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Global stagnation and regional variations in steel recycling

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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

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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

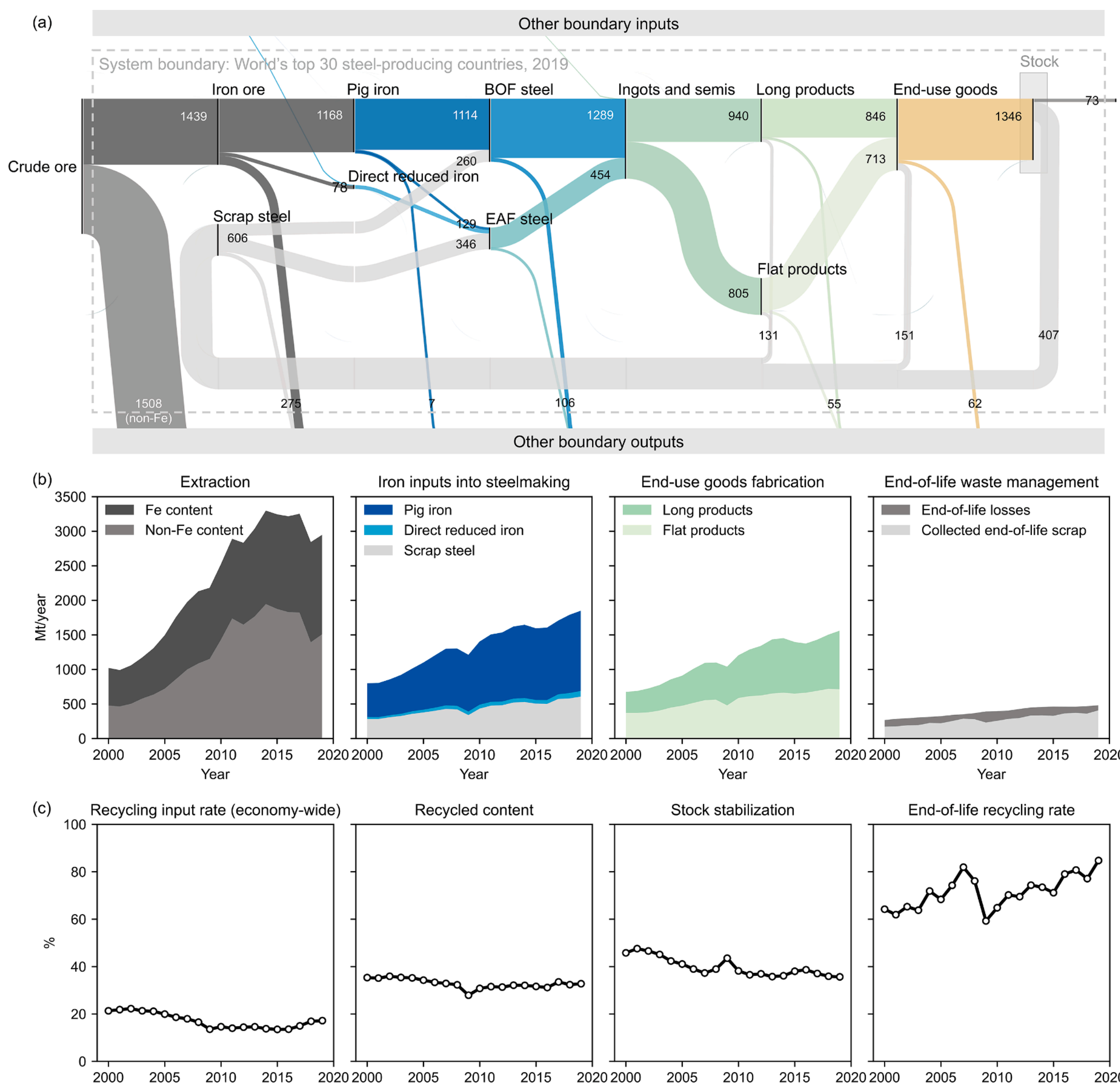

Fig. 1. Iron and steel flows combined for the group of 30 top steel-producing countries. (a) Sankey diagram illustrating global iron and steel flows in 2019. (b) Scale-related indicators showing trends in extraction, steelmaking, fabrication, and end-of-life waste from 2000 to 2019. (c) Recycling-related 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

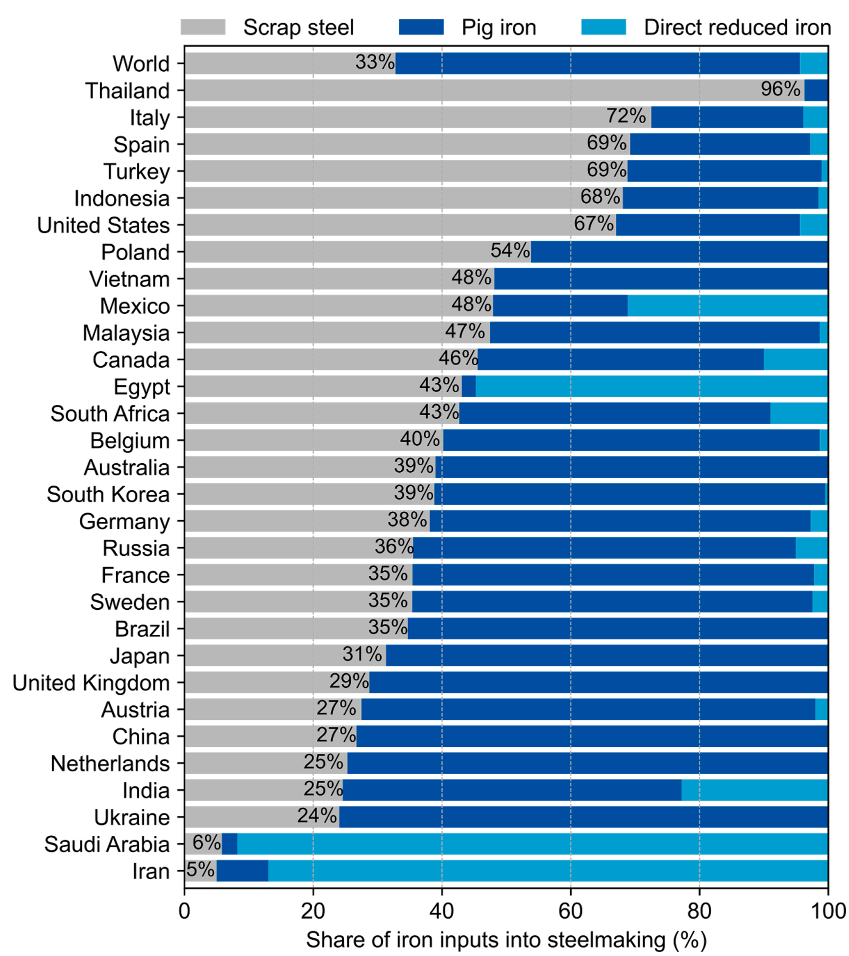

Fig. 2. Ranking of recycled content among the world's top 30 steel-producing countries in 2019. The labeled percentages indicate the share of recycled steel used in steelmaking for each country.

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

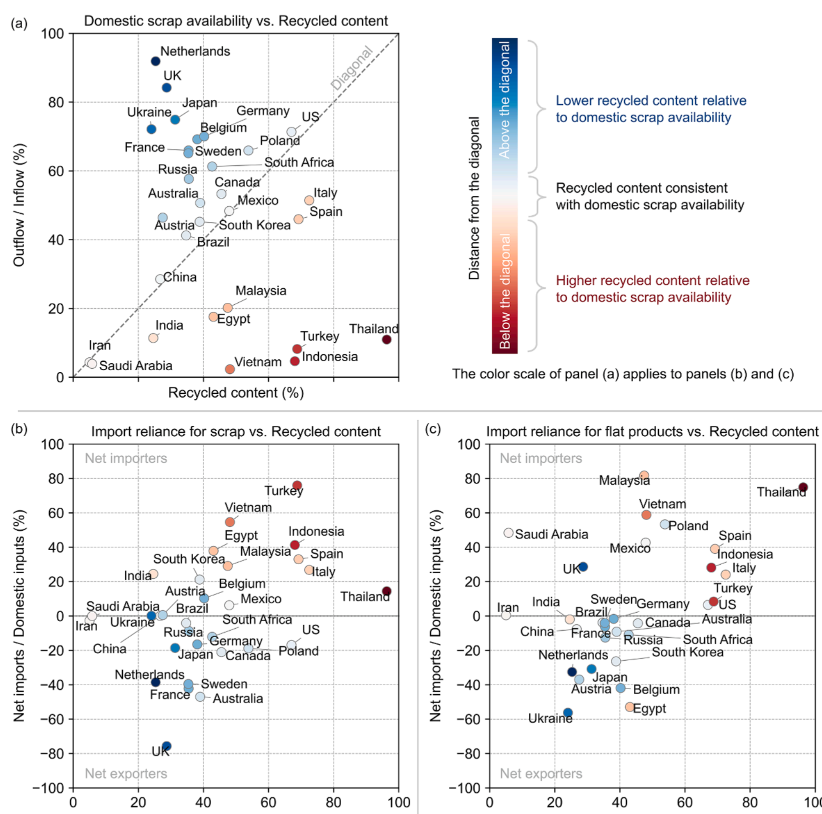

Fig. 3. Underlying factors behind recycled content around the world. (a) Relationship between stock stabilization and recycled content. (b) Relationship between import reliance for scrap steel and recycled content. (c) Relationship between import reliance for flat products and recycled content. All data 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.

