



Barriers to circularity in the metals industry: an analytical framework of feedback and lock-in effects

Jonas Grafström^{1,2} · Gregory Poelzer¹ · Jens Pettersson²

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Abstract

The metals sector faces multiple and interconnected barriers to achieving circularity. This study examines steel, aluminum, and copper to illustrate how challenges vary between metals. While copper can often be recycled without quality loss, steel and aluminum face alloy-related limitations that drive downcycling and quality degradation. Using a matrix-based analytical framework, the study maps the interactions between economic, technological, institutional, and social constraints, distinguishing between primary drivers, secondary effects, feedback loops, and lock-in mechanisms. The results show strong reinforcing links between economic, technological, and institutional domains, with social factors playing a more indirect role. These findings align with observed industry patterns while adding a structured, quantitative perspective. By clarifying how different barriers combine and reinforce one another, the analysis identifies priority areas for intervention to advance metals recycling and support the transition toward a more circular economy.

Keywords Circular economy · Metals · Systemic barriers · Feedback loops · Institutional constraints · Policy strategy

JEL Classification Q32 · Q38 · L72 · O13

Nomenclature

\mathfrak{B}	Set of barrier domains: Economic (E), Technological (T), Institutional (I), Social (S)	b_{SE}	Social → Economic
i, j, k	Indices for matrix operations	b_{TI}	Technological → Institutional
$B \in \mathbb{R}^{4 \times 4}$	Barrier Interaction Matrix	b_{IT}	Institutional → Technological
b_{ij}	Directional influence from domain i to j (0–3)	b_{TS}	Technological → Social
b_{ET}	Economic → Technological	b_{ST}	Social → Technological
b_{TE}	Technological → Economic	b_{IS}	Institutional → Social
b_{EI}	Economic → Institutional	b_{SI}	Social → Institutional
b_{IE}	Institutional → Economic	B^1	First-order matrix
b_{ES}	Economic → Social	B^2	Second-order matrix
		B^n	Higher-order influence matrix
		B^{\sim}	Cumulative influence matrix
		λ	Decay factor for higher-order effects
		Ψ	Barrier impact vector
		$\mathbb{1}$	Unit column vector
		ρ_{ij}	Reciprocity index
		L^3	3-node feedback loop strength
		\mathcal{L}^n	Set of all feedback loops of length n
		A^n	Total feedback intensity of loops of length n
		ϕ	Most embedded (dominant) domain in loop system
		Amplifier	Barrier with high outbound influence
		Bottleneck	Barrier with high inbound reinforcement

✉ Jonas Grafström
 jonas.grafstrom@ltu.se

Gregory Poelzer
 gregory.poelzer@ltu.se

Jens Pettersson
 jens.pettersson209@gmail.com

¹ Luleå University of Technology, Luleå 971 87, Sweden

² The Ratio Institute, Stockholm SE-113 59, Sweden

Lock-in	Self-reinforcing configuration resistant to change
Feedback loop	Closed directional path of barrier reinforcement

Introduction

The metals sector is among the most resource-intensive industries, yet its transition toward circularity remains uneven. While many metals are theoretically recyclable without quality loss, practical barriers differ markedly between material types. Chemically stable metals such as copper and nickel can often be recovered in pure form and reintroduced into supply chains without degradation flows (Dominish et al. 2018; Compañero et al. 2021; Dworak et al. 2022). By contrast, steel and aluminium are frequently alloyed with elements that are difficult to separate once mixed, resulting in downcycling and quality loss. These characteristics make circularity particularly challenging for steel and aluminium, where thermodynamic and process limitations compound other structural constraints (Reuter et al. 2019; Hagelüken and Goldmann 2022).

Infrastructure gaps and regulatory inconsistencies continue to delay the adoption of circular technologies, such as advanced sorting systems, traceability tools, and modular design strategies (Hagelüken and Goldmann 2022). This paper focuses on the systemic barriers affecting those materials, identifying how economic, technological, institutional, and social factors interact to limit circular outcomes.

Efforts to expand circularity in the industry have so far remained fragmented. Technical interventions are often introduced without complementary changes in policy or market structure, and firm-level innovations have struggled to scale in the absence of institutional alignment. Although numerous circularity barriers have been identified, they are typically examined in isolation (Grafström and Aasma 2021). Little attention has been paid to the structure of their interaction or to the reinforcing effects that may produce system-level resistance to change (Kirchherr et al. 2018; Reuter et al. 2019).

This paper addresses that gap by analyzing the metals industry as a system of interdependent constraints. The metals industry here refers to (but is by no means limited to) steel, aluminum, and copper, spanning mining, processing, reuse, and recycling. The analysis places primary emphasis on steel and aluminum, who have particularly acute circularity barriers due to alloy complexity and degradation risks. In contrast, more chemically stable metals such as copper do not experience the same thermodynamic limitations during recycling. Their high nobility enables recovery without significant quality loss, and they are typically reintegrated

into production systems without downgrading (Reuter et al. 2019; Hagelüken and Goldmann 2022).

The paper develops a formal matrix model to represent how barriers influence one another across four domains: economic, technological, institutional, and social. Each link in the matrix reflects the directional strength of influence from one barrier domain to another, based on a synthesis of empirical evidence from peer-reviewed studies. The model is extended analytically to capture second-order effects, feedback loops, and lock-in structures. These extensions allow for the identification of amplifying versus dependent barriers, and of leverage points where coordinated intervention may yield systemic impact.

The purpose is not to replicate existing reviews, but to formalize the barrier landscape as a system of interaction. In doing so, the paper provides both a conceptual framework and a diagnostic tool for understanding why circularity in the metals industry remains as structured as it is, and what types of policy, investment, and institutional change may be required to overcome entrenched constraints.

Circularity does not fail for lack of ideas, but because the structures that surround those ideas often pull in other directions. The metals industry already performs comparatively well, with high recycling rates and established recovery systems. Yet even in this relatively advanced context, barriers persist—not as isolated flaws, but as mutually reinforcing constraints. The framework developed in this paper helps make those structures visible. By representing barriers as a network of interacting influences, it becomes possible to see how certain constraints amplify others, forming loops of resistance that shape the pace and direction of change.

Background

Recent policies such as the EU's Circular Economy Action Plan and Japan's Basic Act on a Sound Material-Cycle Society promote secondary production and reduced reliance on critical minerals (European Commission 2020; Smol et al. 2021). Circularity is now framed not only as an environmental imperative, but also as a strategy to improve competitiveness and industrial resilience (Hagelüken and Goldmann 2022).

Steel is often cited as the world's most recycled material (Kara et al. 2022), yet alloy complexity, contamination, and inadequate scrap classification reduce the quality and scalability of secondary flows (Compañero et al. 2021, 2024). To address impurities, recycled scrap is diluted with virgin steel—sustaining primary dependence and limiting progress toward closed-loop systems (Tan et al. 2021). While some degree of downcycling is unavoidable, such dilution strategies undermine material efficiency and prolong linear

production models. As noted by Hagelüken and Goldmann (2022), thermodynamic limits and technical realities make complete circularity improbable. Still, improvements across the supply chain could push the sector significantly closer to higher circular performance.

