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PAPER

Steel flows and stocks in the Global South highlight development gaps

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Abstract

Steel is a fundamental ingredient in infrastructure development worldwide, yet most countries in the Global South are overlooked as part of the 'rest of the world'. This study fills this gap by analyzing how steel is produced, traded, and accumulated in 16 countries across South America, Africa, and Asia. Despite their regional differences, all countries share key characteristics: limited domestic steelmaking and a persistent reliance on imports. On average, only about one-third of finished steel products (e.g. sheets) and one-fourth of steel embedded in end-use goods (e.g. cars) originate from domestically produced liquid steel. This trend is not limited to iron ore-poor countries. Even major iron ore exporters depend on imports for fabricated steel products, highlighting unequal participation in global value chains. We also find that half of these countries have not yet reached the minimum in-use steel stock required to support decent living standards, and none have exceeded the levels compatible with a well-below 2 °C carbon budget. This situation underscores both a need for further infrastructure development and an opportunity to do so within a finite global carbon budget, provided that fair budget allocation and international support are ensured. Our findings collectively indicate that advancing steel recycling and decarbonization in the Global South must be pursued as a shared global agenda, rather than left as something for these countries to solve alone.

1. Introduction

Over the past two decades, the global steel landscape has shifted rapidly from the Global North to the Global South. At the beginning of the 21st century, most steel was produced and used in a handful of industrialized countries including the United States, Japan, and Germany (Wang *et al* 2021). Today, the situation has completely changed, with emerging economies, led by China and India, producing and using the majority of steel (Vogl *et al* 2021). This shift has fundamentally altered the location of intervention hotspots, where greater attention is needed to advance steel recycling and decarbonization as part of broader efforts to remain within planetary boundaries (Schenker *et al* 2022).

However, much of the academic research focus has historically been on the Global North. Detailed analyzes of iron and steel flows have been undertaken for the United States (Zhu *et al* 2019), Japan (Daigo *et al* 2015), the United Kingdom (Serrenho *et al* 2016), and the European Union (Dworak and Fellner 2021). More recently, growing attention has been given to emerging economies, particularly China (Yang *et al* 2023) and the other BRICS countries (Bataille *et al* 2023). Yet, unlike these major players, most countries in the Global South remain classified under the broad and often-overlooked category of 'rest of the world'. Without a clear understanding of country-specific conditions, the unique challenges faced by Global South countries can be easily obscured by the dominant patterns of the Global North and large emerging economies (Wang *et al* 2022).

While some studies based on material flow analysis (MFA) do cover these countries in detail, the data tend to be limited to earlier periods (Wang *et al* 2007) or focus specifically on in-use stock (Pauliuk *et al* 2013). More recent studies have been increasingly covering Global South countries, but their focus has remained limited to a few major steel-producing countries, such as Indonesia (Wieland *et al* 2022, Gao *et al* 2025, Watari *et al* 2025). Economy-wide MFAs aim to capture nearly all countries (Wiedenhofer *et al* 2024), yet data for the Global South receive less attention due to their relatively smaller industrial activities. Recent studies have started addressing this imbalance by focusing specifically on the ASEAN countries (Emami *et al* 2024). Nevertheless, detailed insights into how steel is produced, traded, and accumulated across the Global South remain limited and are overshadowed by findings on bulkier materials, such as sand and gravel.

This study fills this gap by analyzing steel flows and stocks in 16 countries across South America, Africa, and Asia. These countries exemplify the mostly under-explored and often ignored countries of the Global South. By examining production structures, trade dependencies, and stock development, and assessing their idiosyncrasies and similarities, we aim to provide a better understanding of how these regions fit into the global steel system and what their positions mean for advancing steel recycling and decarbonization.