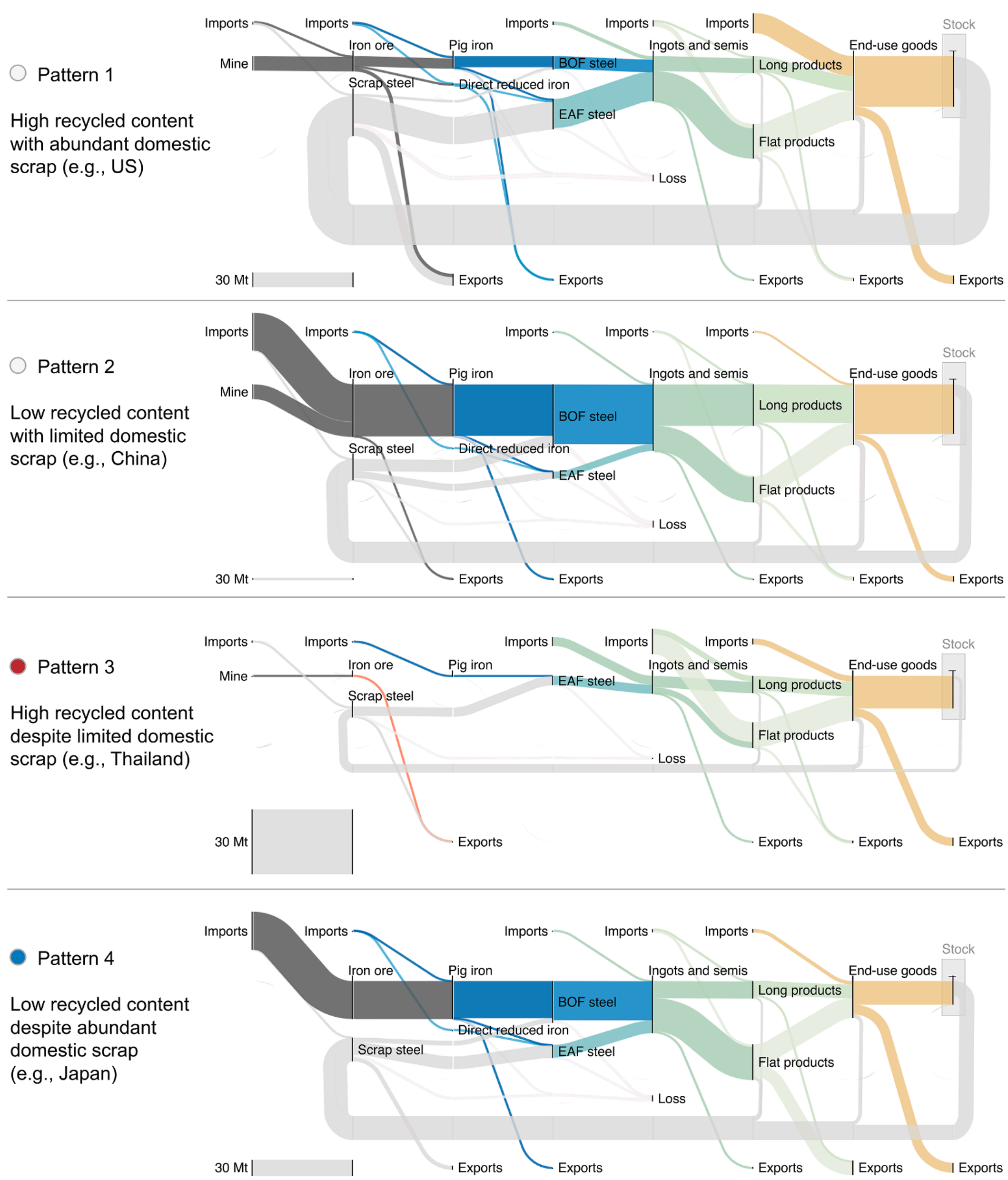

Fig. 4. Four distinct patterns of iron and steel flows based on recycled content and domestic scrap availability. These patterns illustrate how recycled content levels vary across countries due to different industrial structures. All data represent the year 2019. The Sankey diagrams for all target countries 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

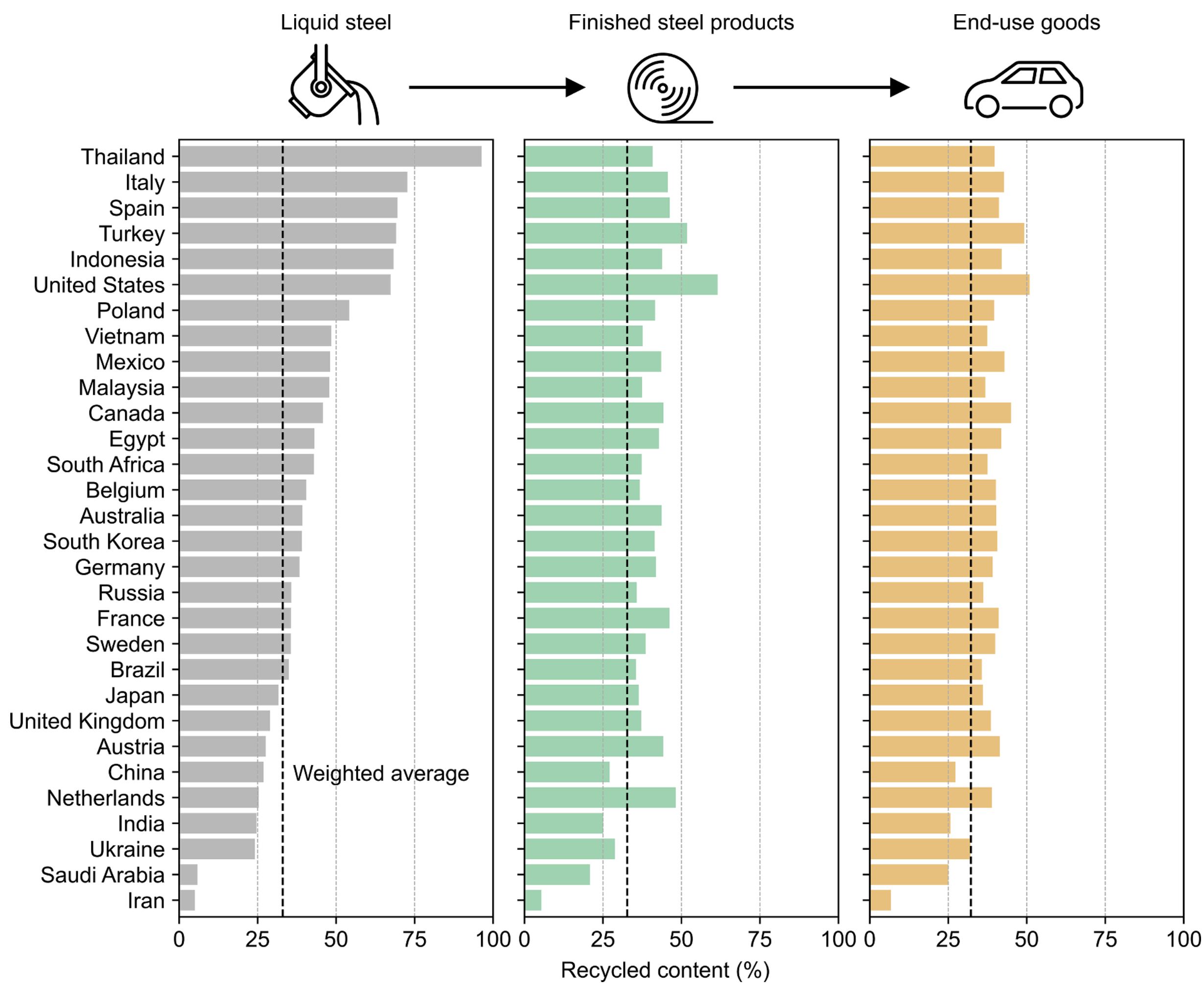

Fig. 5. Recycled content of steel products across countries and supply chain stages. The recycled content shown represents the steel products used in each country (i.e., domestic production + imports - exports). All data refer to 2019. The dashed line shows the weighted average of the 30 countries.

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 steel-making 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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Supplementary Information

Global stagnation and regional variations in steel recycling

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1. System definition

The national-scale Sankey diagrams for iron and steel flows are structured according to the system outlined in **Fig. S1**. This system consists of a series of production processes (P) and mass flows between these processes (F). While iron and steel products include several accompanying elements, such as carbon, phosphorus, and alloy metals (e.g., nickel), this study focuses on tracking the flow of iron through these processes.

The process starts with the extraction and processing of iron ore (P1-2), which contains varying amounts of iron, depending on the type and location of the mines. The refined iron ore (~65% iron content) is either fed into blast furnaces to produce pig iron (~94% iron content) (P3) or into direct reduction furnaces to produce sponge iron (~92% iron content) (P4). Additionally, scrap collected from various processes represents another iron source (P5).