Global steel production continues to grow, particularly in emerging economies where infrastructure gaps and limited scrap supply sustain demand for virgin inputs. Although total recycled volume has increased, its share remains stable (Aboura and Riva 2024), and projections suggest that scrap availability will not keep pace with future demand (Klimek et al. 2024).

Beyond recycling, circularity in the metals industry also depends on improvements in material efficiency, product design, and system integration. Advances in lightweight materials, higher-grade alloying, and waste management offer pathways to reduce raw material input (Kara et al. 2022; IRENA 2023). Circularity also depends on improved efficiency, alloy design, and waste recovery. Steel's durability enables longer service lives, particularly in modular construction and remanufacturing contexts (Dunant et al. 2017).

Like steel, aluminium and copper face losses due to ineffective separation and end-of-life sorting, despite their high theoretical recyclability. Yet the barriers differ in character: steel and aluminium are particularly susceptible to alloy mixing and contamination, which reduce secondary quality and complicate reuse. For copper, such degradation is less pronounced, as its chemical stability allows recovery in near-pure form through metallurgical refining (Reuter et al. 2019; Hagelüken and Goldmann 2022). Aluminium can be recovered at low energy cost, yet large volumes still end up in landfill (Al-Alimi et al. 2024; Gerold et al. 2024). Despite technical gains, structural conditions—ranging from contamination and design constraints to infrastructure gaps—continue to favor linear flows and limit circular outcomes.

Research methodology and model development

This section outlines the analytical approach used to model systemic barriers to circularity in the metals industry. The aim is not to list barriers individually, but to formalize how they interact across economic, technological, institutional, and social domains.

The empirical basis for the analysis consists of peer-reviewed articles published between 2014 and 2025. These were selected from the Scopus database and filtered for citation count, sectoral relevance, and explicit treatment of structural or cross-sectoral barriers—such as infrastructure limitations, regulatory fragmentation, or technological

bottlenecks. The review was used to identify recurrent barrier themes and directional relationships across domains. The literature serves not as the object of analysis, but as a source of evidence for populating the model structure.

The model is based on a square interaction matrix $B \in \mathbb{R}^{4 \times 4}$, where each cell $b_{ij} \in \{0, 1, 2, 3\}$ captures the relative strength of influence from barrier domain i to domain j . Four core domains are included: economic, technological, institutional, and social. Each domain is treated as a node in a directed system, and connections between them are weighed using qualitative evidence from the selected studies. The model is then extended analytically to capture second-order effects, feedback loops, and mutual reinforcement.

Second-order interactions are derived by matrix multiplication, tracing indirect influence across two-step pathways. A cumulative matrix aggregates multi-step effects using a decay parameter, allowing for sensitivity analysis. Additional indicators—such as barrier impact scores and reciprocity indices—support the identification of amplifiers and bottlenecks.

The framework draws on systems theory and transition literature, including constraint propagation (Arthur 1989), socio-technical feedback (Geels 2002, 2005), and institutional lock-in (Pierson 2000). Unlike simulation or agent-based models, this structure is static and diagnostic: it is not designed to predict outcomes but to clarify why certain constraint configurations resist change.

Barrier categories in the metals industry

Barriers to circularity differ across the stages of the metals recycling chain. To provide context for the constraints discussed in the following sections, it is useful to distinguish three key stages: (1) collection at the product level, (2) dismantling and mechanical pre-processing—such as size reduction, separation, and basic sorting—and (3) metallurgical processing and refining, which yield target alloys, pure metals, or metal salts. These stages vary in capital requirements, technological complexity, and geographic scale. Mechanical pre-processing is generally less capital-intensive and often carried out locally or regionally, which reduces transport needs for bulky end-of-life products. Metallurgical operations, in contrast, require high material throughput and are usually concentrated in large industrial hubs that source input from multiple regions or countries.

Economic barriers

Advanced sorting and traceability systems require upfront investment that remains difficult to justify in the absence of clear business models, stable demand, or effective incentives

(Dunant et al. 2017; Hagelüken et al. 2016; Ingaldi and Ulewicz 2024). In uncertain markets, firms hesitate to redirect resources away from established production methods (Singh et al. 2020; Kirchherr et al. 2018).

Even where secondary processes are technically feasible, demand structures often reinforce the use of virgin materials. Reuse is constrained by limited buyer interest, deconstruction costs, and inconsistent supply quality (Dunant et al. 2017; Tingley et al. 2017). Virgin materials, by contrast, is generally cheaper, quality-assured, and supported by long-standing procurement practices, which limits the market reach of reused alternatives (Reuter et al. 2019; Hagelüken and Goldmann 2022). These constraints are specific to certain metals; for materials such as copper, recycled output is chemically equivalent to primary input and typically does not face similar demand barriers.

Material complexity and design choices increase processing costs and reduce the economic viability of recycling. Steel and aluminium, in particular, require precise separation by alloy type to maintain material quality. Without such fine sorting, recovered output is often downgraded, which limits its usability and market value (Dominish et al. 2018; Kanyilmaz et al. 2023; Nechifor et al. 2020). Even with advanced systems, quality loss can still occur due to contamination or repeated thermal cycles during processing (Broadbent 2016; Cooper et al. 2020; Dworak et al. 2022). In contrast, copper and other chemically stable metals can generally be recovered in high purity without alloy-specific sorting.

The spatial configuration of the metals sector introduces additional cost burdens. Processing infrastructure is often concentrated in locations disconnected from where waste arises, or scrap is generated. This misalignment raises transportation costs and complicates logistics. In the case of tailings valorisation, for example, assessments show marginal or negative net present values, undermining the financial rationale for circular recovery efforts (Giurco et al. 2014).

Competitive pressure often leads firms to favour low-cost, low-efficiency recycling options. In jurisdictions where quality metrics are not enforced, or where pricing fails to account for material degradation, circular strategies remain economically marginal. In such cases, high-quality processing is outcompeted by volume-driven operations, sustaining a cycle of underinvestment in advanced techniques (Daehn et al. 2017; Branca et al. 2020; Lima et al. 2024). Part of this tension stems from the gap between macro-level benefits and micro-level incentives (Ahmadov et al. 2025). While circular models can improve supply security, reduce emissions, and support long-term resource stability, these gains do not typically carry a price signal. Firms make decisions based on cost, risk, and return within narrow planning cycles, which limits uptake unless external incentives or

mandates are in place. These dynamics also vary by market structure. Circularity is often more feasible in business-to-business contexts, where transactions involve fewer actors, higher transparency, and closer coordination. In business-to-consumer settings, fragmentation and information gaps present additional barriers.

In the absence of coordinated public support, firms have little incentive to make long-term commitments to circular systems. Green procurement rules, tax differentiation for secondary materials, or blended finance mechanisms could shift the economic calculus. Yet in many markets, such instruments remain underdeveloped or poorly targeted (Kinnunen and Kaksonen 2019).