2. Methods

The country selection starts with the Steel Statistical Yearbook published by the World Steel Association (2024). Of the approximately 70 countries for which all key data points are available, we exclude those affiliated with the Global North (i.e. Europe, North America, and developed Asia and Oceania) and the BRICS countries (Brazil, Russia, India, China, South Africa, Egypt, Ethiopia, Indonesia, Iran, and United Arab Emirates), as they are already well represented in existing energy and material system models. The resulting dataset covers 16 countries: five in South America (Argentina, Chile, Colombia, Ecuador, and Peru), seven in Africa (Algeria, Angola, Ghana, Kenya, Morocco, Nigeria, and Tanzania), and four in Asia (Malaysia, the Philippines, Thailand, and Vietnam). Together, these countries account for >5% of global crude steel production, as well as having growing populations and economic activities (World Steel Association 2024). Although marginal at present, prior work suggests that these countries will be the primary drivers of future production growth (Bataille *et al* 2021).

Our analysis begins with mapping iron and steel flows across various product stages while accounting for international trade. The primary data source is the Steel Statistical Yearbook, with 2000–2019 selected as the target years. These data provide production and trade quantities for a range of iron and steel products (see table S1 in the supplementary information, SI). System parameters, such as process yields and iron contents, are sourced from the existing literature and used to define a set of mass balance equations (see tables S2 and S3 in the SI). These equations are subject to two fundamental constraints: (1) all mass flows must be non-negative, and (2) process yields must not exceed 100%. When data inconsistencies violate these conditions, a reconciliation algorithm is employed to resolve mass imbalances (see section 2 of the SI for details). While the latest edition of the Steel Statistical Yearbook available to the authors includes data up to 2022 for some variables, previous research has shown that more recent data are frequently subject to revision (Harvey 2022). To ensure consistency and data reliability, we limit our analysis to 2019, a year in which no major revision was observed in the latest report and for which a complete dataset is available across all key variables. This timeframe also avoids the COVID pandemic period, which may not reflect typical patterns.

The next step focuses on the use phase of steel products (i.e. in-use steel stock). Using an inflow-driven dynamic stock model (Wiedenhofer *et al* 2019), we estimate the historical evolution of in-use steel stock at the country level from 1900 to 2019, supplemented with data from Pauliuk *et al* (2013). This is a time-cohort-based method that calculates in-use steel stock as the sum of steel inflows embedded in surviving products each year (Müller *et al* 2014). Due to the limited availability of country-specific data on the lifetime of steel-containing end-use goods, we rely on estimates from previous studies to inform our assumptions. Specifically, we adopt the product lifetime distributions reported by Pauliuk *et al* (2013) and Cao *et al* (2017), which provide differentiated lifetime parameters across product categories and countries (see table S4 in the SI).

To contextualize the estimated in-use stocks, we compare them against two key benchmarks: (i) minimum stock requirements for decent living standards and (ii) feasible global stock within a carbon budget. This comparative analysis is inspired by the doughnut economy framework (Raworth 2017), which emphasizes the need to ensure human well-being while staying within planetary boundaries. In this context, all countries should ensure adequate infrastructure for decent living standards while staying within material stock levels compatible with ecological limits. The thresholds for minimum stock requirements are based on Fisch-Romito (2021) and Vélez-Henao and Pauliuk (2023). The former study takes a top-down approach, comparing steel stock levels with basic infrastructure access, whereas the latter study adopts a bottom-up approach, linking steel use to specific goods and services. According to these studies, achieving decent living standards requires a minimum of 2–3 tonnes of in-use steel stock per capita to support basic service provision (e.g. shelter, mobility, and sanitation). Carbon-budget compatible stock levels are derived from the model of Watari *et al* (2023), which simulates future global steel cycles under a Paris-compliant carbon budget. Specifically, we use the interquartile range of stock estimates associated with a carbon budget that corresponds to an 83% probability of staying below 2.0 °C, which is consistent with the 'well-below 2 °C' commitment of the Paris Agreement. According to this model, the global economy could accumulate up to ∼6 tonnes of in-use steel stock per capita within a finite carbon budget. Exceeding this level may constitute overaccumulation or excessive consumption (Pauliuk 2024).