The subsequent phase is steelmaking, which primarily employs two types of furnaces: basic oxygen furnaces (BOFs) and electric arc furnaces (EAFs). In BOFs, pig iron is the main source of iron, along with scrap to moderate temperatures and refine the final steel composition. The proportion of scrap is generally limited to around 30% of the charge. In contrast, EAFs can operate with a higher proportion of scrap, sometimes up to 100% (P7). Historically, open hearth furnaces played a significant role in steelmaking, employing a similar charging method of pig iron and scrap to BOFs. Our dataset incorporates open hearth furnaces as part of the BOF process (i.e., ore-based process). The production of castings in foundries is not included in our dataset due to limited data availability and production volumes.

The molten steel (~98% iron content) from BOFs or EAFs is then cast into semi-finished products, such as slabs, billets, and blooms, as well as ingots (P8). Further processing involves rolling and forming these semi-finished products into finished steel products, which can be broadly categorized as long products (e.g., reinforcing bars, wire rods, and structural sections) or flat products (e.g., sheets, plates, and strips). Long products typically utilize billets and blooms processed through rolling mills (P9), while flat products use slabs and undergo hot rolling, cold rolling, and coating for desired properties (P10). The finished steel products are then cut, welded, formed, and assembled into components and structures to form end-use goods (e.g., cars) (P11).

Finally, manufactured end-use goods become part of the capital stock (i.e., in-use stock) and provide services we need, such as thermal comfort, transport, and communications (P12). Throughout the supply chain, there are considerations regarding international trade (P0) and iron losses (P13). Within this system boundary, the stock account functions as both a sink for iron entering capital stocks and a source for iron being processed as scrap. Consequently, the system does not distinguish whether the difference between iron inputs to and outputs from the stock represents a net addition to stock (NAS) or losses.

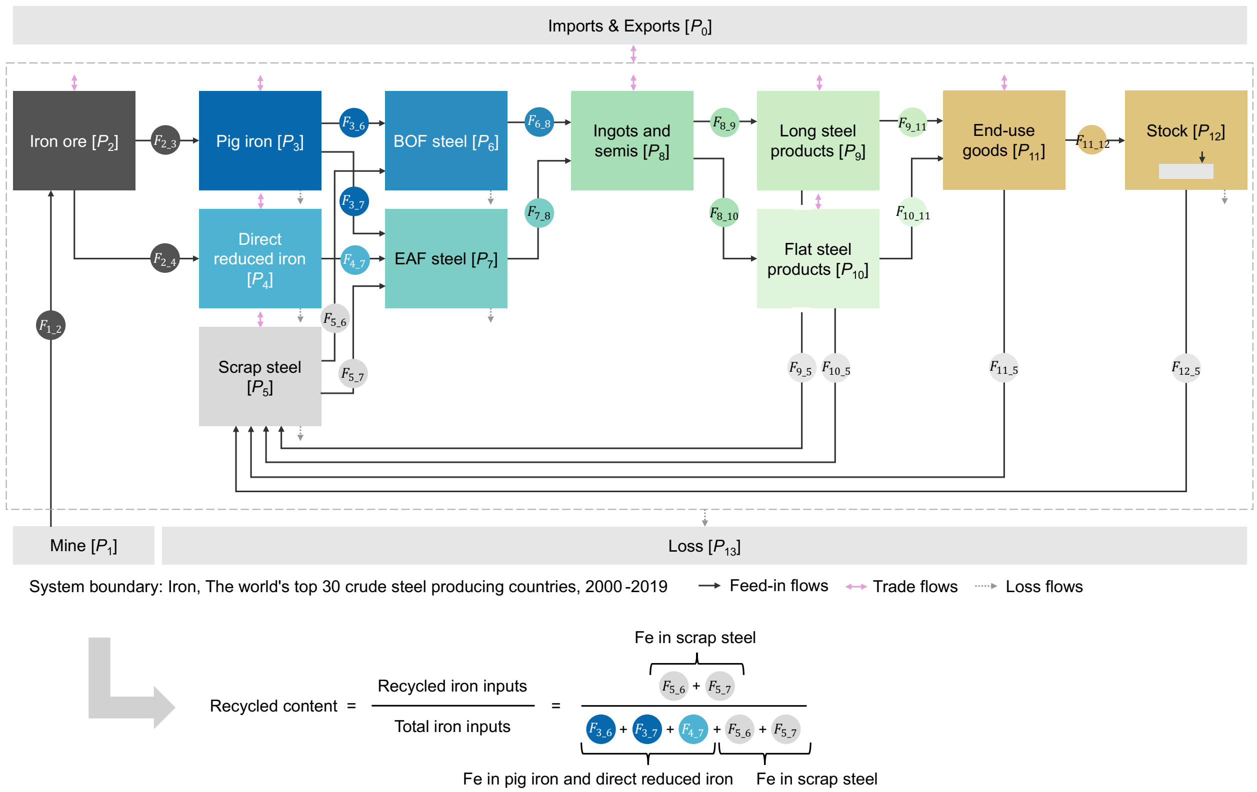


Fig. S1 System definition for iron and steel flows for national-scale Sankey diagrams.

2. Mass balance equations

The series of mass balance equations can be summarized as follows. In these equations, P represents the production process, F represents the mass flows between processes, σ denotes the process yield, and λ indicates the scrap content in BOF inputs. Each variable has a subscript indicating the type of commodity. For instance, P_2 indicates iron ore production and F_{2_3} indicates the iron content in flows from iron ore production (P_2) to pig iron production (P_3).

Iron ore flows:

$$F_{2\_3} = \frac{P_3}{\sigma_3} \tag{1}$$

$$F_{2\_4} = \frac{P_4}{\sigma_4} \tag{2}$$

$$F_{0\_2} = (F_{2\_3} + F_{2\_4}) - (P_2 - F_{2\_0}) \tag{3}$$

$$F_{1\_2} = P_2 \tag{4}$$

Pig iron flows:

$$F_{3\_6} = \frac{P_6}{\sigma_6} - F_{5\_6} \tag{5}$$

$$F_{3\_7} = (P_3 + F_{0\_3} - F_{3\_0}) - F_{3\_6} \tag{6}$$

$$F_{3\_13} = F_{2\_3} - P_3 \tag{7}$$

Direct reduced iron flows:

$$F_{4\_7} = P_4 + F_{0\_4} - F_{4\_0} \tag{8}$$

$$F_{4\_13} = F_{2\_4} - P_4 \tag{9}$$

Scrap steel flows:

$$F_{5\_6} = \lambda \frac{P_6}{\sigma_6} \tag{10}$$

$$F_{5\_7} = \frac{P_7}{\sigma_7} - (F_{3\_7} + F_{4\_7}) \tag{11}$$

$$P_5 = F_{5\_6} + F_{5\_7} + F_{0\_5} - F_{5\_0} \tag{12}$$

$$F_{5\_13} = (1 - \sigma_5) P_5 \tag{13}$$

BOF and EAF steel flows:

$$P_6 = F_{6\_8} \tag{14}$$

$$P_7 = F_{7\_8} \tag{15}$$

$$F_{6\_13} = (F_{3\_6} + F_{5\_6}) - P_6 \tag{16}$$

$$F_{7\_13} = (F_{3\_7} + F_{4\_7} + F_{5\_7}) - P_7 \tag{17}$$

Ingots and semi-finished product flows:

$$P_8 = F_{6\_8} + F_{7\_8} \tag{18}$$

$$F_{8\_9} = \frac{P_9}{\sigma_9} \tag{19}$$

$$F_{8\_10} = \frac{P_{10}}{\sigma_{10}} \tag{20}$$

$$\sigma_9 = \sigma_{10} = \frac{(P_9 + P_{10})}{(P_8 + F_{0\_8} - F_{8\_0})} \tag{21}$$

$$F_{9\_5} = F_{8\_9} - P_9 \tag{22}$$

$$F_{10\_5} = F_{8\_10} - P_{10} \tag{23}$$

Finished product flows:

$$F_{9\_11} = P_9 + F_{0\_9} - F_{9\_0} \tag{24}$$

$$F_{10\_11} = P_{10} + F_{0\_10} - F_{10\_0} \tag{25}$$

End-use goods flows:

$$F_{11\_12} = P_{11} + F_{0\_11} - F_{11\_0} \tag{26}$$

$$P_{11} = \sigma_{11}(F_{9\_11} + F_{10\_11}) \tag{27}$$

$$F_{11\_5} = (F_{9\_11} + F_{10\_11}) - P_{11} \tag{28}$$

$$F_{12\_5} = \frac{P_5}{\sigma_5} - (F_{9\_5} + F_{10\_5} + F_{11\_5}) \tag{29}$$

$$\mathrm{NAS} + F_{12\_13} = F_{11\_12} - F_{12\_5} \tag{30}$$

3. Balancing flows

Two fundamental conditions govern the mass balance equations: 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 adjust the mass imbalances. Specifically, as shown in a series of mass balance equations, the iron inputs and outputs across all processes must satisfy the following equation:

$$\text{Domestic use} = \text{Domestic production} + \text{Imports} - \text{Exports} \quad (31)$$

Failure to satisfy this condition in any process indicates a mass imbalance. Thus, balancing flows are calculated as:

$$\text{Balancing flows} = \text{Domestic use} - \text{Domestic production} - \text{Imports} + \text{Exports} \quad (32)$$

Mass imbalances can occur in various forms. We address these using procedures tailored to each pattern. In all cases, production data are given priority over other data such as data on international trade, process yield and iron content. In the Sankey diagram, balancing flows are represented as imports or exports crossing the system boundary. In reality, however, balancing flows are not necessarily international trade; several factors contribute to mass imbalances, as discussed below.

