission intensity for different feedstock and energy sources

Energy/feedstock	Unit	Emission intensity	Source
H2-based DRI	t CO_2/ t Steel	0.0	Assuming RES based hydrogen
Gas-based DRI	t CO_2/ t Steel	0.9	WSA[54]
Pig iron	t CO_2/ t Steel	2.0	ibid.
Thermal coal	t CO_2/ GJ	0.095	MPP STS[55]
BF gas	t CO_2/ GJ	0.26	ibid.
Coke oven gas	t CO_2/ GJ	0.044	ibid.
BOF gas	t CO_2/ GJ	0.19	ibid.
Natural gas	t CO_2/ GJ	0.055	ibid.

Table 9: Scope 1 emission intensity per technology for 18% scrap share for ore-based production

Technology	Emission intensity [t CO_2/t]	Note	Source
Avg BF-BOF	2.2		ibid.
BAT BF-BOF	2.1		ibid.
EAF	0.16	100% scrap-based, gas-based	ibid.
DRI-EAF	0.1		ibid.
DRI-EAF_H2	0.1	RES-based hydrogen	ibid.
DRI-Melt-BOF_H2	0.1	RES-based hydrogen	ibid.

2.3. Costs

The cost module investigates and quantifies the impact of mandated scrap shares for ore-based production on levelised cost of production.

To calculate levelised costs per technology, the model assumes 8% Weighted Average Cost of Capital (WACC) and a 20 year average lifetime of a steel plant. Further relevant model inputs are listed below.

Table 10: EU commodity price assumptions

Commodity	Price			Source
	Unit	2023	2030	
Scrap	EUR/t[34]	474	474	UN Comtrade[35][56]
Iron ore	EUR/t[34]	117	117	USGS[36][57]
Gas-based DRI	EUR/t[34]	409	409	Expert input
H2-based DRI	EUR/t[34]	-	591	Calculation[37]
Metallurgical coal	EUR/t[34]	107	129	MPP STS[58]
Thermal coal	EUR/t[34]	50	61	ibid.
Natural gas	EUR/GJ[34]	4.7	7.2	ibid.
Low-carbon hydrogen	EUR/kg[34]	3.1	2.5	ibid.
Electricity	EUR/MWh[34]	86	67	ibid.
CO_2 cost	EUR/t CO_2[34]	87	154	Thomson Reuters

2.4. Copper contamination

The copper contamination module investigates and quantifies the impact of mandated scrap shares for ore-based production on the current product portfolio of the EU, examining the contamination of different iron feedstocks and their compatibility with either producing long or flat steel products. To obtain these insights, the module calculates the weighted average contamination of a selection of feedstocks as well as the weighted average copper tolerance of the current product portfolio in the EU.

Additionally, the module allows to assess the trade-off between changing the product portfolio of the EU, focusing less on premium production, hence negatively impacting the expected revenue versus additional costs of copper removal to accommodate the modelled scrap share mandates.

34 USD/EUR conversion rate 1.1.
35 UN COMTRADE data set covers years 2018-2022 and is corrected for outliers and 2020 real USD values, all prices are derived by averaging over all exports.
36 Global average of 2022.
37 The price for hydrogen-based DRI is derived from gas-based DRI + price premium of 200 USD/t.

Table 11: Copper tolerance per product category

Product category	Long/Flat	Copper tolerance[%]	2022 production share[38]	Source
Bars	Long	0.4 %	17%	[59], p. 5
Wire rod	Long	0.3 %	15%	[60]
Tubes/shapes	Long	0.13 %	8%	[61], p. 5
Flat products	Flat	0.06 %	60%	ibid.

Table 12: Copper concentration in iron feedstock

Feedstock	Copper (and other contaminants) concentration [% m/m]	Scrap share in total supply [%][39]	Source
Pig iron	0.01%	-	[62]
Scrap Q1	0.13%	21%	ibid.
Scrap Q2	0.21%	10%	ibid.
Scrap Q3	0.3%	35%	ibid.
Scrap Q4	0.4%	34%	ibid.

38 EUROFER (2022), underlying assumption production share stays flat until 2030.
39 Underlying assumption scrap quality shares stay flat until 2030.

GLOSSARY

Artificial intelligence (AI) in sorting: Used to enhance the capabilities of sorting technologies by enabling better decision-making algorithms in identifying and categorising scrap materials during the sorting process.

Basic Oxygen Furnace (BOF): A steelmaking furnace that produces steel from molten iron, often in conjunction with some scrap, by reducing the carbon content of the mixture with the aid of pure oxygen.