To gain a nuanced understanding of how steel stocks relate to economic activity and social well-being across different national contexts, we investigate their relationships with gross domestic product (GDP) (The World Bank 2025) and the human development index (HDI) (UNDP 2024). Three regression models are tested: linear ($y = a + bx$), log-linear ($y = a + b\ln(x)$), and exponential ($y = ae^{bx}$). This approach disregards country- and year-specific effects, as our goal is to identify general patterns across the dataset rather than to explain variations between individual countries or time periods. The models are evaluated based on their goodness-of-fit and complexity using the Akaike information criterion (AIC):

$$\mathrm{AIC} = n\ln\left(\frac{\mathrm{RSS}}{n}\right) + 2k \tag{1}$$

where n is the number of observations, RSS is the residual sum of squares, and k is the number of model parameters. A lower AIC value indicates a better balance between model accuracy and complexity.

3. Results

3.1. Typologies of steel flow structures

Each country shows a distinct pattern of iron and steel flows, but certain commonalities are evident that allow for broad classification into three patterns (figure 1). The first pattern is characterized by significant iron ore extraction and exports, but limited domestic steelmaking capacity. This pattern includes Chile and Peru, both of which are major iron ore producers. These countries extract large quantities of iron ore but export nearly all of it without processing it for domestic steelmaking. As a result, they rely heavily on imports of finished steel products (e.g. sheets) and steel embedded in end-use goods (e.g. cars).

The second pattern comprises countries with minimal domestic iron ore extraction and ore-based steelmaking. These countries comprise Angola, Ecuador, Ghana, Kenya, Morocco, Nigeria, the Philippines, Tanzania, and Thailand, all of which act as pure recyclers. In these countries, the primary role of the domestic steel industry is to recycle scrap steel in electric arc furnaces to produce construction-grade long products (e.g. rebar). Due to limited domestic scrap availability, the majority of steel demand is met through imports of finished steel products and end-use goods.

The third pattern includes countries that operate integrated blast furnace–basic oxygen furnace (BF–BOF) systems and produce a wider range of steel products. This group consists of Algeria, Argentina, Colombia, Malaysia, and Vietnam, where BF–BOF systems are used to process both domestic and imported iron ore. However, their steelmaking capacity falls short of domestic steel demand, resulting in a reliance on imported fabricated products.

Overall, despite having some regional differences in steel flow patterns, all 16 countries share the same fundamental characteristics: limited domestic steelmaking and dependence on imports. Among these countries, only two iron-rich nations—Chile and Peru—were consistent net exporters of iron and steel products from 2000 to 2019 (figure 2). In contrast, all of the other countries were net importers over the same period. If iron ore trade is excluded, even Chile and Peru become net importers, highlighting the region's dependence on imported fabricated products.

3.2. Import dependency

The observed patterns of limited domestic steelmaking and persistent reliance on imports raise a simple question: to what extent are the steel needs of Global South countries met by domestic steelmaking? Quantifying this extent is not only relevant for understanding trade exposure, but also for quantifying the degree to which domestic producers actually have control over the recycling and emissions profile of their steel use.

Across all 16 countries, imports increasingly dominate the supply of steel products downstream in the value chain (figure 3). On average, about 72% of semi-finished steel products used in these countries originate from domestically produced liquid steel. However, this share drops to just 33% for finished steel products and further declines to 24% for steel embedded in end-use goods. Among the 16 countries, Argentina has the highest share of domestically produced steel in end-use goods, followed by Vietnam. Only