Iron ore:

In some iron ore-producing countries, estimated domestic production (domestic use - imports + exports) is significantly lower than reported domestic production. This discrepancy may stem from poor international trade reporting or iron ore being diverted for purposes other than the production of pig iron or direct reduced iron. Stockpiling of iron ore could also contribute to this difference. In such cases, the mass balance equations give imported iron ore as a negative input, as indicated in equation (3). To address this imbalance, we apply a constraint that ensures all mass flows remain non-negative. This adjustment sets imported iron ore to zero, and the balancing flows estimated in equation (32) maintain equilibrium between inputs and outputs.

Pig iron and direct reduced iron:

Our dataset also reveals imbalances in the reporting of pig iron and direct reduced iron. For instance, some countries report exports of these commodities that exceed the sum of their domestic production and imports. This means that some portion of these commodities come from nowhere. In such cases, the mass balance equations give domestic use as a negative input, as shown in equations (6) and (8). We apply a constraint to keep domestic use non-negative and estimate the balancing flows using equation (32).

Scrap steel:

In some countries, the estimated domestic use of scrap exceeds the amount required for steelmaking. This results in the mass balance equations calculating recovered end-of-life scrap as a negative input, as it is treated as a source of iron compensating for the iron deficit in steelmaking (see equation (29)). Several factors may explain this inconsistency: poor reporting of international trade, overestimation of scrap recovery during forming and fabrication, or scrap steel being stockpiled rather than used immediately. In this study, we apply a constraint to keep recovered end-of-life scrap non-negative and use equation (32) to estimate balancing flows, which are represented as additional scrap leaving the system boundary.

Ingots and semis:
When the domestic output of finished steel products (e.g., plates) exceeds the domestic input of semi-finished products (e.g., slabs), the forming process appears to have a yield greater than 100% (equation (21)). This imbalance can be attributed to poor international trade reporting, inventory stockpiling, or simplified assumptions about the iron content of semi-finished and finished products. In such cases, we assume a 95% iron yield in the forming process, based on global data, and apply equation (32) to correct the imbalance.

4. Data sources

Most production and trade data are taken from the Steel Statistics Yearbook published by the World Steel Association [1], which are supplemented by statistics from the US Geological Survey [2]. These sources provide the data shown in **Table S1**, whereas other mass flows are estimated using the mass balance equations described above. Data sources for other key parameters are summarized in **Table S2**. All production and trade data are converted into iron content. As trade in end-use goods is recorded as finished steel equivalent (i.e., the amount of finished steel needed to produce end-use goods), fabrication scrap is subtracted to determine the iron content in end-use goods. While more recent data are available, newer data are often subject to revisions. For consistency, we limit our analysis to 2019.

Table S1 List of data provided by the World Steel Association and the US Geological Survey.

Data	References
Production of usable iron ore	US Geological Survey [2]
Production of iron ore (iron content)	US Geological Survey [2]
Iron content of exported iron ore	US Geological Survey [2]
Production of pig iron	World Steel Association [1]
Production of direct reduced iron	World Steel Association [1]
Production of BOF steel	World Steel Association [1]
Production of EAF steel	World Steel Association [1]
Production of long products	World Steel Association [1]
Production of flat products	World Steel Association [1]
Exports of iron ore	World Steel Association [1]
Exports of pig iron	World Steel Association [1]
Imports of pig iron	World Steel Association [1]
Exports of direct reduced iron	World Steel Association [1]
Imports of direct reduced iron	World Steel Association [1]
Exports of scrap	World Steel Association [1]
Imports of scrap	World Steel Association [1]
Exports of ingots and semis	World Steel Association [1]
Imports of ingots and semis	World Steel Association [1]
Exports of long products	World Steel Association [1]
Imports of long products	World Steel Association [1]
Exports of flat products	World Steel Association [1]
Imports of long products	World Steel Association [1]
Exports of end-use goods	World Steel Association [1]
Imports of end-use goods	World Steel Association [1]

Table S2 Data sources for key parameters.

Parameters	Value	References
Iron content of re-exported iron ore	65.0%*	[3]
Iron content of pig iron	94.5%	[4]
Iron content of direct reduced iron	92.0%	[4]
Iron content of steel products	98.0%	[5]
Iron yield in blast furnaces	99.4%	[7]
Iron yield in direct reduction furnaces	99.4%	[7]
Iron yield in scrap collection and processing	89.0%	[8]
Iron yield in basic oxygen furnaces	93.8%	[7]
Iron yield in electric arc furnaces	95.7%	[7]
Iron yield in forming finished steel products	95.0%**	[1]
Iron yield in manufacturing end-use goods using long products	94.0%	[8]
Iron yield in manufacturing end-use goods using flat products	86.0%	[8]
Scrap content in basic oxygen furnace feeds	***	[5,8–12]

* This parameter only applies to countries reporting exports of iron ore without domestic extraction.

** This parameter is only utilized when balancing flows need to adjust for mass imbalances.

*** This parameter varies by country. Where country-specific data are available, they should be used; otherwise, a default value of 20% is applied.

5. Processed data

All processed data are stored in Excel files for creating Sankey diagrams, which are publicly available on the GitHub repository (https://github.com/takumawatari/steel-flows-sankey). The data structure is organized as a matrix, where the columns represent the inputs of iron into the production process, while the rows represent the outputs and distribution of iron. All values are expressed in 1,000 metric tons. The data can also be viewed by hovering over each flow in the Sankey diagram in the web application or in Jupyter Notebook (**Fig. S2**).

