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Global stagnation and regional variations in steel recycling

Takuma Watari [a,b,c,*], Tomer Fishman [b], Hanspeter Wieland [d], Dominik Wiedenhofer [d]

[a] Material Cycles Division, National Institute for Environmental Studies, Tsukuba, Japan
[b] Institute of Environmental Sciences, Leiden University, Leiden, the Netherlands
[c] Institute for Sustainable Futures, University of Technology Sydney, Australia
[d] Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna, Austria

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ABSTRACT

Steel is widely regarded as the world's most recycled material, yet little information exists on just how circular the steel industry actually is, both globally and nationally. This study traces iron and steel flows across the top 30 steel-producing countries, showing that the share of recycled iron inputs into global steelmaking has stagnated at ~30 % over the past two decades. Although waste management practices have improved, the rapid growth of global in-use steel stock has prevented progress in making steel flows more circular. While some countries show higher recycled content than others, ranging from <10 % to >90 %, this does not necessarily reflect leadership in recycling practices. Rather, high circularity in some places is often supported by low circularity elsewhere through scrap imports or 'offshoring' the production of high-quality flat products. As long as global steel stock continues to grow, improvements in local circularity do not necessarily lead to global progress.

1. Introduction

"Steel is the most recycled material in the world and is fundamental to the circular economy". This rather ubiquitous claim can be found across a wide range of platforms (World Steel Association, 2023). Indeed, thanks to its magnetic properties and structural integrity, scrap steel is relatively easy to separate and recycle compared to other materials (Reck and Graedel, 2012). Given the destructive impact of ore-based steelmaking, which currently accounts for 5 % of global raw material extraction considering only iron ore (Plank et al., 2022) and 8 % of CO_2 emissions (Lei et al., 2023), the benefits of steel recycling are indisputable. The key question, however, is: just how circular is the steel industry, both globally and nationally? While the question is a seemingly simple one, finding the answer presents a considerable challenge. Information on the use of recycled materials is not always available for all countries, and even when it is, it tends to be defined differently across datasets (Graedel et al., 2011). Without consistent data and a clear system definition, it is difficult, if not impossible, to properly monitor the degree of progress toward a more circular steel industry and identify effective intervention points.

Several pioneering initiatives have attempted to address this issue based on material flow analyses (MFA), which systematically trace the flows of materials within a defined system (Graedel, 2019). Detailed analyses of iron and steel flows have been conducted for major economies since the 1990s (Chen and Graedel, 2012). Wang et al. (2007) were among the first to provide a comprehensive global picture by mapping steel flows across multiple countries and regions for the year 2000. Cullen et al. (2012) expanded this effort with a much more detailed breakdown of intermediate and final steel products for the year 2008. Harvey (2022) later updated this work for the years 2011–2015 with an improved data handling algorithm. More recently, Gao et al. (2025) investigated iron and steel flows in 25 countries for the year 2017. However, these studies present only isolated snapshots at different points in time and use varying system definitions. As a result, it is difficult to track long-term trends in steel recycling consistently at both the global and country scales.

While time-series data exist for some major economies, such as China (Song et al., 2020), the United States (Cooper et al., 2020), Japan (Watari et al., 2023), and the European Union (Dworak and Fellner, 2021), meaningful cross-country comparisons require reconciling differences in system definitions. Recent advances in economy-wide MFA, which tracks a range of materials across multiple countries, could help bridge this gap (Wiedenhofer et al., 2024). Yet, detailed iron and steel flows are often overshadowed by more bulky materials such as sand and gravel. Collectively, none of the existing studies have systematically explored the variations in recycling status between major

* Corresponding author.
E-mail address: watari.takuma@nies.go.jp (T. Watari).

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steel-producing countries, nor have they investigated the causes of these differences. Despite the growing interest in moving toward a more circular steel flow, the historical evolution and current state remain unclear.

The aim of this study is to fill this gap by systematically and consistently mapping iron and steel flows around the world. Visualized through Sankey diagrams, this representation functions as a map of the physical aspects of the economy (Müller et al., 2023). Our dataset and resulting diagrams differ from existing studies in three distinctive ways. First, the data cover the world's top 30 crude steel-producing countries from 2000 to 2019. These countries account for >95 % of current total crude steel production (World Steel Association, 2024); thus, the data capture nearly all steel production while maintaining national-level resolution. Second, the data distinguish between long products (e.g., reinforcing bars, wire rods, and structural sections) and flat products (e.g., sheets, plates, and strips). This distinction is intended to reflect the nature of recycling, as not all recycled steel is currently used for every type of product. Currently, most recycled steel is processed into billets and blooms, with limited use in slab production due to contamination concerns (Daigo et al., 2021). Third, the diagrams are interactive and open source. This feature facilitates visually intuitive and informative monitoring systems, moving beyond a series of data tables (Font Vivanco et al., 2019). Together, these features allow the resulting dataset and Sankey diagrams to provide a basis for monitoring recycling practices in a consistent format and to address the fundamental yet poorly understood question: How circular is the steel industry globally and nationally?