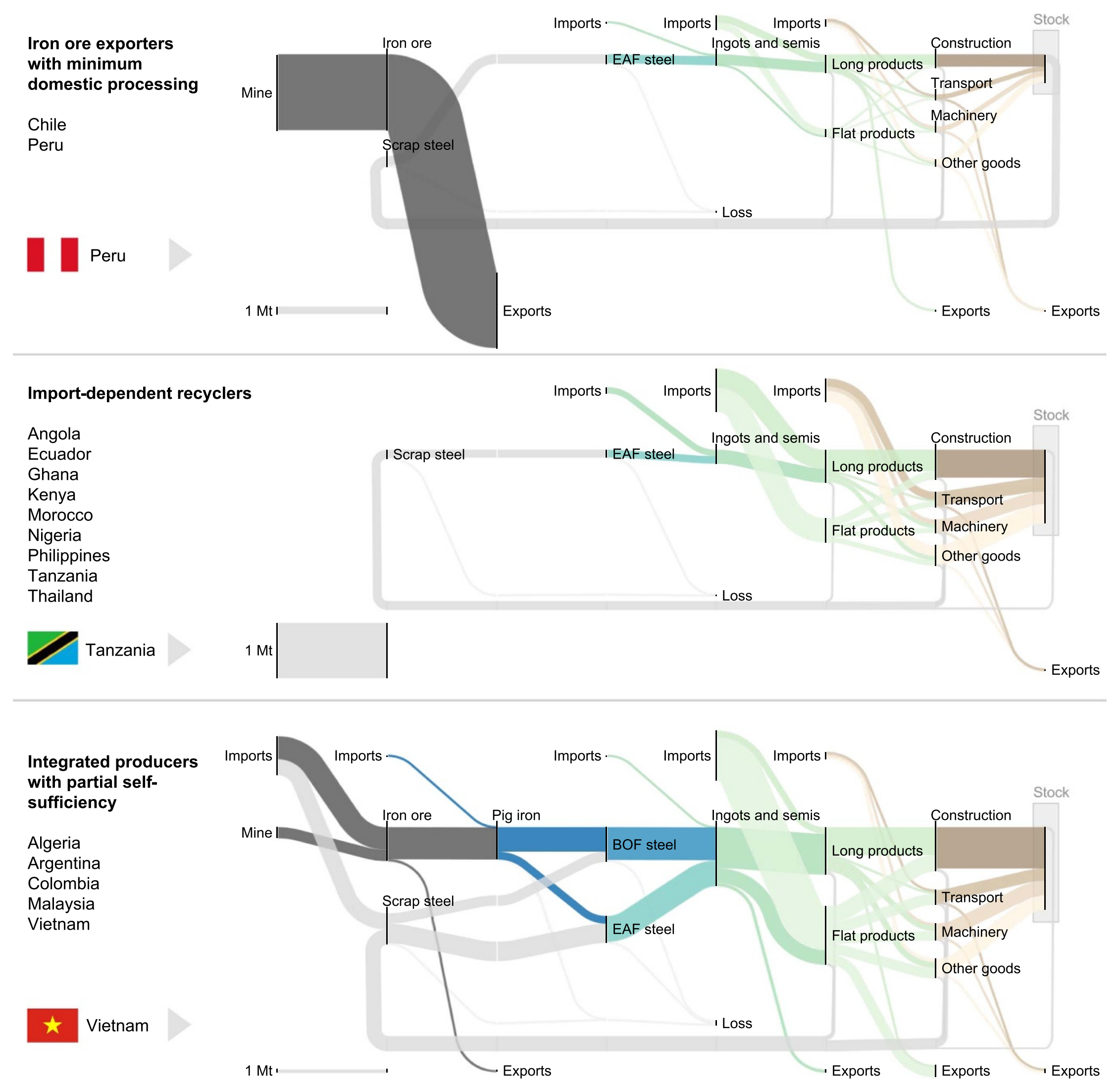

Figure 1. Typologies of iron and steel flows in 16 Global South countries for the year 2019. The figure illustrates three overarching patterns identified across the countries analyzed: 'Iron ore exporters with minimal domestic processing', 'Import-dependent recyclers', and 'Integrated producers with partial self-sufficiency'. These pattern labels were subjectively assigned by the authors to summarize the main characteristics of national steel flow structures. The figure was designed with floweaver (Lupton and Allwood 2017). The diagrams for all 16 countries can be found in the SI.

these two countries source more than 40% of the steel in their end-use goods from domestic production, while all others rely on imports for more than three-quarters of their needs.

One of the key factors influencing import dependency is the composition of domestic steel production. In general, lower levels of import dependency are associated with a greater reliance on ore-based steelmaking, rather than on domestic scrap recycling. Across all 16 countries, domestically produced scrap-based steel accounts for less than a third of steel embodied in end-use goods, with the remainder coming from ore-based steel or imports.