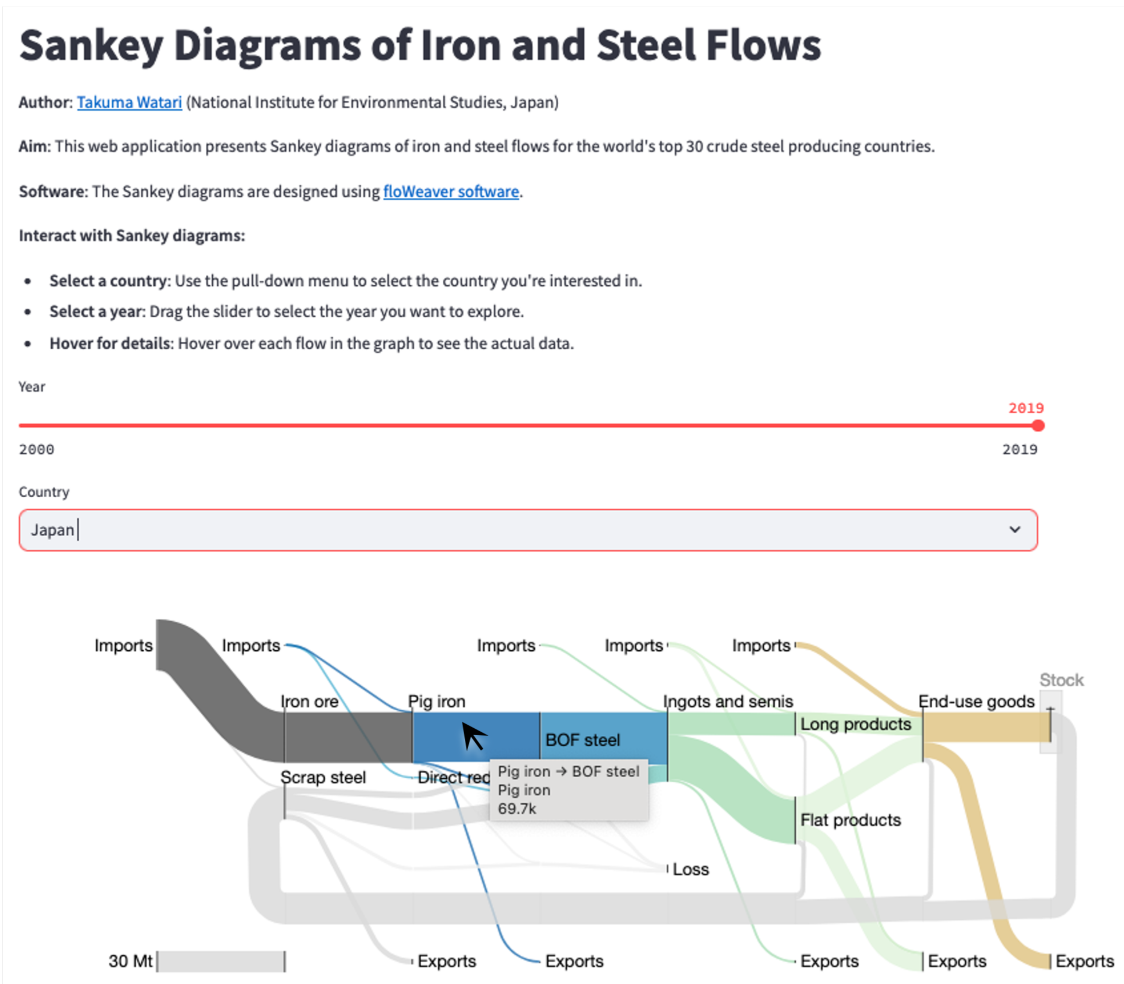


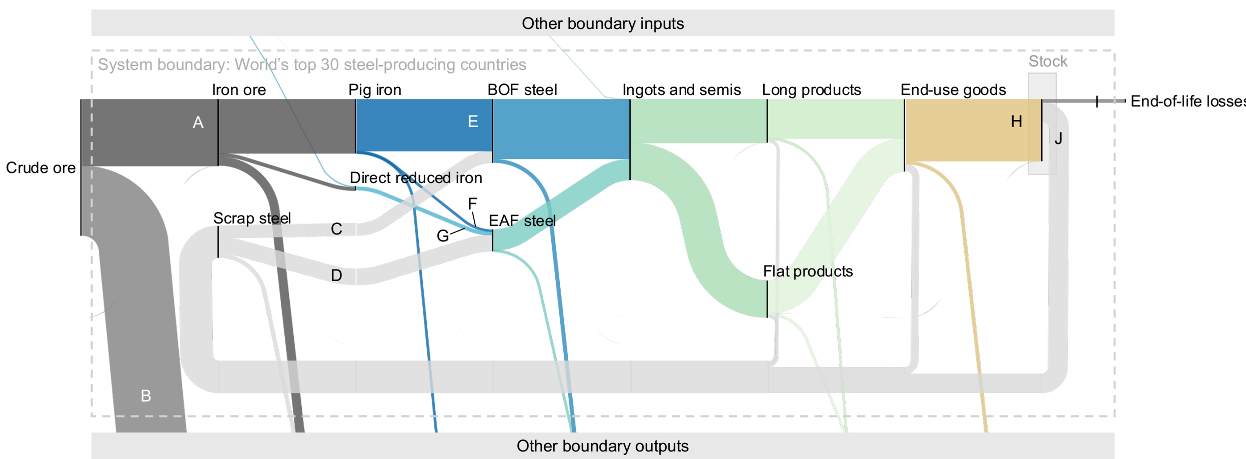
Fig. S2 Screenshot of the web application. This example shows a Sankey diagram for Japan in 2019, highlighting a flow of 69.7k (i.e., ~70 Mt) of iron contained in pig iron used in the production of BOF steel. The web application is accessible via the following link: https://steel-flows-sankey.streamlit.app/.

6. Global Sankey diagrams and recycling indicators

We use data from the world's top 30 crude steel-producing countries to create our global Sankey diagrams, with two key adjustments. First, we incorporate the extraction of crude ore, which contains both iron and non-iron materials that are separated during processing. This enables us to calculate the 'economy-wide recycling input rate', an indicator that reflects the share of recycled iron in total material inputs, including the non-iron content from crude ore.

Second, we account for end-of-life waste (i.e., outflow) from in-use stock. This allows us to calculate the 'end-of-life recycling rate', which measures the proportion of iron in end-of-life waste that is functionally recycled. Crude ore extraction data are sourced from the UNEP-IRP Global Material Flows Database [13], while end-of-life waste data comes from [14], adjusted to match the number of countries included in this analysis.

The definition of recycling indicators is based on existing studies [15,16] (**Fig. S3**).



- **Economy-wide recycling input rate** = Recycled iron inputs / Total material inputs = (C + D) / (A + B + C + D)
- **Recycled content** = Recycled iron inputs / Total iron inputs = (C + D) /(C + D + E + F + G)
- **Stock stabilization** = Outflow / Inflow = (I + J) / H
- **End-of-life recycling rate** = Recycled end-of-life scrap / Outflow = J / (I + J)

Fig. S3 Definitions of recycling indicators for global iron and steel flows.

7. Selection and definition of indicators to explain regional differences in recycled content

To better understand the underlying reasons for regional variations in recycled content, we analyze countries using key 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 [17]. Second, industrialized countries are increasingly exporting scrap rather than recycling it domestically [18]. Third, recycled steel is often downcycled into long products rather than flat products due to difficulties in contamination control [19].

Building on these insights, we focus on three indicators. The first and most intuitive is stock stabilization – the balance between iron entering society as goods and iron exiting as scrap. In theory, the more balanced these inflows and outflows are, the greater the potential for increasing the recycled content [20]. The other two indicators capture the role of international trade: a country's import reliance on 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.

Stock stabilization is measured as the ratio of iron exiting the in-use stock to iron entering it. This metric corresponds to how much iron inflow is used to replace iron outflow and how much is used to expand the in-use stock. A value closer to 1 indicates that a larger share of iron inflow is used to compensate for iron outflow, suggesting a more stabilized stock.

$$\text{Stock stabilisation} = \frac{\text{Outflow}}{\text{Inflow}} = \frac{F_{12\_5} + F_{12\_13}}{F_{11\_12}} \tag{33}$$

Import reliance for each product x (e.g. scrap, flat products, and long products) is calculated as the ratio of net imports ($F_{0\_x} - F_{x\_0}$) to domestic inputs ($P_x - F_{x\_0}$). This metric quantifies the share of a product's domestic supply that depends on imports. A positive value indicates import dependence, while a negative value reflects a net export contribution.

$$\text{Import reliance}_x = \frac{\text{Imports}_x - \text{Exports}_x}{\text{Domestic production}_x - \text{Exports}_x} = \frac{F_{0\_x} - F_{x\_0}}{P_x - F_{x\_0}} \tag{34}$$

8. Validation and sensitivity

We compare our estimates of collected end-of-life scrap and total scrap use with existing studies for four countries – China, Japan, the United States, and the United Kingdom – where multiple data sources are available [5,8,11,12,21–24]. Overall, the trends in our data align well with existing studies, although there are some differences in the absolute values (**Fig. S4-7**). Such differences may arise from various sources, including modeling procedures and parameters used.

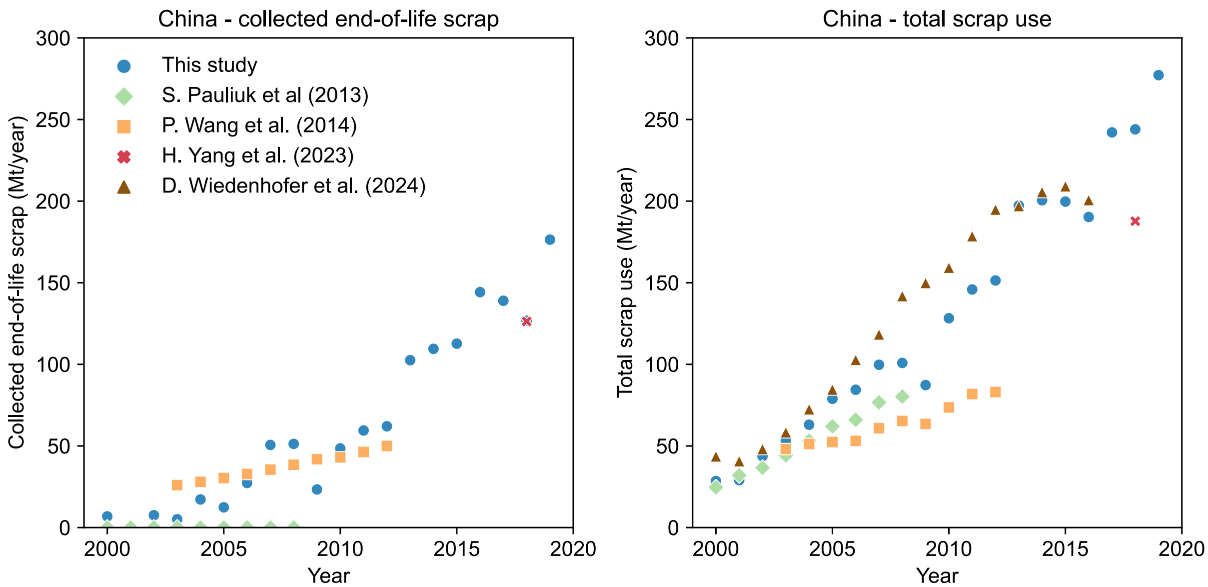


Fig. S4 Comparison of scrap estimates from this study with those from previous studies for China.