Technological barriers

High-quality recycling requires advanced systems for sorting, separation, and metallurgical processing, but these technologies remain capital-intensive and unevenly distributed across regions (Cooper et al. 2020; Dworak et al. 2022; Watari et al. 2023). In many cases, facilities rely on older or volume-oriented systems that cannot reliably distinguish between alloy grades or manage tramp element contamination (Daehn et al. 2017; Lima et al. 2024). Without investment in high-precision technologies, recycled output, particularly for steel and aluminum, is often restricted to low-value applications. This limitation does not apply in the same way to copper, where high-purity recovery is typically achievable and the secondary material retains full functionality.

Contamination presents a recurring obstacle, particularly in steel recycling. Elements such as copper are difficult and costly to remove once introduced into the scrap stream, leading to persistent degradation in material quality (Taghipour et al. 2022). The absence of consistent classification standards and the mixing of high- and low-quality scrap further compound the problem (Daehn et al. 2017; Dworak et al. 2022). These conditions reduce the availability of high-grade recycled input and increase reliance on virgin material to meet quality specifications.

Product design introduces a second layer of constraint. Most consumer and industrial products are not developed with disassembly or end-of-life processing in mind. In construction, for example, structural steel is often embedded in forms that are difficult to recover or repurpose due to a lack of standardized connection systems or traceability protocols (Dunant et al. 2017; Kanyilmaz et al. 2023). In the electronics sector, rapid product evolution and complex material mixes outpace the capacity of available recycling infrastructure to separate valuable inputs from non-recoverable waste (Broadbent 2016; Murthy and Ramakrishna 2022).

A further complication arises from the mismatch between technological capacity and regulatory priorities. In many jurisdictions, policy instruments still focus on mass-based recycling targets rather than material quality or traceability. This emphasis encourages volume-driven processes at the expense of technological precision, undermining incentives to invest in higher-performance systems (Velenturf et al. 2019; Hagelüken and Goldmann 2022). Long development cycles for advanced technologies, coupled with the absence of clear implementation pathways, delay both adoption and standardization (Winans et al. 2017).

Tailings, which often contain recoverable metals, require site-specific treatment methods that remain technically feasible but commercially marginal. High transport costs, variable material composition, and the need for specialized equipment limit broader uptake (Wang et al. 2014; Edraki et al. 2014; Falagán et al. 2017).

Institutional barriers

Regulatory regimes frequently lag technological developments and market shifts, creating an environment of uncertainty that discourages long-term investment (Daehn et al. 2017; Cooper et al. 2020; Smol et al. 2021). Fragmentation across jurisdictions exacerbates these problems. Within the European Union, for example, recycling and waste legislation differ substantially between member states, complicating cross-border coordination and leading to uneven compliance requirements (Kinnunen et al. 2022).

In some cases, tax regimes actively disincentivize improved environmental performance. For instance, it may be more expensive to dispose of detoxified waste than to release untreated material, creating perverse outcomes in national regulatory systems (Kinnunen et al. 2022).

Transitions to more circular systems require information sharing, standardization, and collaborative planning among governments, firms, and research institutions. In practice, actors operate in silos, limiting the potential for systemic alignment (Hagelüken et al. 2016; Reuter et al. 2019; Watari et al. 2023). In the construction sector, concerns about liability and insurance in relation to reused materials persist due to the absence of clear certification and traceability mechanisms (Dunant et al. 2017; Kanyilmaz et al. 2023).

In other cases, overly prescriptive rules restrict experimentation with new recovery models or alternative reuse pathways. A lack of national standards for product traceability and recyclability further contributes to policy uncertainty and administrative delays (Kirchherr et al. 2018).

Corporate conservatism can also act as a form of institutional drag. Many firms remain hesitant to adopt circular practices unless prompted by external mandates or market pressures. Original equipment manufacturers (OEMs) are

likely the main player since they control the usage of most materials (Kurilova-Palisaitiene et al. 2024). A review of sustainability reports by mining companies found that references to circularity remain infrequent and rarely inform operational decision-making (Upadhyay et al. 2021). OEMs, which influence product design, material specifications, and end-of-life management, are especially relevant for establishing circular systems. Mining companies can provide valuable data on raw material flows, but their direct role in creating closed-loop product cycles is more limited.

Without stronger external signals or policy alignment, businesses have few incentives to change course (Ranängen and Lindman 2017). Such limitations are not only structural but also connected to the behaviors, preferences, and perceptions of the actors involved, which are discussed in the following section.

Social and behavioral barriers

Within firms, many barriers stem from established routines, limited internal expertise, and reluctance to deviate from proven business models. Decision-making structures in engineering, procurement, and operations often reinforce short-term performance benchmarks, making it difficult to prioritize circular design or reuse strategies (Daehn et al. 2017; Tingley et al. 2017; Taghipour et al. 2022). Knowledge gaps and internal skepticism can delay adoption even in cases where technical options are available and economically viable (Griffin and Hammond 2021; Ingaldi and Ulewicz 2024).

Consumer preferences influence demand for secondary materials on a general level. For the metals industry, however, this is much less the case. Metals are traded on exchanges, so firms do not know where the metal comes from, and many consumers do not know the content of the metal product. Studies have shown that customers frequently associate reused or recycled materials (in general) with reduced performance, creating reputational and marketing challenges for firms operating in construction, manufacturing, and electronics (Reuter et al. 2019; Hagelüken and Goldmann 2022). These perceptions are reinforced by the absence of trusted quality standards or certification schemes. Even in cases where secondary materials meet technical specifications, weak market confidence can limit commercial viability. For the metals industry there are firms that pitch their reused material as a selling pitch but for the bulk of the material used it is not a prominent issue.

More broadly, the absence of clear public messaging, feedback mechanisms, and performance metrics weakens collective momentum toward circular systems. Where recovery programs exist, participation is often undermined by complexity, inconvenience, or the perception that

recycling has a limited real impact. This disconnect reduces consumer engagement and reduces the supply of recoverable materials (Dominish et al. 2018; Hagelüken and Goldmann 2022).

Analytical results

Section 5 presents the analytical core of the paper. The section proceeds in four stages: the construction of the matrix model, the empirical weighting of barrier relationships, the identification of feedback cycles, and the detection of high-leverage intervention points.

The interaction matrix: structure and rationale

Barriers to circularity in the metals industry are rarely isolated. Constraints across technological, economic, institutional, and social domains tend to reinforce one another, forming cycles of limited uptake, weak policy signals, and ongoing reliance on virgin production. To capture this interdependence, a structured analytical model is introduced: the Barrier Interaction Matrix (BIM). The matrix formalizes the strength and direction of influence between barrier domains and provides a basis for tracing system-level resistance to change.