2. Methods

2.1. Material flow analysis and Sankey diagrams

Sankey diagrams for iron and steel flows are constructed based on a system definition that considers 13 product stages plus international trade (Fig. S1 in the Supplementary Information (SI)). The process begins with the extraction of iron ore and follows the journey of the iron as it is transformed into various products. While iron and steel products include several accompanying elements, such as carbon, phosphorus, and alloy metals (e.g., nickel), this study tracks all the products as the flow of iron. The primary data for this analysis are sourced from the Steel Statistics Yearbook published by the World Steel Association (World Steel Association, 2024), supplemented by statistics from the US Geological Survey (U.S. Geological Survey, 2024). These sources provide production data on key materials, as well as data on international trade across the supply chain. The mass flows between processes are calculated using mass balance equations, grounded in the law of mass conservation. Two fundamental conditions govern these calculations: all masses must be non-negative, and process yields must not exceed 100 %. When discrepancies arise that violate these conditions, balancing flows are introduced to correct the mass imbalances. In such cases, production data are always prioritized over other estimated data, such as international trade, process yields, and iron content. A detailed description of the mass balance equations, data reconciliation, and data sources is provided in Sections 1–5 of the SI.

Understanding the full picture of iron and steel flows can be challenging when flipping back and forth between numerous data tables. To provide an intuitive grasp of the dataset, we develop interactive, open-source Sankey diagrams using floWeaver (Lupton and Allwood, 2017). These diagrams are accessible via a web application (https://steel-flows-sankey.streamlit.app/) and a GitHub repository (https://github.com/takumawatari/steel-flows-sankey), covering the last two decades (2000 to 2019) for the world's top 30 crude steel-producing countries.

2.2. Recycling indicators

Progress toward a more circular steel industry can be measured using a variety of indicators, each of which captures different aspects within a system (Moraga et al., 2019). Among these indicators, two of the most widely used metrics are 'recycled content' and 'end-of-life recycling rate', which measure the share of recycled materials used in total material inputs and the share of materials in end-of-life waste that are functionally recycled, respectively (UNEP, 2011). While the 'end-of-life recycling rate' often receives attention in policy discussions, we focus more on 'recycled content' for two key reasons. First, it is the reduction of ore-based material inputs that matters, not just an increase in the use of recycled materials. In the context of the steel industry, the primary objective of improving circularity is to mitigate energy consumption (Worrell and Carreon, 2017), CO_2 emissions (Speizer et al., 2023), air pollution (Li and Hanaoka, 2022), and ecological impacts (Giljum et al., 2022), all of which can only be realized when recycled materials 'replace' virgin ore-based materials rather than 'adding' to the total material inputs. Second, even perfect end-of-life recycling contributes only marginally to reducing ore-based material inputs under high demand growth conditions (Haas et al., 2015). The logic is simple: as long as total material inputs continue to grow, recycled materials can only provide a portion of this input due to the inherent time lag between materials being produced and the materials becoming available as scrap.

These factors underscore the importance of tracking 'recycled content'. The terms 'recycled content' and 'recycling input rate' are sometimes used interchangeably (Chen, 2013) and sometimes have different meanings (Espinoza and Soulier, 2018); they are also starting to be referred to with new terms, such as 'input socioeconomic cycling rate' (Wang et al., 2020) or 'circularity rate' (Miatto et al., 2024). In this study, we use the term 'recycled content' in line with UNEP's proposal (UNEP, 2011) and define it as the share of recycled iron in total iron inputs to steelmaking. Meanwhile, we define the 'recycling input rate' as a complementary indicator that represents the share of recycled iron in economy-wide material inputs, including non-iron materials in crude ore (Wiedenhofer et al., 2019). This economy-wide indicator provides a broader view of circularity, reflecting all material flows and human impacts of mining, even though these flows do not always hold a direct economic value.

It is important to note that crude ore extraction is often not reported by most countries as it is considered an intermediate product (Tuck et al., 2017). Reported figures may refer to either crude ore or usable ore that has been beneficiated. These reporting inconsistencies make it difficult to make fair cross-country comparisons. Therefore, this study estimates the 'economy-wide recycling input rate' only at the global level. A similar limitation applies to the 'end-of-life recycling rate', as reliable national statistics on end-of-life waste are not available. Thus, crude ore extraction and end-of-life waste are only represented in the global-level Sankey diagram, not in the national-level diagrams. Further details can be found in Section 6 of the SI.

2.3. Underlying factors of regional variations

To better understand the reasons behind regional variations in recycled content, we analyze several indicators closely linked to recycling practices. The choice of indicators is informed by existing studies that highlight key aspects of steel recycling. First, growing in-use stock limits scrap availability and poses a barrier to closing the loop (Haas et al., 2020). Second, industrialized countries are increasingly exporting scrap rather than recycling it domestically (Wang et al., 2022). Third, scrap steel is often downcycled into long products rather than flat products due to difficulties in contamination control (Daehn et al., 2017).

Building on these insights, we focus on three indicators. The first and most intuitive is domestic scrap availability, which is determined by stock stabilization – the balance between iron entering the in-use phase as goods and iron leaving as scrap. In theory, the more balanced these inflows and outflows are, the greater the potential for increasing the recycled content (Pauliuk, 2018). The other two indicators capture the role of international trade: a country's import reliance for scrap steel and finished flat products. Each is defined as the ratio of net imports to domestic inputs, reflecting a country's dependence on imports or its role as exporters.

Beyond such simple country comparisons, we trace how the recycled content of different steel products evolves along global supply chains to explore the role of international trade in regional recycled content. This is done by expanding the trade dimension of our dataset using bilateral physical trade data. The expanded dataset functions as a multi-regional physical input-output table, which enables us to explicitly track steel products passing through multiple countries during their lifecycle (Wieland et al., 2022). A further detailed explanation is provided in Sections 7–9 of the SI.