3.3. Stocks and human development

The limited role of domestic recycling in meeting steel demand in the Global South is closely linked to trends in stock development. All 16 countries are in a phase of stock expansion, meaning that much of their steel-containing end-use goods remain in use and are not yet available for recycling (figure 4). Half of these countries have not yet reached even the minimum steel stock required for decent living standards: they are still in the process of building basic infrastructure.

A previous analysis showed a strong correlation between per capita GDP and in-use steel stock in the Global North, where economic growth drives steel products accumulation, or vice versa (Müller *et al* 2011). Our analysis confirms a similar trend in the Global South but indicates a wide variation: while linear relationships are evident in the pooled dataset, national histories do not necessarily follow a single trend. This phenomenon has also been observed among several industrialized countries (Yang *et al* 2024), and is

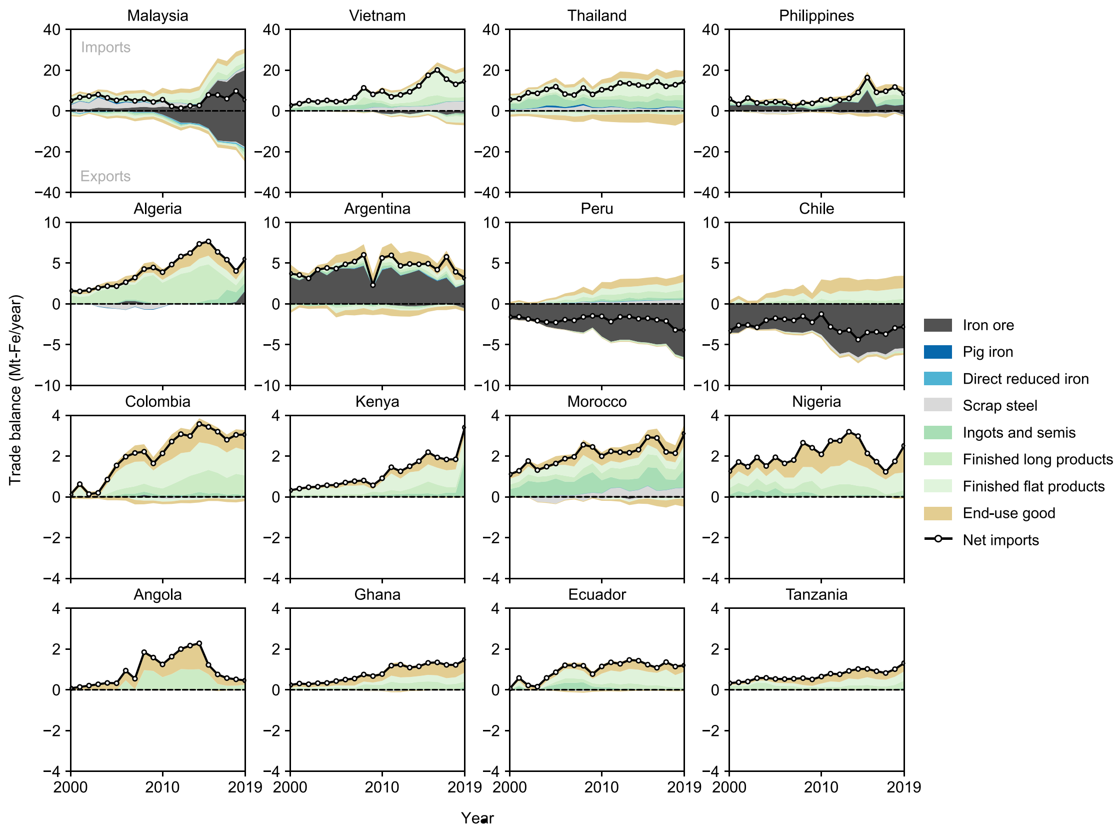

Figure 2. Trade balance of iron and steel products from 2000 to 2019. Imports are shown as positive values and exports as negative values. Note the varying vertical axes scales between rows.