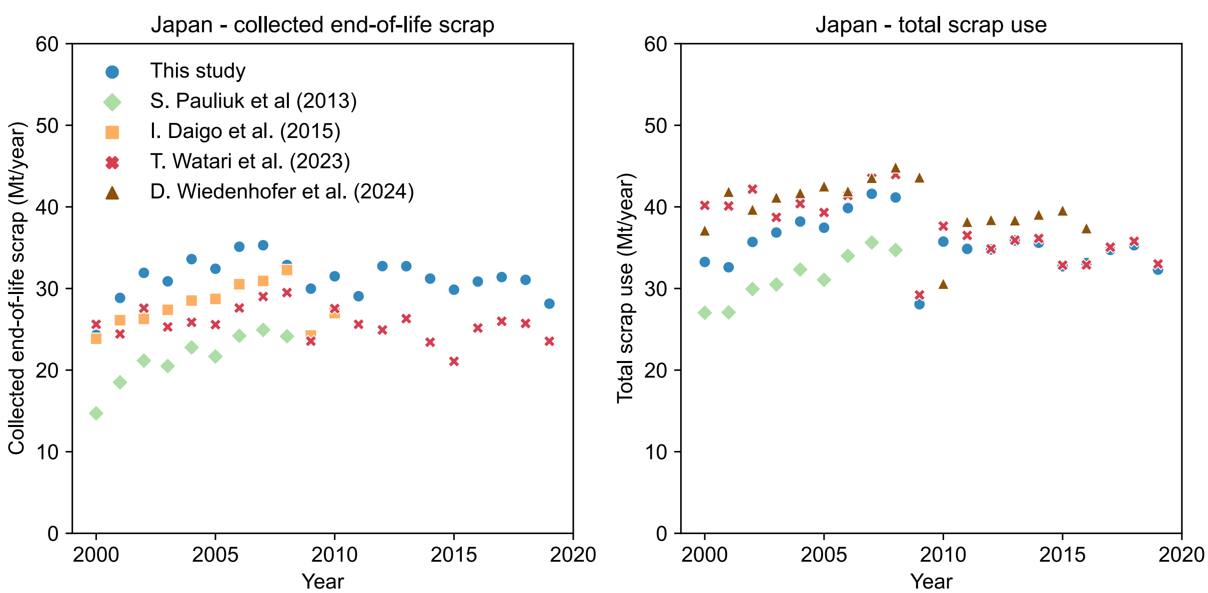


Fig. S5 Comparison of scrap estimates from this study with those from previous studies for Japan.

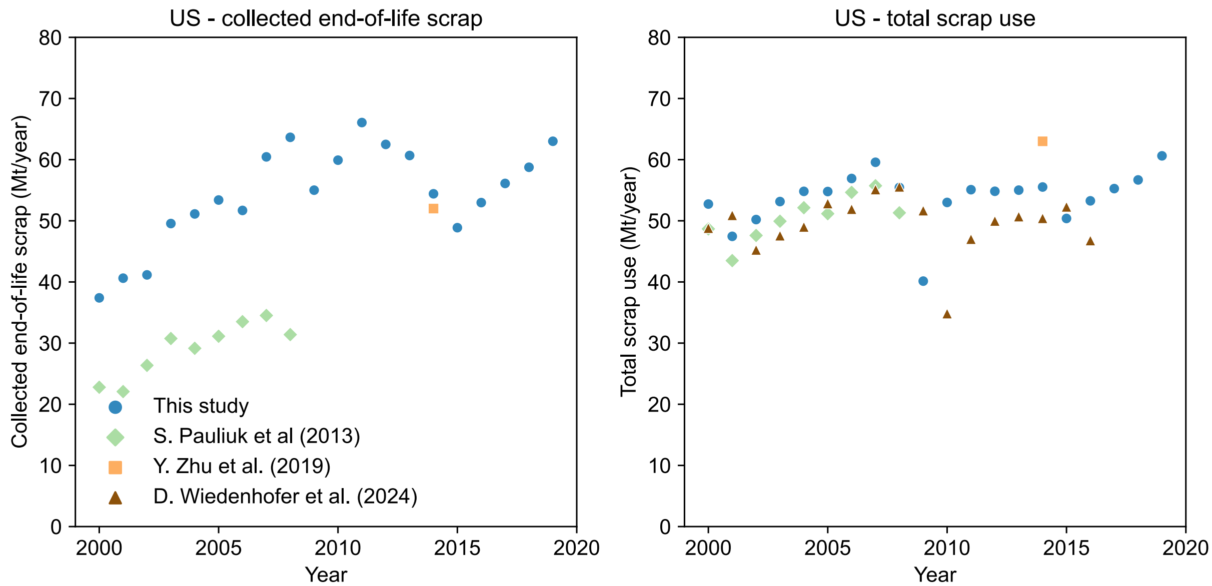


Fig. S6 Comparison of scrap estimates from this study with those from previous studies for the US.

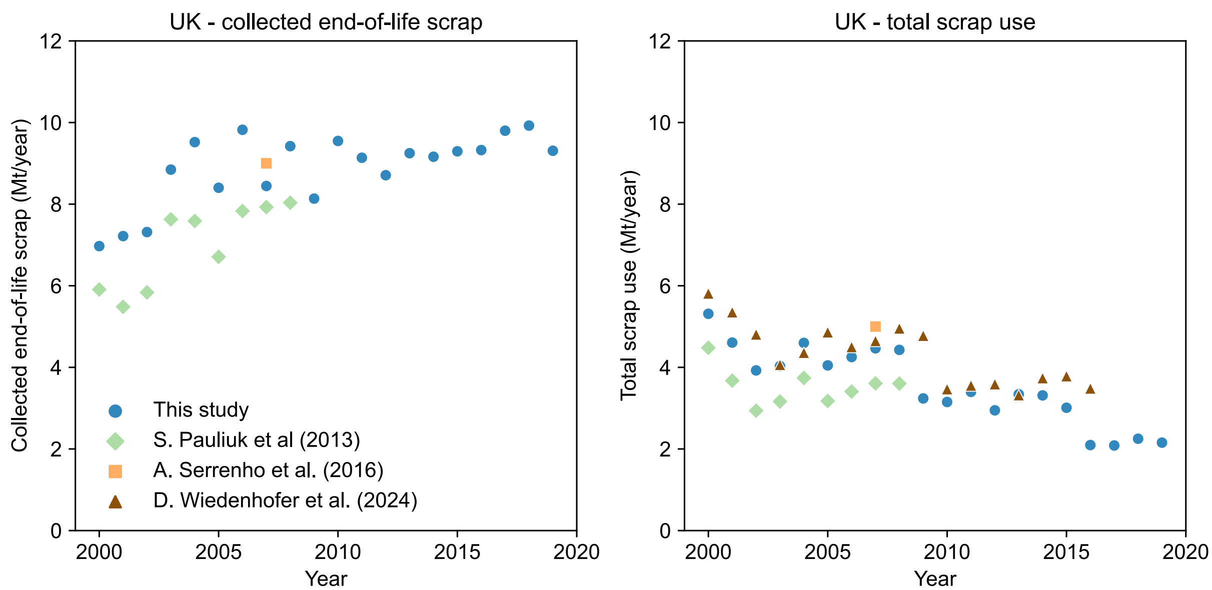


Fig. S7 Comparison of scrap estimates from this study with those from previous studies for the UK.

Our estimates of the global end-of-life recycling rate are highly dependent on the estimated outflows (i.e., the denominator of this indicator). As estimates of outflows are known to be highly sensitive to assumptions about the lifetime of steel products, we perform a sensitivity analysis by varying the assumed product lifetime. The original data from Watari et al. [14] assumes an average lifetime of 38 years. We adjust this assumption both upwards and downwards and recalculate the end-of-life recycling rate (**Fig. S8**).

When a longer lifetime is assumed, the estimated recycling rate for the last 20 years exceeds 100% in many periods, implying that more scrap is recycled than is generated annually. While stockpiled scrap can be used when prices rise [23], it is unrealistic to assume that this has happened consistently over two decades. Conversely, assuming a shorter lifetime reduces the absolute recycling rate but does not alter the overall trend of a gradual increase over the last 20 years.

We also compare our estimates with three existing studies [6,7,25]. Although the data available for direct comparison are limited, we can confirm that our estimates for 2000, 2007 and 2008 are in good agreement with these studies.

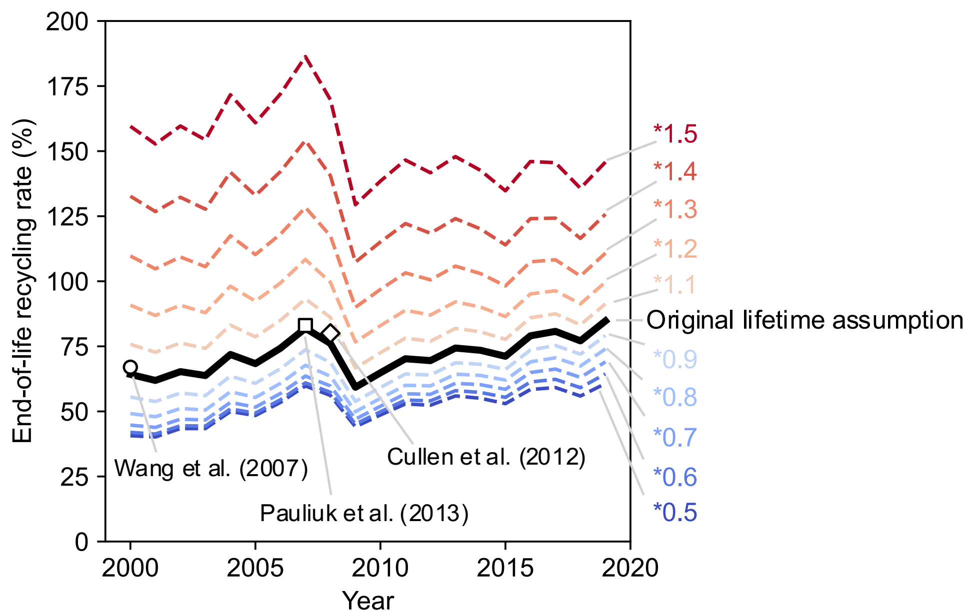


Fig. S8 Sensitivity of the estimated global end-of-life recycling rate. The asterisk (*), followed by a number, indicates a scenario where the original average lifetime is multiplied by that factor. For example, *1.5 represents an assumption of 1.5 times the original lifetime.