3. Results

3.1. Global iron and steel flows

Despite steel's inherent recyclability, just one-third of iron inputs to steelmaking come from recycling (Fig. 1a). In 2019, the world's top 30 steel-producing countries required 1849 million metric tons (Mt) of iron inputs for steelmaking, of which 606 Mt was derived from recycled scrap. This gives a global recycled content of 33 % – a level comparable to other major metals such as aluminum (International Aluminium Institute, 2023), copper (Loibl and Tercero, 2021), zinc (Rostek et al., 2022), and tin (Bradley et al., 2024), when direct reuse and re-melting are included.

However, focusing solely on iron flows overlooks the broader material needs of steelmaking associated with mining. Extracting iron ore involves mining crude ore, which contains both iron and non-metallic

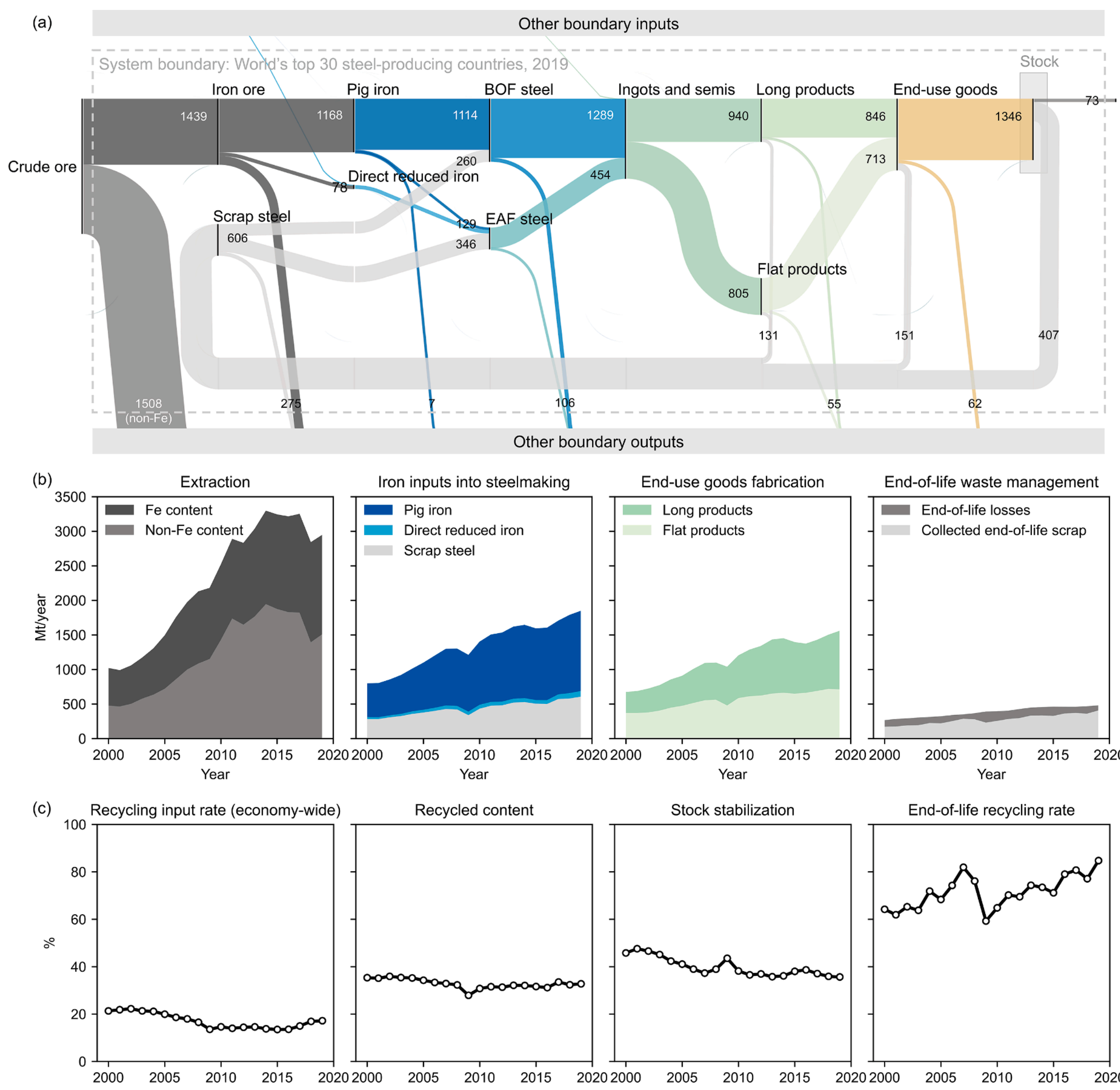

Fig. 1. Iron and steel flows combined for the group of 30 top steel-producing countries. (a) Sankey diagram illustrating global iron and steel flows in 2019. (b) Scale-related indicators showing trends in extraction, steelmaking, fabrication, and end-of-life waste from 2000 to 2019. (c) Recycling-related indicators showing trends in economy-wide recycling input rate, recycled content, stock stabilization, and end-of-life recycling rate from 2000 to 2019. Boundary inputs and outputs in panel (a) include crude ore extraction, international trade, and losses (e.g., gangue, tailings, slag, and landfill). Note that while iron and steel products include several accompanying elements, this study tracks only the flow of iron content for all products. The exception is crude ore, which includes the mass of oxygen and gangue. For simplicity and mass balance consistency, non-iron content is represented as a boundary-bound output immediately after mining, even though this may not always be an accurate description of the production process. All flows are shown to scale in Mt/year.

minerals (e.g., tailings) that must be separated out during processing. When considering these unused material inputs, including all recycled scrap and crude ore extraction, total material inputs amounted to ∼3550 Mt. In this broader context, the economy-wide recycling input rate – the share of recycled iron in the total material inputs – drops to just 17 %.