The model defines a set of four core domains $B = \{E, T, I, S\}$: economic (E), technological (T), institutional (I), and social (S). Each domain comprises mechanisms such as capital intensity, contamination risk, regulatory fragmentation, or reputational perception that shape the adoption and performance of circular practices. These domains are treated as nodes in a directed system. Their relationships are captured in a square matrix $B \in \mathbb{R}^{4 \times 4}$, where each entry $b_{ij} \in \{0, 1, 2, 3\}$ reflects the influence strength from domain i to domain j .

$$B = \begin{bmatrix} 0 & b_{ET} & b_{EI} & b_{ES} \\ b_{TE} & 0 & b_{TI} & b_{TS} \\ b_{IT} & b_{IT} & 0 & b_{IS} \\ b_{SE} & b_{ST} & b_{SI} & 0 \end{bmatrix} \quad (1)$$

Each entry is directional and asymmetrical, influence from one domain to another need not be reciprocated. Diagonal entries are set to zero, as barriers are not assumed to reinforce themselves directly. For example, b_{ET} expresses the extent to which economic constraints—such as high capital requirements or uncertain payback periods—reduce the likelihood of deploying advanced technologies. b_{TI} captures how limited technological feasibility constrains policy ambition or regulatory scope. b_{IS} reflects how institutional weakness—such as fragmented standards or delayed

certification—undermines social confidence or firm trust. Finally, b_{SE} or b_{ST} capture how negative perceptions or organizational conservatism reduce investment appetite or limit the adoption of technical alternatives.

This representation enables the identification of system-wide patterns. Domains with strong outbound influence function as amplifiers, shaping downstream adoption dynamics. Domains with strong inbound connections may act as pressure points or persistent bottlenecks. In the next section, the matrix is empirically populated and used to trace influence intensity across multiple layers of interaction.

Weighting the matrix: empirical patterns

To operationalize the Barrier Interaction Matrix, directional weights are assigned to each cell based on evidence from the literature. Each $b_{ij} \in \{0, 1, 2, 3\}$ reflects the frequency and strength with which domain i is found to influence domain j across peer-reviewed studies. The scale is ordinal: higher values indicate more consistently observed or strongly supported relationships, but the scores are not derived from statistical estimation.

The most frequently cited influence pathway is from economic to technological barriers. High investment costs, infrastructure intensity, and uncertain payback periods restrict the deployment of advanced recycling and traceability technologies ($b_{ET} = 3$) (Hagelüken et al. 2016; Daehn et al. 2017; Dworak et al. 2022). Similarly, limited technical feasibility undermines the development and enforcement of regulatory frameworks, particularly where quality certification or material tracking is absent ($b_{TI} = 3$) (Cooper et al. 2020).

Bidirectional influence is evident between institutional and economic domains. Institutional fragmentation and inconsistent policy signals reduce investment appetite and delay long-term commitments ($b_{IE} = 3$) (Kirchherr et al. 2018; Kinnunen et al. 2022). Conversely, weak economic incentives and fragmented markets limit the scope and ambition of regulatory design ($b_{EI} = 2$).

Institutional-to-technological influence gets a high score based on the literature ($b_{IT} = 3$). Policy tools such as extended producer responsibility or content quotas are only effective when matched by the availability of viable technologies. A lack of technical readiness, in turn, undermines confidence in regulatory intervention. Although reciprocal influence exists, technological constraints often appear as a prerequisite for effective rulemaking, hence the higher weighting.

Social influences are generally assigned lower scores, but their role is non-negligible ($b_{SE} = 1$) (Dominish et al. 2018; Hagelüken and Goldmann 2022). Institutional credibility also shapes trust in reuse systems ($b_{IS} = 1$) (Reuter et al. 2019). Links from technical or economic domains to the

social sphere, such as b_{TS} or b_{SE} , are assigned lower values, as influence in this direction is generally indirect.

The empirical weights define the architecture of constraint propagation in the system. They highlight which barriers act as root causes, and which are typically outcomes of upstream limitations. This structure serves as the foundation for the feedback and lock-in analysis that follows in Section 5.3.

The matrix in Fig. 1 visualizes the relative strength of interaction between the major barrier categories identified in the mining and metals industry. Each entry reflects an ordinal weighting derived from the literature, where higher values indicate stronger and more consistent directional influence. For example, economic constraints are shown to exert a strong influence on technological development due to the high upfront costs associated with advanced recycling and processing systems. In

turn, technological immaturity reinforces institutional hesitation, as regulators are less likely to introduce ambitious mandates in the absence of proven implementation capacity.

Cumulative influence and propagation

While direct interactions between barriers shape immediate system behavior, longer pathways often carry cumulative influence that is less visible but structurally significant. A domain that may not appear dominant in direct influence can still exert system-wide impact through its role as an indirect transmitter of constraint. To capture this, the Barrier Interaction Matrix is extended beyond first-order effects through matrix multiplication.

Let $B^{(1)}$ represent the first-order interaction matrix, where each entry $b_{ij}^{(1)}$ represents the strength of influence of