9. Expanding trade dimensions using bilateral trade data

The original dataset provides recycled content estimates at the steelmaking stage at the country level, but not further downstream. This limitation arises because steel products often pass through multiple countries during their lifecycle. Consequently, accurate regional estimates require explicit tracking of imported and exported steel products across the entire supply chain. Graedel et al. noted that calculating recycled content at the country level is highly challenging due to the lack of data on the recycled content of imported metals [26]. To address this gap, we incorporate bilateral trade data and reformat the 2019 dataset into multi-regional physical input-output tables (PIOTs). **Fig. S9** illustrates the matrix structure, which explicitly considers both the origin country and the production process of imported products.

The construction of multi-regional PIOTs is based on modifications to the original dataset for the world's top 30 crude steel-producing countries. One key adjustment involves re-exports. In the original dataset, some countries report imports exceeding domestic use, suggesting that a portion of imported products is subsequently re-exported. However, multi-regional PIOTs require that imports do not exceed domestic use. To ensure consistency, import quantities are capped at domestic use, and any excess is subtracted from export quantities. Another modification concerns semi-finished products. The original dataset aggregates various semi-finished products without distinguishing between specific types, such as slabs, billets, and blooms. To improve resolution, semi-finished products are disaggregated into long product precursors and flat product precursors based on the domestic production ratios of long and flat products. In this case, flat product precursors, which require stricter contamination control, are assumed to be primarily produced using BOF steel, while any remaining demand is fulfilled by EAF steel. If BOF steel production exceeds the demand for flat product precursors, the surplus is allocated to long product precursors.

Each table is subsequently divided into two components, one for domestic products and the other for imported products. In this process, domestically manufactured and imported products are allocated across production processes in the same proportions. For instance, scrap steel is assigned to BOFs and EAFs without distinguishing between domestic and imported sources. The single-regional PIOTs are then linked using bilateral trade data to construct the multi-regional PIOTs. Trade ratios are derived from Wieland et al. [3] for end-use goods (2014) and from the Chatham House [27] for all other products (2019). These data are used to allocate traded products to their respective countries of origin and destination, while any remaining trade flows not accounted for by the 30 target countries are allocated to a "Rest of the World" category. The resulting matrix covers 30 countries plus the rest of the world and includes both domestic transactions and international trade. The largest material flows are observed within individual countries, which appear along the matrix's main diagonal, as shown in **Fig. S10**.

Once the matrix is constructed, recycled content can be derived using a simple matrix operation. Let $\mathbf{F}$ denote the original matrix describing iron flows contained in all steel products, and let $\mathbf{F}'$ represent the matrix describing iron flows contained only in scrap steel. The recycled content matrix, $\mathbf{R}$, is then derived as $\mathbf{R} = \mathbf{F}' \bigodot \mathbf{F}^{-1}$, where $\bigodot$ denotes the Hadamard product (element-wise multiplication).

		Country A			Country B			Country A	Country B	Loss (nature)
		Com. 1	Com. 2	Com. 3	Com. 1	Com. 2	Com. 3	Stock growth	Stock growth	
Country A	Com. 1									
	Com. 2	Domestic transactions			International trade					
	Com. 3									
Country B	Com. 1									
	Com. 2	International trade			Domestic transactions					
	Com. 3									
Mine (nature)										
Stock decline										

Fig. S9 Structure of multi-regional physical input-output tables.

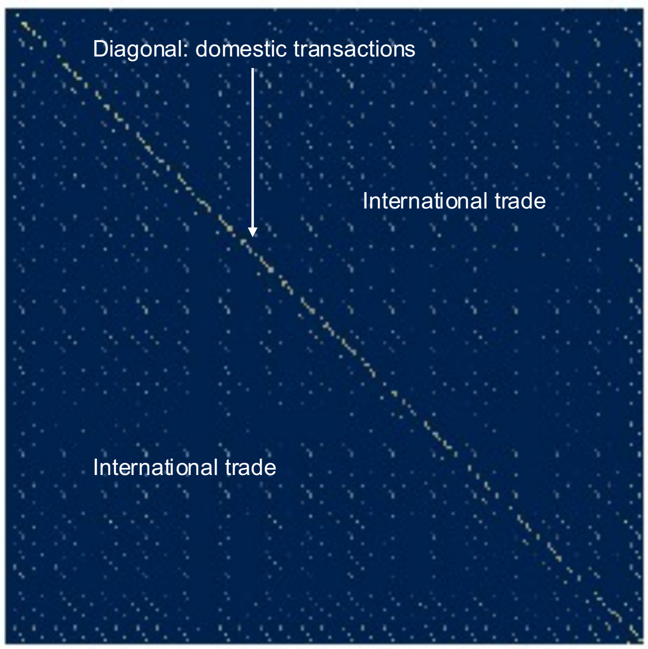


Fig. S10 Heatmap of the transaction matrix on a logarithmic scale. The lighter the color, the higher the value. The data refer to 2019.

Tracking the recycled content along global supply chains using the multi-regional PIOTs is valuable as it explicitly accounts for bilateral trade flows. However, constructing and updating such PIOTs require significant time and computational resources. A simplified approach could potentially provide a more practical and easily updatable solution for monitoring recycled content. To explore this potential, we compare recycled content estimates derived from the multi-regional PIOT with those obtained using a simplified method proposed by Espinoza et al. [28]. The simplified method assumes a single global market, where all imported products share the same global recycled content, disregarding country-specific trade relationships.

The comparison shows only minor differences between the two approaches overall, suggesting that the simplified method can serve as a reasonable alternative in many cases (**Fig. S11**). Given the tendency of recycled content to converge toward the global weighted average, this close alignment is reasonable. However, discrepancies emerge in certain regions, such as the Netherlands, Austria, France, and Canada. In these regions, recycled content estimates from the multi-regional PIOT are higher than those from the simplified method. This disparity reflects trade patterns: imports of finished steel products in these regions predominantly originate from nearby countries — such as within Europe or, in Canada's case, from the United States — where traded finished steel products have relatively higher recycled content. For end-use goods, which are largely imported from China in many countries, discrepancies between the methods remain limited. This is because China, as a dominant player in global steelmaking, has recycled content that is closely aligned with the global market. These findings suggest that the simplified method, which assumes a uniform global recycled content for all imported products, offers a practical and less resource-intensive alternative.

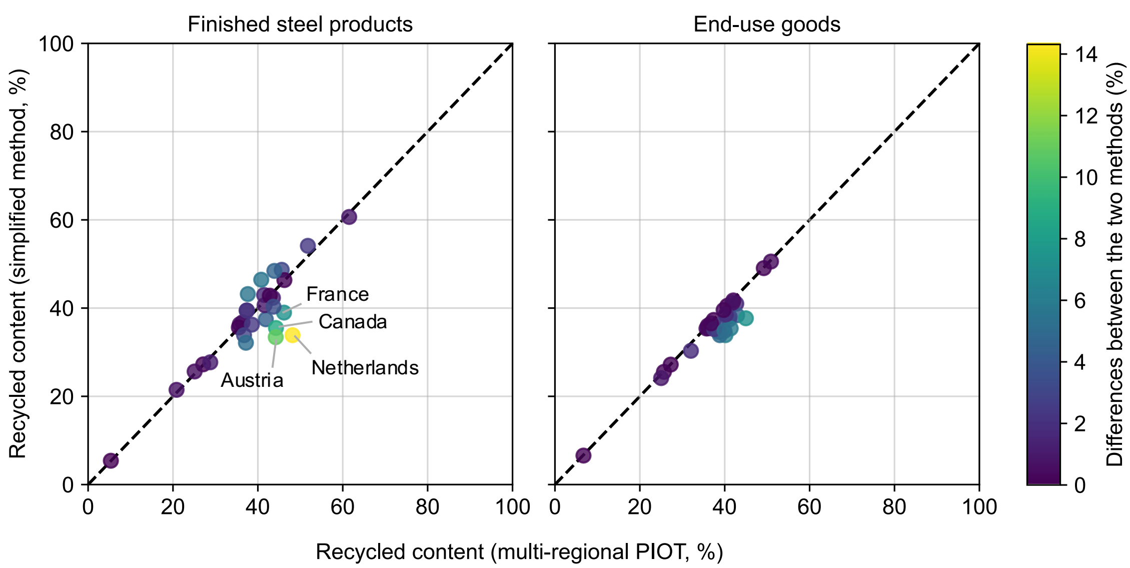


Fig. S11 Comparison of recycled content estimates from a multi-regional PIOT and a simplified method. The simplified method assumes a single global market in which all imported products have the same global recycled content. The dashed diagonal line indicates the equity of the data estimated by the two methods.