The limited circularity of the global steel flow is not due to poor waste management. In fact, 85 % of end-of-life scrap was collected and recycled in 2019. Instead, the key limiting factor is the growing in-use steel stock – the steel embedded in products, buildings, and infrastructure. As demand for steel stocks continues to grow, the steel inflows into society far exceed the outflows of steel available for end-of-life recycling. In 2019, for instance, inflows were 2.8 times higher than outflows, meaning that even with perfect recycling with no losses, recycling alone could only have met part of the demand.

3.2. Stagnation in global recycled content

This imbalance between inflows and outflows is not a short-term phenomenon but rather part of a long-term trend (Fig. 1b and c). Over the past two decades, the global steel industry has made significant efforts to recycle more end-of-life scrap. Between 2000 and 2019, the end-of-life recycling rate improved from 65 % to 85 %, resulting in an increase in iron inputs from recycled scrap from 283 Mt to 606 Mt. Yet, despite this progress, the global circularity of the steel industry at the input stage has stagnated. Both the economy-wide recycling input rate and the recycled content in steelmaking have declined, from 21 % to 17 % and from 35 % to 33 %, respectively.

The root cause of this stagnation is, again, the expansion of in-use steel stocks. Over the past two decades, the rate at which steel has flowed into the use phase has, almost without exception, consistently outpaced the availability of steel for recycling at the end of product life cycles. As a result, even as end-of-life recycling rates have improved, the system cannot "close the loop" fast enough to keep up with the growing demand for steel.

This decline in circularity at the steelmaking stage has been further exacerbated by increasing extraction of lower-grade crude ore, which requires beneficiation to increase iron content (Tuck et al., 2017). This additional processing has reduced the economy-wide recycling input rate, as the need for more extensive ore processing dilutes the impact of recycled iron inputs. Just as global stagnation has been observed in energy efficiency, in part due to rising steel demand (Wang et al., 2021), our data indicates that a similar trend is emerging in steel recycling: Steel demand is growing faster than improvements in recycling efficiency, which ultimately limits the recycled content.

3.3. Variations in regional recycled content

While the global recycled content has stagnated at around 30 %, a closer look at the world's top 30 steel-producing countries reveals significant regional variations (Fig. 2). In 2019, Thailand led the world with 96 % recycled content, followed by Italy (72 %), Spain (69 %), Turkey (69 %), Indonesia (68 %), the US (67 %), and Poland (54 %). Only these seven have recycled content above 50 %. On the other end of the spectrum, the seven countries with the lowest recycled content – Iran (5 %), Saudi Arabia (6 %), Ukraine (24 %), India (25 %), The Netherlands (25 %), China (27 %), and Austria (27 %) – all fall short of

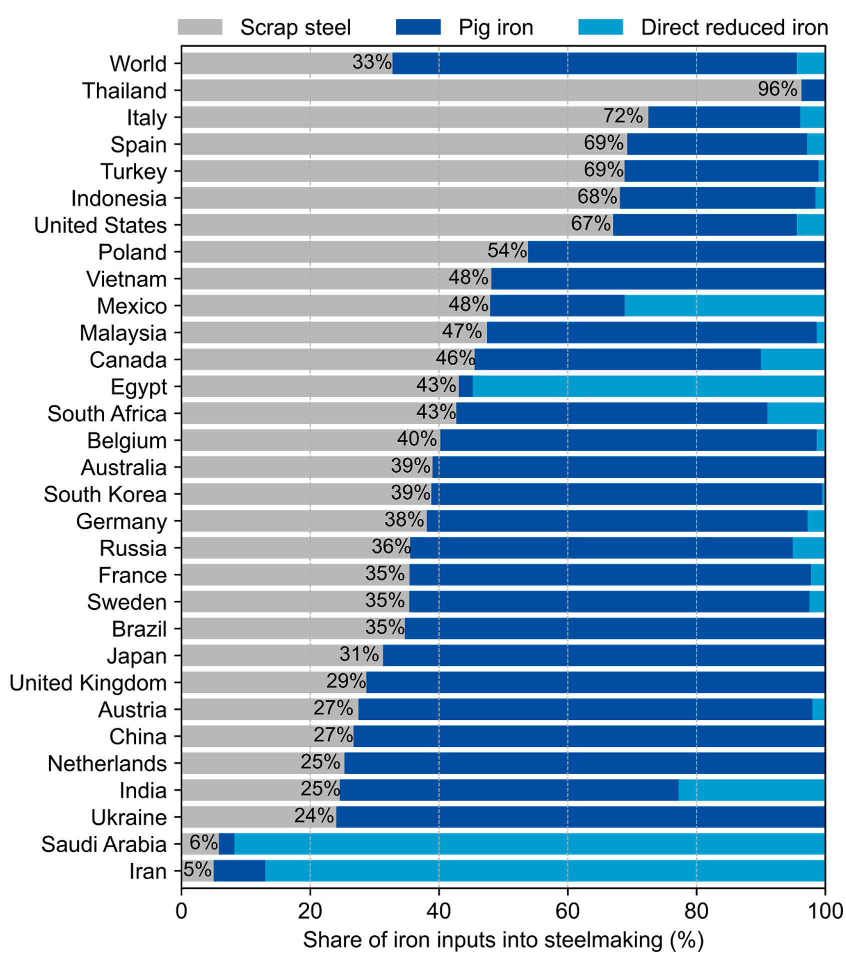

Fig. 2. Ranking of recycled content among the world's top 30 steel-producing countries in 2019. The labeled percentages indicate the share of recycled steel used in steelmaking for each country.