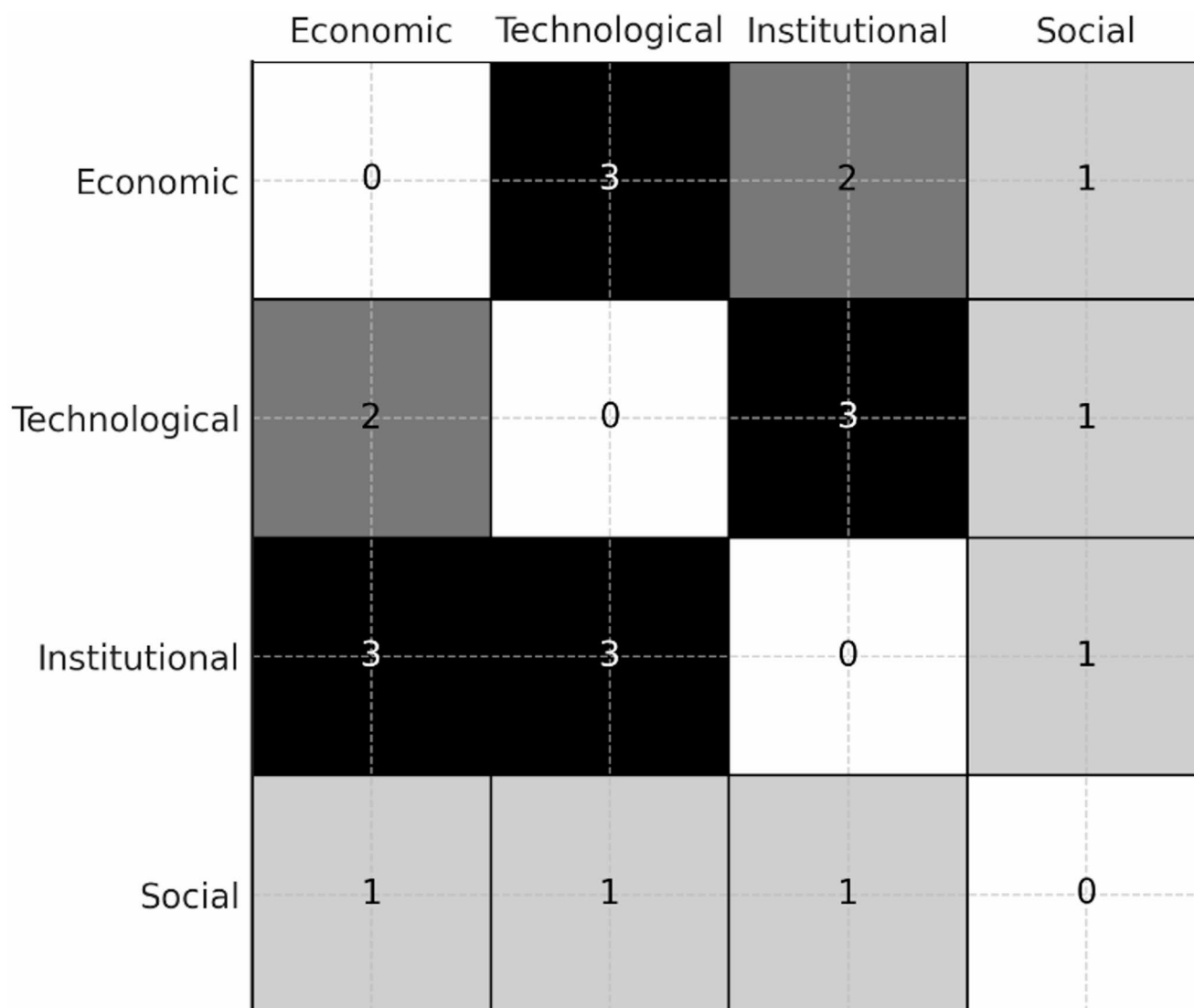


Fig. 1 Directional influence matrix of circularity barriers in the metals industry

barrier i on barrier j . This first-order matrix forms the basis for higher-order calculations. A second-order matrix $B^{(2)}$, is constructed by:

$$B^{(2)} = B^{(1)} * B^{(1)} \tag{2}$$

Here, each element $b_{ij}^{(2)}$ captures the total indirect influence that barrier i exerts on barrier j via all possible two-step pathways through an intermediate barrier k . In effect, $b_{ij}^{(2)}$ reflects how influence propagates from one domain to another not in isolation but through the mediating structure of the system itself.

For example, if economic constraints limit technological development $B_{ET}^{(1)} = 3$, and technological stagnation, in turn, weakens policy implementation $B_{TI}^{(1)} = 3$, then the indirect pathway from economic to institutional barriers is captured in $b_{EI}^{(2)}$. The value of this entry will reflect the compounding nature of these dependencies:

$$b_{EI}^{(2)} = \sum_{k=1}^4 b_{EI}^{(1)} * b_{TI}^{(1)} = 3 * 3 = 9 \tag{3}$$

Even if the direct influence from economic to institutional is moderate (e.g., $b_{EI}^{(2)} = 2$), the total pathway effect is amplified to $b_{EI}^{(1)} * b_{EI}^{(2)} = 11$. When these indirect effects are taken into account, the combined influence rises to a total score of 11, a moderate direct connection can still play a major role in the overall system.

To further deepen the analysis, higher-order influence matrices can be introduced recursively:

$$B^{(n)} = B^{(n-1)} * B^{(1)}, \text{ for } n \geq 2 \tag{4}$$

In this way, third-order $B^{(2)}$ or even fourth-order matrices can be constructed to explore multi-step feedbacks. While such matrices are increasingly abstract, they can offer insight into path-dependent effects and policy inertia, particularly where reinforcing cycles dominate. To integrate these layers into a unified assessment, we propose a cumulative influence matrix:

$$\tilde{B} = \sum_{n=1}^N \lambda^{n-1} B^{(n)} \tag{5}$$

Here, $\lambda \in [0,1]$ is a decay parameter representing diminishing influence with each additional step. The decay parameter λ reflects diminishing structural influence as the number of steps between domains increases. It ensures that direct connections are weighted more heavily than long, indirect chains when calculating cumulative system influence. A

value such as $\lambda = 0.5$ places half the weight on second-order effects compared to first-order interactions. The matrix \tilde{B} can then be interpreted as a weighted sum of structural influence up to order N , allowing for system-wide sensitivity mapping. From this, one can derive a barrier impact vector:

$$\psi = \tilde{B} * 1$$

where 1 is a column vector of ones. The resulting vector ψ assigns a cumulative influence score to each barrier, reflecting not only its direct but also its propagated role in the system. Barriers with high ψ_i values are those whose alleviation would likely yield the most far-reaching systemic benefits. For example, assume a domain has first-order scores of [3, 2, 1] and a second-order vector of [6, 3, 1.5], with $\lambda = 0.5$. Its cumulative influence score is:

$$\psi = \sum b^{(1)} + \lambda \sum b^{(2)} = (3 + 2 + 1) + 0.5 * (6 + 3 + 1.5) = 6 + 5.25 = 11.25 \tag{6}$$

This suggests the domain functions as a strong amplifier of system-wide constraints. This cumulative framework forms the basis for the feedback loop and lock-in analysis in the next section. It provides a map not only of who influences whom, but of how influence circulates and consolidates across the system.

Feedback loops and structural lock-in

A key implication of the matrix structure developed in Sections 5.1 to 5.3 is the presence of reinforcing cycles that sustain systemic resistance. These feedback loops emerge when barriers interact in closed paths, amplifying each other's influence and making the system less responsive to isolated interventions. In the mining and metals industry, this is observed in cycles of policy hesitation, capital withholding, and technological stagnation—patterns that persist even in the presence of viable alternatives.

Figure 2 visualizes how economic, institutional, technological, and social barriers reinforce one another across multiple feedback paths. These loops mirror those formalized in the matrix model, where directional influence accumulates across pathways and contributes to structural lock-in. The figure complements the quantitative logic of Section 5 by highlighting recurring loop patterns described in the literature.

Formally, a feedback loop is defined as a closed sequence of directional influences over the set of barrier domains. A loop of length three—among the shortest and most structurally meaningful—can be written as:

$$L^{(3)} = b_{ij} * b_{jk} * b_{ki}, \text{ where } i, j, k \in \text{Bandi} \neq j \neq k \tag{7}$$