10. Additional results

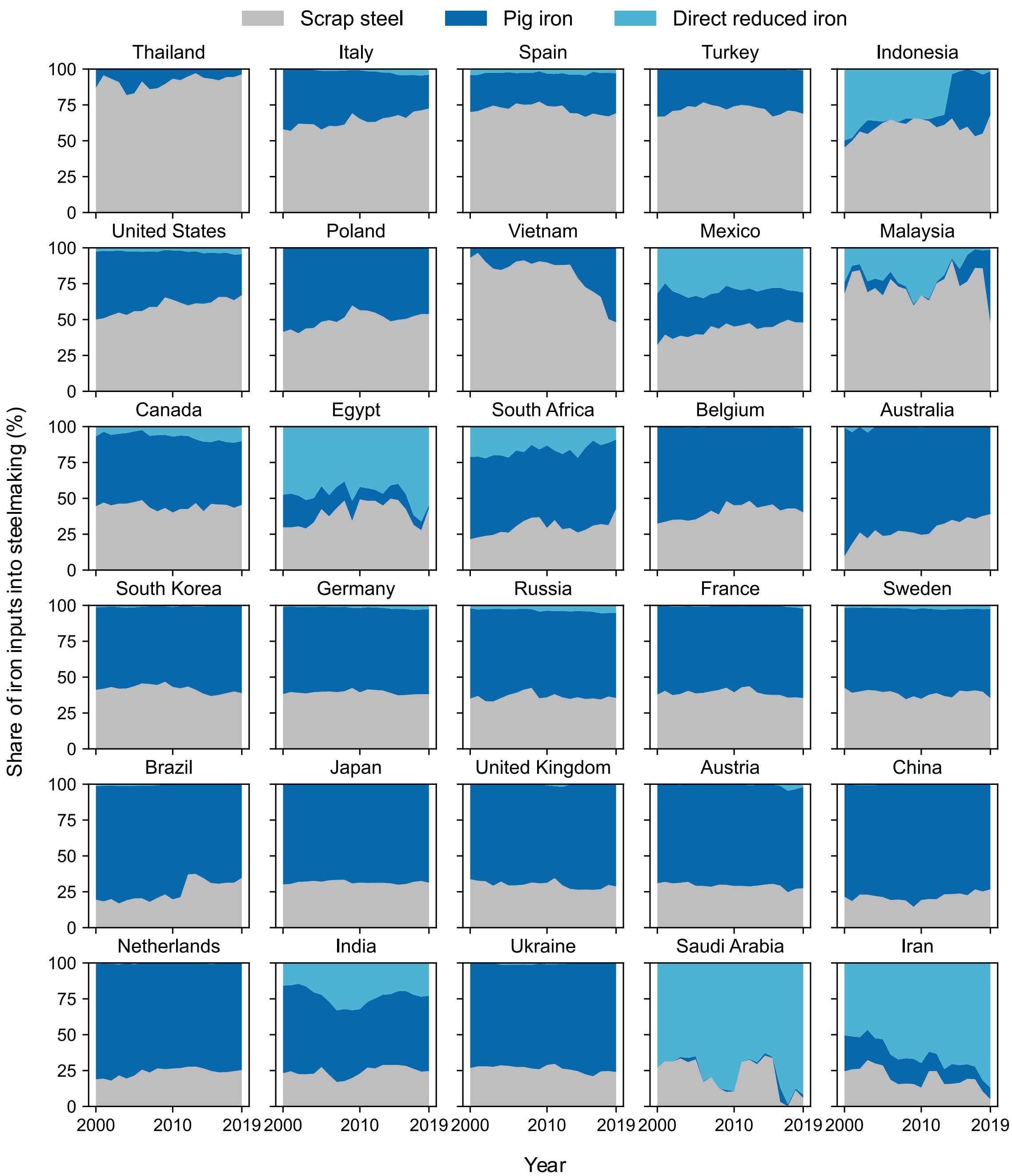


Fig. S12 Share of iron inputs into steelmaking for the world's top 30 crude steel-producing countries from 2000 to 2019.

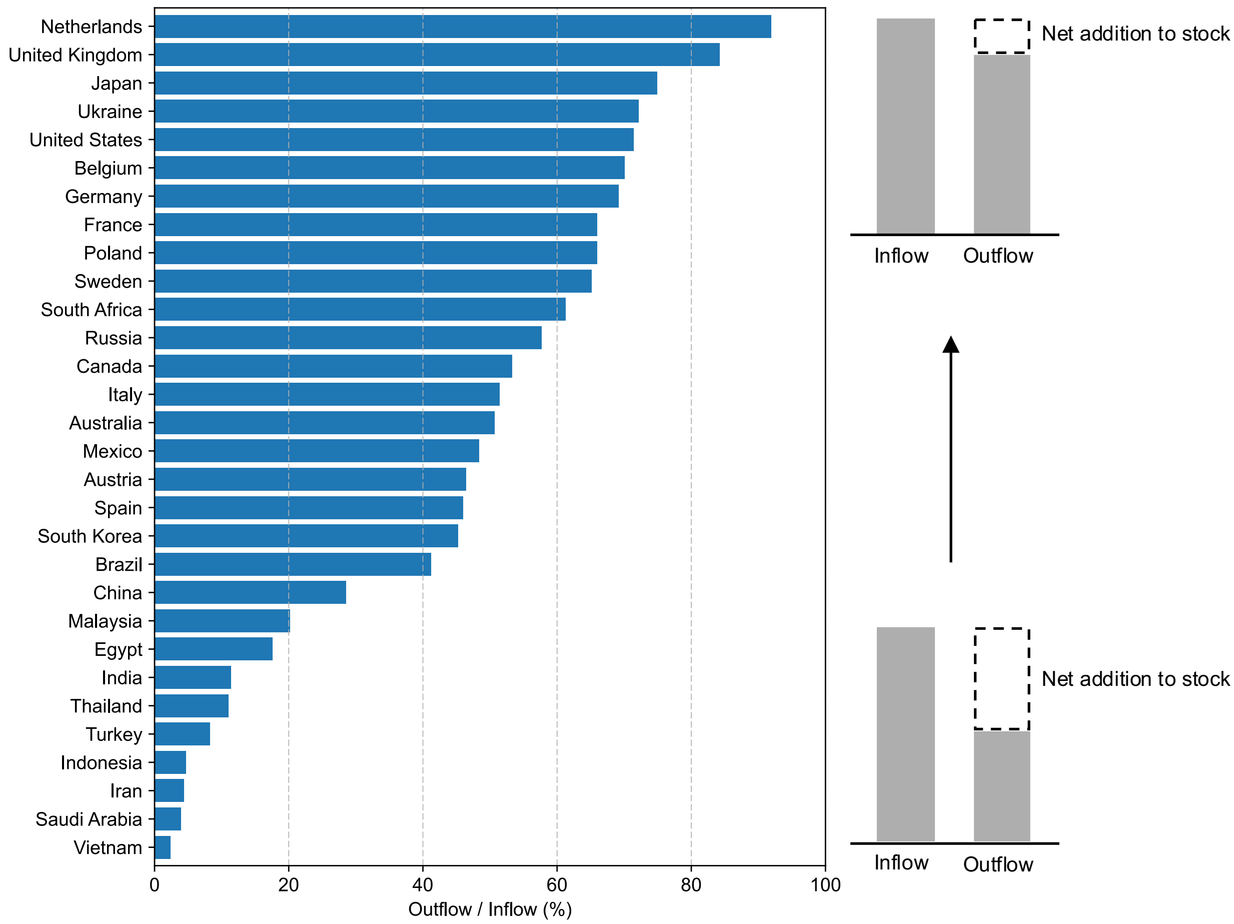


Fig. S13 The outflow-to-inflow ratio, indicating stock stabilization. Inflows are directly taken from the dataset, whereas outflows are approximated by multiplying the collected end-of-life scrap by the global end-of-life scrap recycling rate estimated in this study. For Saudi Arabia and Iran, where collected end-of-life scrap is estimated to be zero, we refer to the data in Ref. [29]. Note that the outflows are approximated without considering the hibernating behavior of material stocks [23]. Data refer to 2019.

Table S3 Patterns of iron and steel flows in the context of recycling practices. Pattern 1: High recycled content with abundant domestic scrap. Pattern 2: Low recycled content with limited domestic scrap. Pattern 3: High recycled content despite limited domestic scrap. Pattern 4: Low recycled content despite abundant domestic scrap. Note that each pattern is assigned relative characteristics. Data refer to 2019.

	Recycled content	Ranking	Pattern
Thailand	96%	1	3
Italy	72%	2	3
Spain	69%	3	3
Turkey	69%	4	3
Indonesia	68%	5	3
United States	67%	6	1
Poland	54%	7	1
Vietnam	48%	8	3
Mexico	48%	9	1
Malaysia	47%	10	3
Canada	46%	11	1
Egypt	43%	12	3
South Africa	43%	13	1
Belgium	40%	14	4
Australia	39%	15	4
South Korea	39%	16	4
Germany	38%	17	4
Russia	36%	18	4
France	35%	19	4
Sweden	35%	20	4
Brazil	35%	21	2
Japan	31%	22	4
United Kingdom	29%	23	4
Austria	27%	24	4
China	27%	25	2
Netherlands	25%	26	4
India	25%	27	2
Ukraine	24%	28	4
Saudi Arabia	6%	29	2
Iran	5%	30	2

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