30 %.

But does a higher recycled content necessarily indicate leadership in circular steel practices? For instance, is Thailand's 96 % recycled content truly a reflection of superiority in recycling efforts? And conversely, should a country with lower recycled content be seen as lagging behind? To unpack these nuances, we need to examine the key factors driving regional differences in recycled content.

3.4. Regional recycled content shaped by trade dynamics

Our analysis shows that while domestic scrap availability – driven by in-use stock growth – explains recycled content in some countries, it is unlikely to be the determining factor in most cases (Fig. 3a). Instead, recycled content is shaped by complex trade dynamics.

A simple expectation would be that countries with growing in-use stock rely more on ore-based steelmaking due to limited domestic scrap availability, while those with stable stock levels achieve higher recycled content. This holds true in some cases: the United States, for example, has a relatively stable stock and high recycled content, while India, with rapid stock growth, relies more on ore-based steelmaking. However, this pattern does not hold across all cases. Several industrialized countries, such as the UK, Japan, and The Netherlands, have stable in-use stock, meaning their outflows of scrap nearly match their inflows of new steel. In theory, these countries could meet most of their steel needs with just domestic end-of-life scrap, yet this is not currently the case. The opposite is also true for several countries, including Thailand, Indonesia, and Turkey, which have relatively high recycled content despite growing in-use stock. Many countries are, in fact, far from having recycled content that is consistent with domestic scrap availability, visualized as a 1:1 diagonal in Fig. 3a. This means that the rate of stock growth alone does not effectively explain regional variations in recycled content.

A second factor helps explain why many countries deviate from the diagonal: scrap trade. In countries with stable in-use stock, a significant portion of collected scrap tends to be exported rather than recycled domestically (Fig. 3b). This trend is particularly notable in the UK, where more than half of the collected scrap is exported. On the other hand, countries that achieve relatively high recycled content despite growing in-use stock often rely on imported scrap. Turkey, for instance, is a major importer of scrap steel exported from the UK. Similarly, countries with relatively high recycled content, such as Thailand and Indonesia, act as net importers of scrap steel. These countries rely on imported scrap to compensate for some of the shortfall in domestic scrap generation. Nevertheless, these two factors still do not fully explain the limited recycled content observed in countries with stable stock and limited scrap exports. Belgium, for example, holds abundant domestic scrap and exports little, yet its recycled content remains relatively low.

A third factor provides additional insight: industrialized countries tend to prioritize ore-based steelmaking to produce and export flat products (Fig. 3c). In Belgium, for instance, the domestic steel industry almost exclusively produces flat products through the blast furnace-basic oxygen furnace (BF-BOF) process and is a net exporter of these products. Therefore, their main motivation for steelmaking is not domestic demand, but rather their steelmaking is driven by exports. This pattern is common in other industrialized countries, such as Japan, South Korea, and The Netherlands. In contrast, there is a clear trend for countries with higher recycled content to be more dependent on imports. Interestingly, the top 10 countries with respect to recycled content are all net importers of flat products. A notable example is Thailand, which has the highest recycled content, at 96 %, and is almost entirely

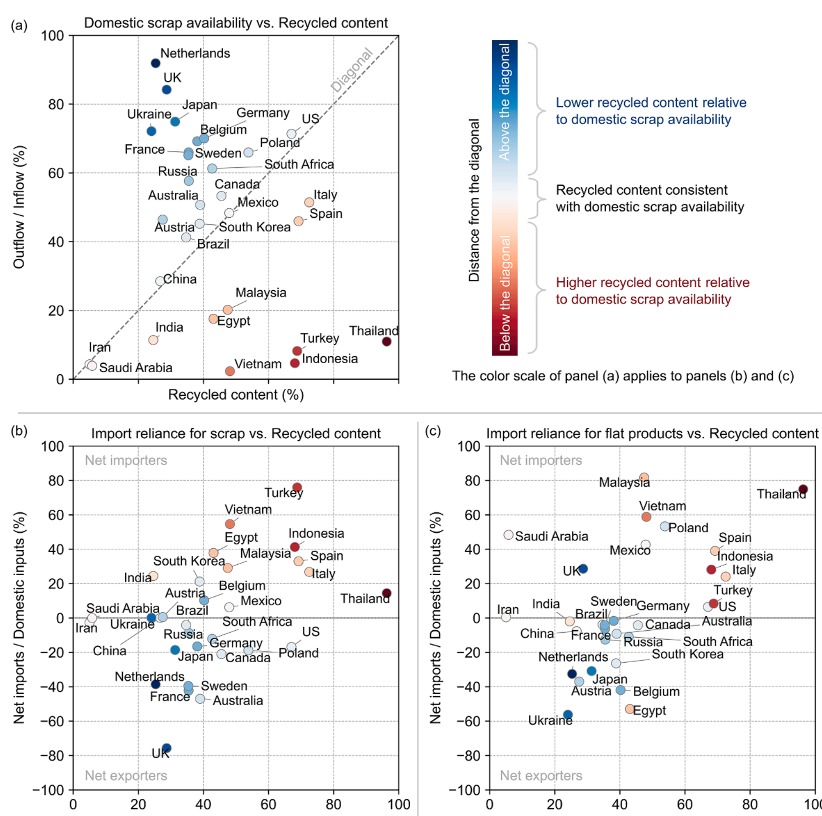

Fig. 3. Underlying factors behind recycled content around the world. (a) Relationship between stock stabilization and recycled content. (b) Relationship between import reliance for scrap steel and recycled content. (c) Relationship between import reliance for flat products and recycled content. All data refer to 2019. Colors are based on the data in panel (a) and represent the distance from the diagonal. The horizontal axes of the three panels are identical. Darker blue/red indicates lower/higher recycled content relative to domestic scrap availability, respectively.

dependent on imports to meet its demand for flat products.