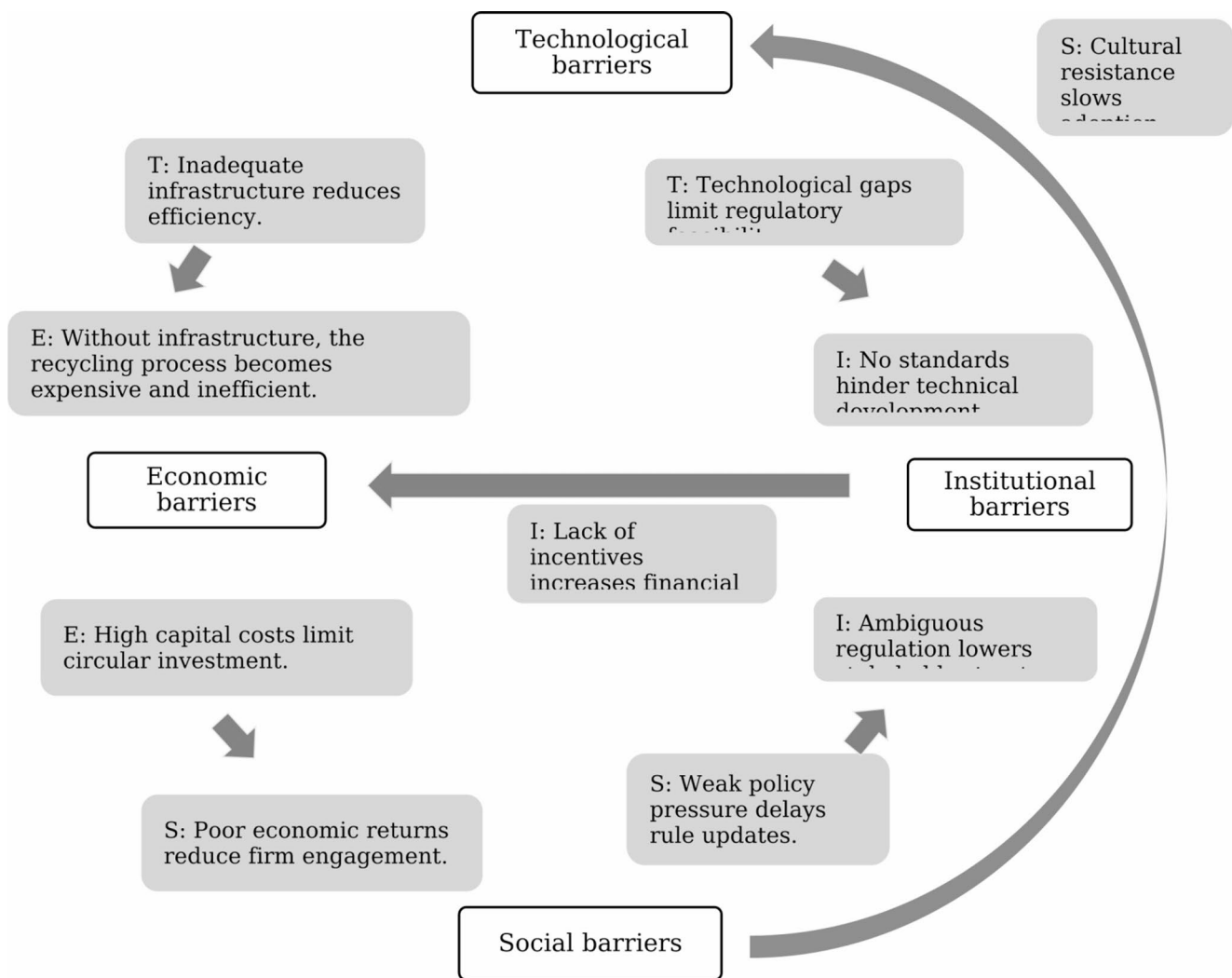


Fig. 2 Illustrative feedback loops between circularity barriers in the metals industry

The scalar product $L^{(3)}$ provides a proxy for the intensity of self-reinforcing constraint propagation along that path. For instance, if $b_{ET} = 3$, $b_{TI} = 3$, $b_{IE} = 3$, then the loop strength of the cycle $E \rightarrow T \rightarrow I \rightarrow E$ is:

$$L_{ETI}^{(3)} = 3 * 3 * 3 = 27 \tag{8}$$

Higher values of $L^{(n)}$ indicate stronger reinforcement. Loops near the maximum possible product (27 for a 3-cycle) signal a structure where domains continuously reproduce one another's constraints. This provides a formal measure of what in policy and systems theory is often called lock-in. In contrast, lower-strength feedback such as social \rightarrow institutional \rightarrow economic \rightarrow social with weights $b_{SI} = 1$, $b_{IE} = 3$, $b_{ES} = 1$ yields:

$$L_{SIE}^{(3)} = 1 * 3 * 1 = 3 \tag{9}$$

To evaluate the total feedback structure, we define the loop set $\mathcal{L}^{(n)}$ as the set of all such loops of length n , and the system-level feedback intensity as:

$$\Lambda^{(n)} = \sum_{L \in \mathcal{L}^{(n)}} L^{(n)} \tag{10}$$

This global indicator reflects the extent to which a system is trapped in reinforcing constraint cycles. High values of Λ signal deeply embedded resistance. Comparing Λ values across systems, regions, or policy environments could offer insight into structural transition barriers and the relative difficulty of reform.

Feedback loops can be further classified by a dominant pathway. When cycles are concentrated around technical domains they signal technological lock-in. For example, where lack of infrastructure, product complexity, and down-cycling reinforce one another. When loops concentrate

around policy and economic feedback, they reflect institutional lock-in, often visible in misaligned regulation, poor enforcement capacity, and fragmented markets. Behavioral lock-in arises when skepticism and firm conservatism reinforce mutual distrust and discourage experimentation. To identify the primary lock-in pattern, the model defines:

$$\varphi = \arg \max_{x \in \{T, I, S\}} \left(\sum_{L \in \mathcal{L}^{(n)}, \text{contains } x} L^3 \right) \quad (11)$$

Finally, mutual reinforcement between domains can be expressed through a pairwise reciprocity index:

$$p_{ij} = b_{ij} * b_{ji} \# \quad (13)$$

High values of ρ_{ij} indicate a strong bidirectional constraint, suggesting that interventions in only one direction (e.g., policy incentives without technological readiness) are unlikely to be effective. In the matrix, the economic–institutional pairing, $\rho_{EI} = b_{EI} \cdot b_{IE}$, stands out as a structurally locked node, requiring coordinated reforms on both fronts.

Together, these metrics provide a formal language for describing why and how certain barriers persist despite targeted interventions. By moving from a static inventory of constraints to a dynamic map of their systemic interactions, this framework offers a tool for both diagnosis and design. It shifts the focus from “what is missing” to “how elements reinforce each other”.

Discussion

The results presented in Sections 5.1 through 5.3 highlight the mining and metals industry as a system shaped by deeply interconnected barriers. What emerges from the matrix structure and feedback analysis is not a landscape of isolated problems, but a network of constraints that amplify each other through cyclical influence. These feedback loops, particularly those linking economic, technological, and institutional domains, matters for understanding why circular initiatives often stall despite apparent technical feasibility or political interest.

One of the clearest findings is that capital constraints and policy ambiguity form a reinforcing cycle that impedes innovation. The matrix weightings and loop analysis show that when firms hesitate to invest due to uncertain returns or policy instability, this delays the development and deployment of key technologies such as traceability tools, advanced sorting systems, or low-contamination alloy separation. These technological gaps, in turn, limit the scope of what regulators can reasonably mandate, which perpetuates weak institutional signals and discourages further

investment. This closed feedback loop is consistent with empirical observations in both the steel reuse literature and secondary mining case studies (Dunant et al. 2017; Kinnunen et al. 2022; Kirchherr et al. 2018).

From a policy perspective, this dynamic suggests that targeting any single barrier in isolation is likely to produce only marginal improvements. For example, introducing tax incentives without addressing material traceability or quality assurance will fail to resolve credibility concerns. Likewise, technology grants may underperform if there is no corresponding reform of waste classification systems or procurement rules. The systemic interdependence revealed in the matrix suggests that policy sequencing matters: interventions that simultaneously lower investment risk and strengthen institutional credibility—such as green public procurement tied to verified recycled content—may prove especially effective.