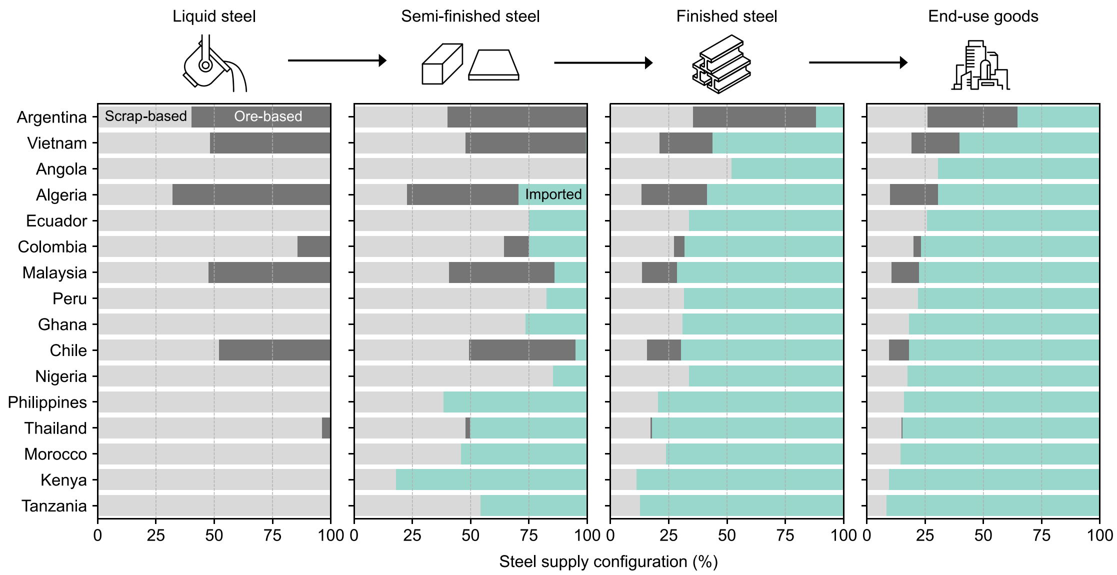

Figure 3. Supply configuration of liquid steel, semi-finished steel, finished steel, and steel embedded in end-use goods for the year 2019. The share of domestically produced liquid steel, whether scrap-based or ore-based, decreases along the supply chain due to international trade.

partly explained by the complex interplay of economic structures, urbanization patterns, and geographic conditions (Song *et al* 2020). Broadly, Latin American countries tend to have lower per capita steel stocks for any given value of affluence, whereas many Asian countries experience more rapid stock expansion at more modest economic activity levels. Meanwhile, African countries show more diverse trajectories, with some following patterns similar to those in Asia and others resembling those in South America. These varied relationships between per capita GDP and steel stock suggest that despite an overall stable linear relationship,