3.5. Four patterns of iron and steel flows

Collectively, iron and steel flows across the world can be broadly categorized into four main patterns, each reflecting varying levels of recycled content for different reasons (Fig. 4). The first pattern is characterized by high recycled content due to abundant domestic scrap. A key example is the United States, where electric arc furnaces (EAFs) are predominantly used to recycle domestic scrap and supply most of the country's steel needs.

In contrast, the second pattern is observed in growing economies such as China, where recycled content remains relatively low due to a shortage of domestic scrap. In this pattern, most steel produced via the BF-BOF process is directed toward domestic manufacturing and is used to feed the country's growing in-use steel stock.

The third pattern achieves a relatively high recycled content despite limited domestic scrap availability. Thailand, for example, fits this model, where instead of producing steel domestically, they "offshore" the manufacturing of high-quality flat products. Thus, the central role of the domestic steel industry is to recycle scrap generated in the forming and fabrication processes in EAFs.

Finally, the fourth pattern shows a relatively low recycled content despite abundant domestic scrap. Japan, for instance, prioritizes the BF-BOF process to produce and export flat products. As a result, some of the collected scrap is exported rather than recycled locally due to difficulties in contamination control.

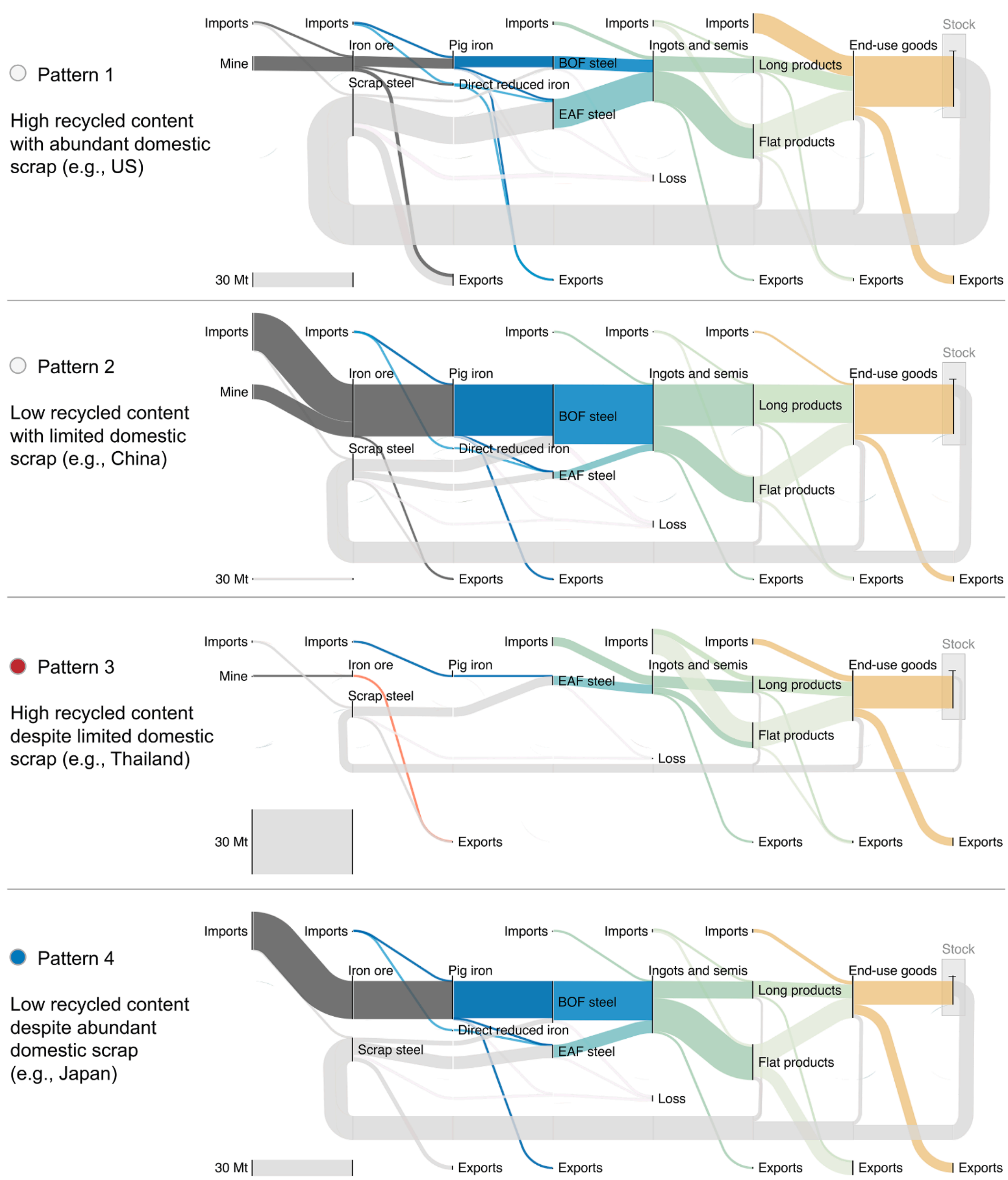

Fig. 4. Four distinct patterns of iron and steel flows based on recycled content and domestic scrap availability. These patterns illustrate how recycled content levels vary across countries due to different industrial structures. All data represent the year 2019. The Sankey diagrams for all target countries over a 20-year period can be accessed via a web application (https://steel-flows-sankey.streamlit.app/). The flow shown in red is a balancing flow from the data reconciliation process. Crude ore extraction and end-of-life waste are not included in these national-level Sankey diagrams.