A second insight concerns the role of social barriers, which although assigned lower direct influence scores, still play a significant role in shaping the feedback structure. Cultural resistance within firms, skepticism among consumers, and inertia in professional norms all contribute to downstream effects that are difficult to reverse once established. This becomes especially problematic when social barriers reinforce institutional ones—such as when consumer disinterest reduces political incentives for regulatory reform, or when limited industry trust in reused materials constrains the ambition of sectoral agreements.

Crucially, the matrix model also points to potential leverage points—barriers whose disruption could produce cascading effects across the system. Institutional reform stands out in this regard. Because institutional barriers exhibit strong bidirectional ties with both economic and technological dimensions, even modest improvements in regulatory clarity or coordination could break high-impact cycles. For example, aligning recycling rate targets with quality-based standards rather than mass-based quotas would directly improve both technical performance and investor confidence.

Circularity as a coupled system of interdependent barriers offers a lens through which to evaluate both policy design and industrial strategy. It shifts the emphasis from linear causality to intervention through structural leverage. Rather than framing progress in terms of overcoming obstacles one by one, the model suggests that coordinated, multi-domain strategies are more likely to yield meaningful outcomes. This also reinforces the need for greater institutional experimentation, system-level monitoring, and investment in cross-sector governance structures. The leverage points identified in Table 1 reflect where interventions may disrupt the strongest feedback loops mapped in Section 5.

Table 1 Leverage points for circularity intervention in the metals industry

Leverage point	Systemic role	Strategic action
Institutional reform	Strong feedback loops connect institutional barriers with both investment and technological adoption.	Introduce quality-based recycling targets and harmonize traceability standards to improve regulatory credibility.
Technological clarity	Technical limitations influence economic returns and constrain policy enforceability.	Support interoperable recycling technologies and invest in standardized material classification and certification tools.
Economic derisking	Investment uncertainty reinforces technological stagnation and policy reluctance.	Implement blended finance instruments to reduce investment risks and catalyze private capital for high-quality recycling infrastructure. The public sector should also ensure that its own end-of-life products, such as electronic devices, vehicles, and other equipment, are demonstrably processed in certified, high-quality recycling facilities.
Social trust building	Perceptions shape the level of political engagement and industrial ambition.	Facilitate awareness campaigns, sector-led demonstration projects, and transparent performance metrics for secondary use.

Conclusion

The results from the matrix analysis echo what many have already argued—that moving metals recycling toward a truly circular model requires a system-wide view. What is new here is that the modelling confirms those calls with a structured, quantitative lens. The approach makes it possible to separate primary drivers from secondary effects and to identify the feedback mechanisms that keep existing practices in place. By linking these patterns to the barriers mapped in the study, the analysis shows both why change has been slow and where the most effective leverage points might be.

The barriers outlined here are not theoretical constructs; they are present in day-to-day decisions in procurement offices, on construction sites, and in policy discussions where momentum often fades when confronted with practical limits. A regulation to encourage reuse may be drafted, only to stall because the underlying material flows are unknown. These frictions persist because existing systems are built to reinforce the patterns they already follow. Changing those patterns will take more than incremental improvements — it will require coordinated action, deliberate experimentation, and a willingness to question established defaults.

The analysis shows that barriers to circularity in the mining and metals sector operate as a connected system rather than in isolation. Economic, technological, and institutional constraints strengthen each other through feedback mechanisms, while social factors play a more indirect role. The matrix framework makes it possible to see which domains act as primary drivers, which depend on others, and where resistance is amplified. Economic constraints, such as high capital requirements, are intertwined with technological limitations like quality degradation and insufficient traceability. These, in turn, are both shaped by and contribute to institutional challenges, including fragmented regulation and slow policy implementation. The strongest reinforcing loops emerge between economic, technological, and institutional domains, locking the system into linear production models.

The framework helps distinguish amplifiers from downstream effects. Institutional reform emerges as a key leverage point due to its intersection with multiple other barriers. Technological clarity and investment de-risking also offer strategic entry points. Although less central, social and cultural factors remain important for shaping legitimacy and firm-level implementation.

This analysis offers both conceptual and practical insights. The sector should be understood not only in terms of technical feasibility, but as a structure of interacting constraints that shape the pace and direction of change. Progress will depend less on isolated fixes and more on strategies that disrupt reinforcing patterns. Coordinated policy design, cross-sectoral governance, and sequenced investment planning will likely prove more effective than stand-alone measures.

Future work could apply the model in empirical or simulated settings to assess how specific policy interventions affect barrier dynamics. This would help identify high-leverage entry points for breaking lock-ins and accelerating the shift toward circular practices.

Systems rarely break where we expect them to. Like rust forming at a hidden weld, resistance to changing builds in quiet places—in paperwork no one reads, in contracts written a decade ago, in assumptions no one thought to challenge. Circularity is not just a technical fix or a new business model; it is a different rhythm. It asks industries accustomed to linear throughput to adapt to looping flows, shared responsibility, and delayed payoffs. The matrix built in this study does not predict change, but it does map the gravitational pull of the old system. It shows where weight must be shifted, where support is missing, and where pressure can make a difference. That map will not replace strategy, but it can help focus attention where it's needed most—on the loops that hold the system in place, and the seams where it might just come undone.