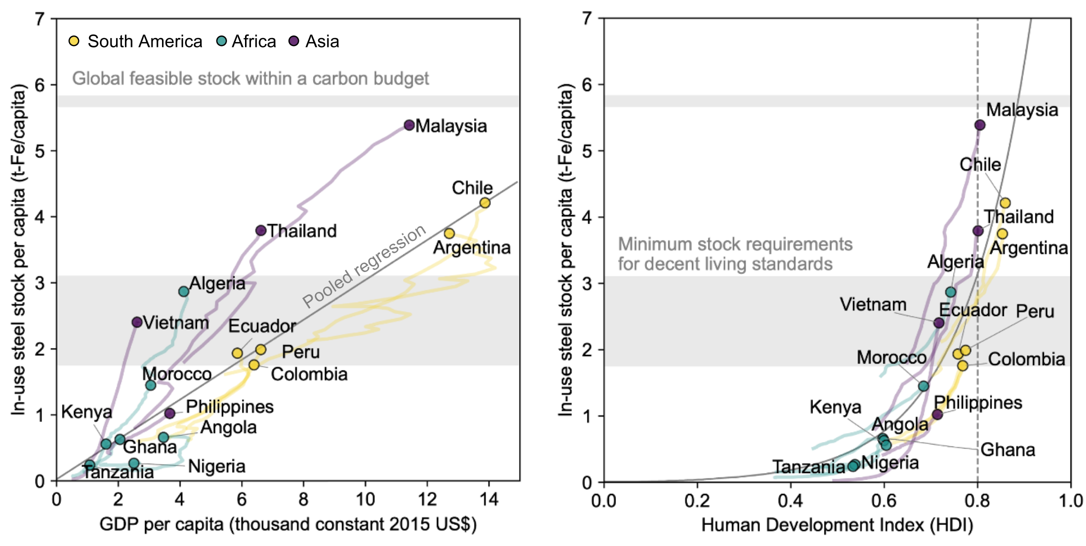

Figure 4. Per capita in-use steel stock development in relation to per capita GDP and HDI from 1990 to 2019. The best-fit regression functional forms (linear for GDP per capita and exponential for HDI) were determined using the AIC. The two shaded horizontal bands represent the minimum stock requirements for decent living standards and the feasible global stock levels within a carbon budget. The band widths reflect the ranges described in various studies (Fisch-Romito 2021, Vélez-Henao and Pauliuk 2023, Watari *et al*. 2023). The vertical dashed line at HDI = 0.8 marks the threshold for high human development (Pauliuk 2018).

GDP may not be a reliable predictor of future steel cycles in the Global South. Aggregated economic activities do not fully capture how steel is embedded in the built environment or how effectively it provides services (Tanikawa *et al* 2021).

The relationship between HDI and steel stock follows a different trend: as countries move towards high human development (HDI $\geqslant$ 0.8), per capita steel stock increases exponentially. This trend suggests that at lower HDI levels, modest increases in steel stocks are associated with significant improvements in human development, while at higher HDI levels, additional steel contributes less to further gains. This pattern aligns with previous findings by Cibulka and Giljum (2020) and Soytas and Sari (2025), showing that the relationship between material use and quality of life is non-linear. Our dataset, to some extent, also reinforces previous estimates of the minimum steel stock required for decent living standards. Namely, no country in the Global South has achieved the 0.8 HDI threshold with steel stock below the independently estimated minimum requirement (∼2–3 tonnes per capita) (Fisch-Romito 2021, Vélez-Henao and Pauliuk 2023). This indicates that below this threshold, basic infrastructure is likely to be inadequate.

Another key insight from this analysis is that none of the 16 Global South countries has yet exceeded the globally feasible stock level within a carbon budget (∼6 tonnes per capita) (Watari *et al* 2023). This means that if the remaining carbon budget were distributed equitably worldwide, there would still be room for infrastructure expansion in the Global South without necessarily breaching finite carbon budgets.

4. Discussion

4.1. Comparative advantage or ecologically unequal exchange?

Collectively, our analysis highlights persistent import dependency in the Global South, particularly on fabricated products, despite some countries exporting raw materials. This trade pattern raises important questions about the nature and equity of global value chains. From the perspective of classical trade theory, the reliance on importing fabricated products while exporting raw materials reflects the principle of *comparative advantage*, whereby countries specialize in producing what they can do most efficiently and import what is relatively less efficient to manufacture domestically (Costinot and Donaldson 2012). In theory, this maximizes the productivity of both the importing and exporting nations.

However, the structure of steel flows observed in our dataset also aligns with patterns emphasized in the theory of *ecologically unequal exchange* (Dorninger *et al* 2021), which argues that lower-income countries tend to be locked into resource extraction while importing high-value fabricated products. In this process, not only do they forego the economic benefits of value-added processing, but they also bear the environmental burdens associated with resource extraction (Hickel *et al* 2022).

Our analysis does not explicitly adjudicate between these theories, but it provides empirical evidence of asymmetries in value-chain participation. Chile and Peru, for instance, export significant amounts of iron ore, yet lack the domestic capacity to process it into steel. Similarly, all other countries in our study depend heavily on imports of higher-value fabricated products. These patterns may reflect not simply economic specialization, but also enduring structural disadvantages embedded in the global economy (Rammelt and Ylla-Catala 2025).