3.6. Recycled content convergence through global supply chains

The observations above suggest that trade patterns, rather than domestic scrap availability alone, shape recycled content. This raises an interesting question: How does the recycled content of steel products evolve as they move through the global supply chain? Expanding the dataset with bilateral trade data reveals a clear trend: recycled content converges from upstream to downstream (Fig. 5). While liquid steel shows wide regional variations in recycled content (ranging from 5 % to 96 %), this range narrows to 5 %–62 % for finished steel products and 7 %–50 % for end-use goods. Notably, countries with relatively high recycled content at the steelmaking stage see a decline in recycled content as steel products move downstream. For example, Thailand achieves the highest recycled content (96 %) at the steelmaking stage, but this drops to 40 % when considering steel embedded in end-use goods. More broadly, the top 10 countries with the highest recycled content at the steelmaking stage all show a decline as steel products progress toward end-users.

These trends highlight that recycled content at the steelmaking stage does not fully capture system-wide circularity. The steel products used by manufacturers, builders, and end-users have substantially different recycled content profiles than those at the point of steelmaking. In fact, once trade is accounted for, differences in recycled content between major crude steel-producing countries become much smaller.

4. Discussion

4.1. Circularity in one place, leakage in another?

Overall, our results indicate that seemingly high circularity in some places is often supported by low circularity elsewhere. While global stagnation in recycled content can be explained by growing in-use stock and the resulting limits on scrap availability, these factors alone do not fully account for the regional differences. In fact, for most nations, international trade patterns play a much larger role in determining the recycled content of their steel products. It is therefore an oversimplification to assume that higher levels of domestic scrap availability will automatically lead to a higher national recycled content. Similarly, countries with higher recycled content are not necessarily leading the way toward a more circular steel industry. As long as the global in-use stock continues to grow, improvements in local circularity do not necessarily lead to global progress.

4.2. Recycled content targets must account for trade dynamics

These insights hold key implications for ongoing policy discourse regarding recycled content targets. As countries around the world recalibrate their strategies to transition toward a more circular economy and achieve net-zero carbon emissions (Raabe et al., 2024), the idea of setting national recycled content targets is beginning to gain momentum (Systemiq, 2023). Our analysis highlights an important caveat to this