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References

- Aboura Y, Riva E (2024) Blast furnace to EAF transition: navigating challenges and market gaps. *Steel Hub Magazine*. Retrieved March 13, 2025, from <https://www.steelhub.com/magazine/blast-furnace-to-eaf-transition-navigating-challenges-and-market-gaps/>
- Ahmadov T, Durst S, Gerstlberger W (2025) Unveiling success factors for implementing and sustaining circular economy practices in small and medium-sized firms: multi-level perspective. *Bottom Line* 38(1):71–98
- Al-Alimi S, Yusuf NK, Ghaleb AM, Lajis MA, Shamsudin S, Zhou W, Adam A (2024) Recycling aluminium for sustainable development: a review of different processing technologies in green manufacturing. *Results Eng* 23:102566. <https://doi.org/10.1016/j.rineng.2024.102566>
- Arthur WB (1989) Competing technologies, increasing returns, and lock-in by historical events. *Econ J* 99(394):116–131
- Branca TA, Colla V, Algermissen D, Granbom H, Martini U, Morillon A, Rosendahl S (2020) Reuse and recycling of by-products in the steel sector: recent achievements paving the way to circular economy and industrial symbiosis in Europe. *Metals* 10(3):345
- Broadbent C (2016) Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *Int J Life Cycle Assess* 21:1658–1665
- Compañero RJ, Feldmann A, Tilliander A (2021) Circular steel: how information and actor incentives impact the recyclability of scrap. *J Sustainable Metall* 7:1654–1670
- Compañero RJ, Feldmann A, Samuelsson P, Jönsson PG (2024) A value of information approach to recycling. *Resour Conserv Recycl* 209:107758
- Cooper DR, Ryan NA, Syndergaard K, Zhu Y (2020) The potential for material circularity and independence in the US steel sector. *J Ind Ecol* 24(4):748–762
- Daehn KE, Serrenho C, A., Allwood JM (2017) How will copper contamination constrain future global steel recycling? *Environ Sci Technol* 51(11):6599–6606
- Dominish E, Retamal M, Sharpe S, Lane R, Rhamdhani MA, Corder G, Florin N (2018) Slowing and narrowing the flow of metals for consumer goods: evaluating opportunities and barriers. *Sustainability* 10(4):1096
- Dunant CF, Drewniok MP, Sansom M, Corbey S, Allwood JM, Cullen JM (2017) Real and perceived barriers to steel reuse across the UK construction value chain. *Resour Conserv Recycl* 126:118–131
- Dworak S, Rechberger H, Fellner J (2022) How will tramp elements affect future steel recycling in Europe?—A dynamic material flow model for steel in the EU-28 for the period 1910 to 2050. *Resour Conserv Recycl* 179:106072
- Edraki M, Baumgartl T, Manlapig E, Bradshaw D, Franks DM, Moran CJ (2014) Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. *J Clean Prod* 84:411–420
- European Commission (2020) Circular economy action plan: for a cleaner and more competitive Europe. Retrieved 2025-01-31 from https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en
- Falagán C, Grail BM, Johnson DB (2017) New approaches for extracting and recovering metals from mine tailings. *Miner Eng* 106:71–78
- Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res Policy* 31(8–9):1257–1274
- Geels FW (2005) Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. *Technol Forecast Soc Change* 72(6):681–696
- Gerold E, Luznik L, Samberger S, Antrekowitsch H (2024) Sustainable extraction and recycling of non-ferrous metals: a review from a European perspective. *Philos Trans R Soc Lond A Math Phys Eng Sci* 382(2284):20240173
- Giurco D, Littlebooy A, Boyle T, Fyfe J, White S (2014) Circular economy: questions for responsible minerals, additive manufacturing and recycling of metals. *Resources* 3(2):432–453
- Grafström J, Aasma S (2021) Breaking circular economy barriers. *J Clean Prod* 292:126002
- Griffin PW, Hammond GP (2021) The prospects for 'green steel' making in a net-zero economy: A UK perspective. *Glob Transit* 3:72–86
- Hagelüken C, Goldmann D (2022) Recycling and circular economy—towards a closed loop for metals in emerging clean technologies. *Mineral Econ* 35(3):539–562
- Hagelüken C, Lee-Shin JU, Carpentier A, Heron C (2016) The EU circular economy and its relevance to metal recycling. *Recycling Basel* 1(2):242–253

- Ingaldi M, Ulewicz R (2024) The business model of a circular economy in the innovation and improvement of metal processing. *Sustainability* 16(13):5513
- IRENA (2023) The G20 circular steel industry: pathways for deep decarbonisation. IRENA. Retrieved 2025-01-31 from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Jul/IRENA_G20_circular-steel_industry_2023.pdf
- Kanyilmaz A, Birhane M, Fishwick R, del Castillo C (2023) Reuse of steel in the construction industry: challenges and opportunities. *Int J Steel Struct* 23(5):1399–1416
- Kara S, Hauschild M, Sutherland J, McAloone T (2022) Closed-loop systems to circular economy: a pathway to environmental sustainability? *CIRP Ann* 71(2):505–528
- Kinnunen PHM, Kaksonen AH (2019) Towards circular economy in mining: opportunities and bottlenecks for tailings valorization. *J Clean Prod* 228:153–160
- Kinnunen P, Karhu M, Yli-Rantala E, Kivikytö-Reponen P, Mäkinen J (2022) A review of circular economy strategies for mine tailings. *Clean Eng Technol* 8:100499. <https://doi.org/10.1016/j.clet.2022.100499>
- Kirchherr J, Piscicelli L, Bour R, Kostense-Smit E, Muller J, Huijbrechtse-Truijens A, Hekkert M (2018) Barriers to the circular economy: evidence from the European union (EU). *Ecol Econ* 150:264–272
- Klimek P, Hess M, Gerschberger M, Thurner S (2024) Circular transformation of the European steel industry renders scrap metal a strategic resource. *ArXiv Preprint arXiv 1:240612098*
- Kurilova-Palisaitiene J, Matschewsky J, Sundin E (2024) Four levels of remanufacturing maturity as a circular manufacturing indicator: a theoretical framework and practical assessment tool. *Resour Conserv Recycling* 211:107899
- Lima AT, Kirkelund GM, Lu Z, Mao R, Kunther W, Rode C, Simoes SG (2024) Mapping circular economy practices for steel, cement, glass, brick, insulation, and wood—a review for climate mitigation modeling. *Renew Sustain Energy Rev* 202:114697
- Murthy V, Ramakrishna S (2022) A review on global e-waste management: urban mining towards a sustainable future and circular economy. *Sustainability* 14(2):647
- Nechifor V, Calzadilla A, Bleischwitz R, Winning M, Tian X, Usubiaga A (2020) Steel in a circular economy: global implications of a green shift in China. *World Dev* 127:104775
- Pierson P (2000) Increasing returns, path dependence, and the study of politics. *Am Polit Sci Rev* 94(2):251–267
- Ranängen H, Lindman Å (2017) A path towards sustainability for the Nordic mining industry. *J Clean Prod* 151:43–52
- Reuter MA, van Schaik A, Gutzmer J, Bartie N, Abadias-Llamas A (2019) Challenges of the circular economy: a material, metallurgical, and product design perspective. *Annu Rev Mater Sci* 49(1):253–274
- Singh RK, Kumar A, Garza-Reyes JA, de Sá MM (2020) Managing operations for circular economy in the mining sector: an analysis of barriers intensity. *Resour Policy* 69:101752
- Smol M, Marcinek P, Koda E (2021) Drivers and barriers for a circular economy (CE) implementation in Poland—a case study of raw materials recovery sector. *Energies* 14(8):2219
- Taghipour A, Akkaltham W, Eaknarajindawat N, Stefanakis AI (2022) The impact of government policies and steel recycling companies' performance on sustainable management in a circular economy. *Resour Policy* 77:102663
- Tan J, Wehde MV, Brønd F, Kalvig P (2021) Traded metal scrap, traded alloying elements: a case study of Denmark and implications for circular economy. *Resour Conserv Recycl* 168:105242
- Tingley DD, Cooper S, Cullen J (2017) Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *J Clean Prod* 148:642–652
- Upadhyay A, Laing T, Kumar V, Dora M (2021) Exploring barriers and drivers to the implementation of circular economy practices in the mining industry. *Resour Policy* 72:102037
- Velenturf AP, Archer SA, Gomes HI, Christgen B, Lag-Brotons AJ, Purnell P (2019) Circular economy and the matter of integrated resources. *Sci Total Environ* 689:963–969
- Wang C, Harbottle D, Liu Q, Xu Z (2014) Current state of fine mineral tailings treatment: a critical review on theory and practice. *Miner Eng* 58:113–131
- Watari T, Hata S, Nakajima K, Nansai K (2023) Limited quantity and quality of steel supply in a zero-emission future. *Nat Sustain* 6(3):336–343
- Winans K, Kendall A, Deng H (2017) The history and current applications of the circular economy concept. *Renew Sustain Energy Rev* 68:825–833

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