4.2. Structural barriers to steel recycling and decarbonization

Asymmetric trade patterns are not just theoretical or economic concerns. Together with stock development trends, they shape the physical conditions under which steel systems must evolve. Our analysis shows that all 16 countries analyzed in this study are still in a phase of stock expansion, meaning that scrap availability will remain limited for them in the coming decades. At the same time, half of these countries have not yet reached the minimum stock requirements for decent living standards, indicating a clear need for further infrastructure development. Thus, to ensure decent living standards, countries in the Global South face two choices: continued reliance on imports or expansion of domestic ore-based steelmaking. In the former case, the recycling and emissions profile of steel products will be dictated by exporting countries, primarily in the Global North and the BRICS group. In the latter case, investing in ore-based steelmaking naturally deteriorates the recycled content of domestically produced steel. Furthermore, adapting low-emission production technologies (e.g. hydrogen-based direct reduction) is likely to be financially and technically out of reach without significant external support (Fan and Friedmann 2021).

Therefore, whether steel is imported or domestically produced, advancing steel recycling and decarbonization in the Global South will ultimately depend on global partnerships and cooperation. While targeted cooperation mechanisms are gaining attention in international policy discussions (Åhman *et al* 2023), our analysis provides empirical evidence of the essential nature of such mechanisms. Without such support, many countries in the Global South will remain structurally constrained in their ability to advance steel recycling and decarbonization.

4.3. Unequal stock development in a finite carbon budget

Such a global agenda intersects with questions of climate equity, particularly in terms of how much material growth remains feasible within a finite global carbon budget. We show that none of the 16 countries in the Global South has yet exceeded the limits set by the carbon budget. In contrast, almost all countries in the Global North have already exceeded this threshold (Watari *et al* 2023). This disparity means that Global South countries still have room to expand steel stock without breaching carbon constraints, but their ability to do so depends on fair carbon budget allocations (Williges *et al* 2022). If Global North countries continue accumulating steel-intensive assets, they may restrict the Global South's capacity to develop essential infrastructure.

As such, the focus of the agenda in the Global North must involve mechanisms to prevent excessive material accumulation (Wiedmann *et al* 2020). Global South countries, meanwhile, need to prioritize materially efficient infrastructure development given the rapid stock growth underway. In this context, our findings resonate with the recent call for a progressive green industrial policy, which emphasizes the need for global justice and greater 'ecological policy space' for the Global South to pursue industrial development (Hauge and Hickel 2025).

4.4. From national averages to local realities

We acknowledge that our analysis has several limitations, most notably the reliance on highly aggregated national-level data. Such data do not capture within-country inequalities, city-scale dynamics, or facility-level variations. Clearly, national averages do not reflect local realities in many respects (Frantz *et al* 2023). Bridging this gap will require integrating more spatially detailed data, an area of research that is rapidly advancing. For instance, Haberl *et al* (2024) created a global map of material stocks in the built environment at a 90 m resolution. Xu *et al* (2023) compiled a dataset of thousands of steel facilities worldwide, detailing their locations, technologies, capacities, energy use, and GHG emissions. Building on such a dataset, Bataille *et al* (2024) produced facility-level scenarios to inform transition strategies. Meanwhile, Rankin and Saxe (2024) developed a bottom-up model to assess variations in housing and infrastructure construction and forecast neighborhood-scale embodied emissions. Integrating such datasets and models represents an exciting research opportunity in this domain. We call for further efforts to recalibrate existing energy and material system models to better reflect the specific geographical and economic contexts of the Global South and to assess development pathways tailored to these economies.

5. Conclusion

This study provides a cross-country assessment of steel flows and stocks in 16 Global South countries, which are often grouped among the 'rest of the world'. We show that despite having some regional differences, all countries share key characteristics: limited domestic steelmaking capacity and persistent reliance on imports, especially for fabricated products. This pattern may not simply reflect economic specialization, but rather also indicate enduring structural inequalities that are embedded in the global economy. We also find that many of these countries have not yet reached the minimum steel stock required to support decent living standards. At the same time, none have exceeded the steel stock levels compatible with a well-below 2 °C carbon budget. This unique position highlights both a need for further infrastructure development and an opportunity to do so within the remaining global carbon budget, provided the budget is distributed equitably. A series of findings indicates that advancing steel recycling and decarbonization in the Global South is not feasible through isolated national actions alone. Rather, it should be treated as a shared global task, not left as something for each country to solve alone.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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