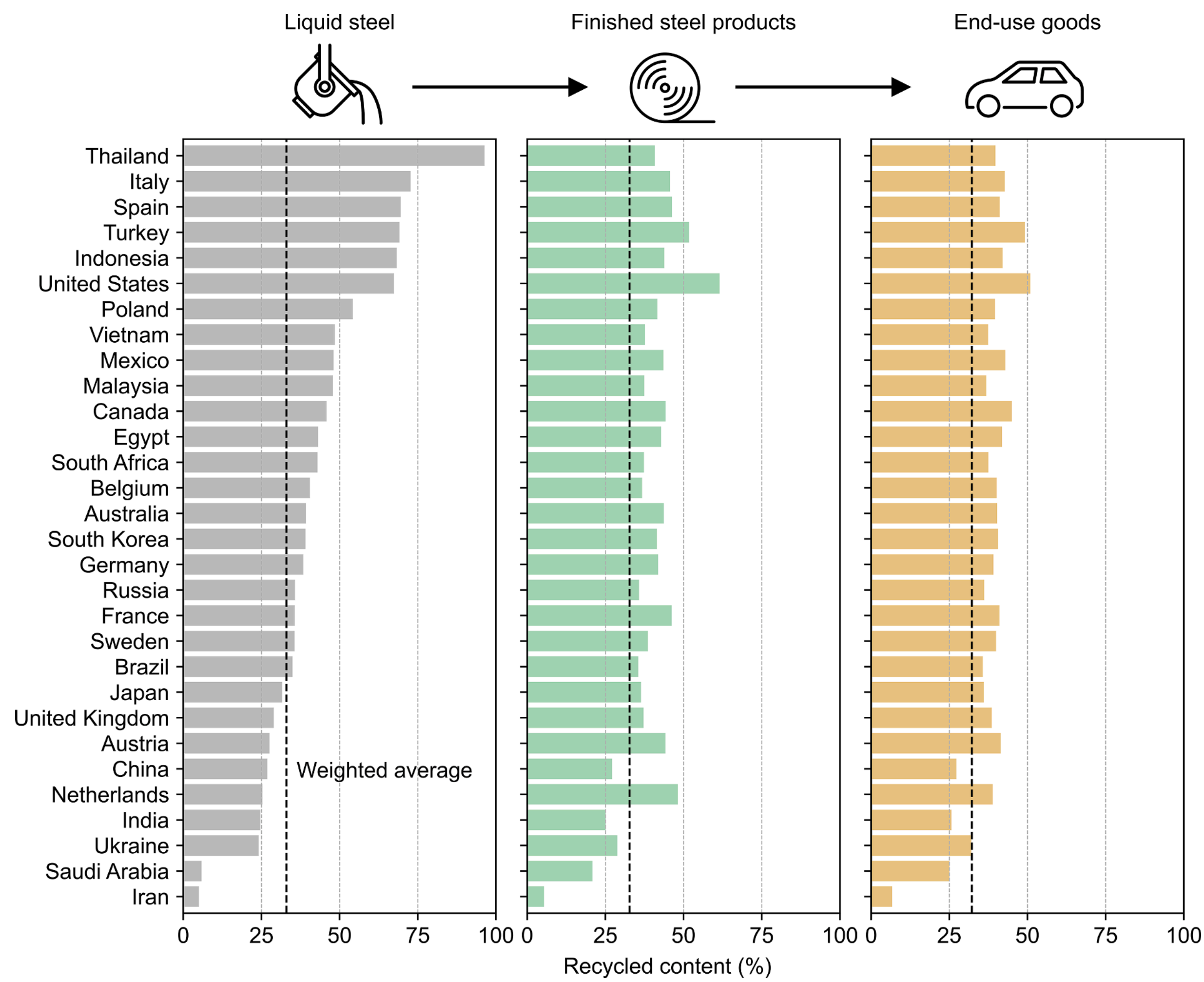

Fig. 5. Recycled content of steel products across countries and supply chain stages. The recycled content shown represents the steel products used in each country (i.e., domestic production + imports - exports). All data refer to 2019. The dashed line shows the weighted average of the 30 countries.

discussion: the recycled content of steel products is shaped by global supply chains rather than confined to national borders. As steel products move through the supply chain, recycled content tends to average out across countries. This means that high recycled content at the steelmaking stage does not necessarily translate into similarly high recycled content in finished steel products or end-use goods.

Without careful consideration of such trade dynamics and the niche roles countries play in supply chains, setting recycled content targets on a country-by-country basis risks outsourcing ore-based steelmaking, increasing import dependency, and failing to enhance global circularity. Meaningful progress requires a stabilization of global stock growth and a clear understanding of how recycled content should be improved on a worldwide scale. Global targets, informed by these insights, should then be translated into actionable national targets to ensure that ambitious targets in one country do not lead to reduced recycled content in others.

4.3. Stabilizing stock growth as a core strategy

In this context, setting effective recycled content targets must address the core barrier to circular steel flows: the continued expansion of in-use stock. At the moment, most of the major steel-producing countries have national targets for materials recovery and recycling, with China and India, for example, setting specific targets for steel recycling (OECD, 2024). However, our analysis demonstrates that efforts to improve recycling practices have been historically counteracted by the continued expansion of global in-use steel stock. Achieving more circular steel flows thus requires addressing not only how scrap steel is recycled but also how much new steel is continuously added to the use phase.

Despite this challenge, current circular economy policies and strategies rarely include explicit targets for stock stabilization through 'efficiency' or 'sufficiency', which aim to deliver the same level of services with less resource inputs (Rudolf and Schmidt, 2025). We emphasize the urgency of embedding these strategies at the core of circular economy initiatives. As this study shows, ambitious recycling efforts at the local scale do not necessarily lead to global progress without directly addressing the ongoing expansion of global in-use stock. This means that achieving a more circular steel flow is challenging at the level of individual countries. Instead, this is a global challenge that demands coordination across all countries, together with stronger governance (Ali et al., 2017).

4.4. Limitations and steps forward

It is important to recognize here that recycling captures only one dimension of circularity (Worrell and Reuter, 2014). The aim of the circular economy is much broader than merely closing the loop through recycling (Kirchherr et al., 2017); it also includes narrowing and slowing down the material loop by reducing overall purchases, making lighter products that last longer, and reusing products or components without the energy-intensive step of recycling (Allwood, 2024). The dataset developed in this study, however, cannot capture the effects of these interventions. In addition, as with all modeling research, our dataset relies on several assumptions, which inherently involves some uncertainty. While the resulting data aligns well with existing studies for major economies, certain disparities exist, and validation is not possible for emerging economies due to limited data availability (See Section 8 in the SI). Addressing these issues remains a key area for future research.

Another important step forward is automating dataset construction and linking it to interactive Sankey diagrams. Continuous monitoring of recycled content at both the product and country levels requires ongoing dataset updates, which demands significant time and computational resources. It is thus useful to automate dataset construction using methods such as RAS-type reconciliation algorithms (Lenzen et al., 2009), constrained optimization (Kopec et al., 2016), or a Bayesian approach (Lupton and Allwood, 2018). We also demonstrate that rather than constructing a multi-regional table annually, a simplified method, such as assuming a uniform global recycled content for all imported products, can serve as a reasonable alternative (See Section 9 in the SI). These datasets can then be effectively visualized using interactive Sankey diagrams developed in this study, offering a more intuitive way of communicating complex results to policymakers and industry partners. We emphasize the need for further efforts in these areas to deepen our understanding of the physical economy and support informed decision-making.

CRediT authorship contribution statement

Takuma Watari: Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tomer Fishman:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Hanspeter Wieland:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Dominik Wiedenhofer:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Takuma Watari reports financial support was provided by the Japan Society for the Promotion of Science and the Royal Society. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108363.

Data availability

The raw data from the World Steel Association and the US Geological Survey can be accessed at https://worldsteel.org/publications/bookshop/ and https://www.usgs.gov/centers/national-minerals-information-center/iron-ore-statistics-and-information, respectively. Please note that restrictions apply to the Steel Statistical Yearbook data, which were acquired and used under license for this study. Processed versions of the data are available on the ZENODO repository (https://doi.org/10.5281/zenodo.15344957). The Sankey diagrams are accessible via a web application (https://steel-flows-sankey.streamlit.app/), along with the processing code on our GitHub repository (https://github.com/takumawatari/steel-flows-sankey) and the ZENODO repository (https://doi.org/10.5281/zenodo.15344957).

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