Blast furnace (BF): The main process unit used globally for the production of iron from iron ore.

Best available technology (BAT): The BF-BOF route with improved efficiency measures compared to the average BF-BOF.

Collection for recycling rate: The proportion of waste materials or products that are collected for recycling out of the total amount that has been placed on the market or generated.

Crude steel: Steel as it emerges in its first solid state, before rolling and other finishing processes.

Direct reduced iron (DRI): Iron produced from iron ore pellets in a DRI furnace.

DRI furnace: An alternative process to the blast furnace for making iron from iron ore in the solid phase.

Electric Arc Furnace (EAF): An electric furnace for making steel from scrap and/or DRI by melting it with an electric arc. Oxygen and other elements are introduced to adjust the final composition of the steel.

Float-sink technology: This separation method relies on the different densities of materials to separate lighter materials from heavier ones in a medium, typically a liquid.

Green hydrogen: Hydrogen fuel that is produced through the process of electrolysis, which splits water into hydrogen and oxygen using electricity generated by renewable energy sources, such as solar or wind power.

High-quality scrap: Scrap that has minimal levels of tramp elements and is suitable for recycling into high-quality steel products.

Home scrap: Scrap steel generated due to the imperfect yields of steelmaking, rolling and finishing processes within a site. Synonyms include return scrap, internal scrap and semi manufacturing scrap.

Hydrogen-based DRI: An alternative DRI process currently under development to produce sponge iron from pellets using hydrogen as the reduction agent instead of a mixture of hydrogen and carbon monoxide as in a regular DRI furnace.

Hyperspectral imaging: Used in sorting, this technology identifies the chemical composition of materials, facilitating the sorting process by distinguishing between different types of materials based on their spectral response.

Iron ore: The primary virgin raw material input to steelmaking.

Levelised cost: Average net present cost of production over asset lifetime.

Metal colour sorting: This technology is used for separating materials based on colour differences, which can be part of the separation process to isolate materials of different types.

Near-infrared sorting: Primarily a separation technology, it is used to differentiate materials based on their molecular composition, which is reflected in their response to near-infrared light.

Pig iron: A solid form of iron with a high carbon content produced from iron ore in a blast furnace or smelting reduction process.

Post-consumer scrap: Scrap steel generated at the end of a steel-containing product's lifetime. Synonyms include old scrap, end-of-life scrap and obsolete scrap.

Primary production: Steel production that uses iron ore as its primary source of metallic input.

Prompt scrap: Scrap steel generated during the manufacture of steel products by first-tier customers, such as vehicle makers. Synonyms include new scrap, industrial scrap and manufacturing scrap.

Recovery rate: The percentage of materials that are recovered from the waste stream and sent for recycling, composting, or energy recovery. It considers all materials that are diverted from landfilling or incineration and are instead used as a resource.

Recycled content: The proportion of a product or material that is made from recycled materials, expressed as a percentage of the total weight or volume of the product.

Recycling rate: Recycling rate is a measure of the amount of waste material that is collected, processed, and converted into new products or materials, expressed as a percentage of the total waste generated or collected.

Scrap: A collective name for home scrap, prompt scrap and post-consumer scrap.

Scrap separation: The process of separating materials at a granular level to remove tramp elements for recycling.

Scrap sorting: The process of categorising and organising different types of steel scrap based on specific properties and characteristics, such as alloy composition and grade. This process facilitates the identification of the various types of steel scrap for further processing or recycling.

Secondary production: Electric furnace production that is primarily fed by scrap, as opposed to pig iron or sponge iron.

System-level emissions: GHG emissions by the EU, Turkey and Pakistan. This acts as a proxy for the effect of recycled content targets on global emissions, but does not provide a full representation of global emissions impact.

Scrap upgrading: The process of improving the quality of scrap through various methods, including metallurgical processes.

Tramp elements: Impurities found in scrap steel that are not easily removed during the steelmaking process. Their presence can adversely affect the properties of steel, limiting the recyclability of the scrap or its suitability for certain applications. Common tramp elements in scrap steel include copper, tin, nickel, and molybdenum, among others.

X-ray fluorescence (XRF): Specifically used in sorting, XRF analyses the elemental composition of materials, helping to categorise them into appropriate grades based on their chemical makeup.

X-ray sorting: This is a separation method where materials are differentiated based on how they absorb or reflect X-rays, often related to their density and composition.

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