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Scrap endowment and inequalities in global steel decarbonization

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ABSTRACT

Scrap steel recycling, powered by emission-free electricity, can produce nearly zero-emission steel at a lower cost than alternative primary production. However, the feasibility of this production method depends on future scrap availability. This study highlights the unequal distribution of future scrap availability worldwide, with the Global North having abundant scrap, while the Global South faces impending scarcity unless scrap is imported. By 2050, the European Union, North America, and developed Asia and Oceania could hold stocks of end-of-life scrap that are equal to their entire steel demand, if they chose to do so. China could also have domestic end-of-life scrap equivalent to about half of its cumulative demand. Conversely, developing countries, such as India and states in Africa, are expected to have severely limited domestic end-of-life scrap, representing less than 5% of their cumulative demand without international trade. This disparity, referred to as “scrap endowment”, is a consequence of the Global North’s historical carbon emissions. The scrap endowment enables the Global North to produce zero-emission steel at a relatively low cost, while the Global South grapples with limited, more costly options. These findings imply the need for equity-focused mechanisms to assist the Global South if both hemispheres are to achieve net-zero emissions by 2050, or soon thereafter.

1. Introduction

The global steel industry is facing a two-fold challenge – meeting the demands of a growing world population while also decarbonizing production processes within a limited timeframe (Wang et al., 2021). With global steel production accounting for approximately 10% of the world’s greenhouse gas emissions (Hertwich, 2021), the industry’s response to this challenge must be swift and comprehensive. While various options are being discussed, there is one solution that has gained widespread recognition and support from academic, industrial, and government quarters – recycling of scrap steel (Fan and Friedmann, 2021; Watari et al., 2021). By utilizing electric arc furnaces (EAF) for scrap recycling, the steel industry can produce almost zero-emission steel when operated with emission-free electricity and at a lower cost than alternative methods, such as blast furnaces with carbon capture utilization and storage (CCUS), hydrogen-based direct reduction, and molten oxide electrolysis (Mission Possible Partnership, 2022). According to the International Energy Agency (IEA), approximately half of the global steel production will need to come from scrap-based EAFs by 2050 in order to stay within a 1.5 °C carbon budget (IEA, 2021). The importance of scrap recycling is evident from the analysis of major crude steel-producing countries, including China (Wang et al., 2023), India (Dhar et al., 2020), Japan (Watari et al., 2023), the United States (Ryan et al., 2020), Germany (Harpprecht et al., 2022), and the United Kingdom (Serrenho et al., 2016).

However, there is an important perspective that has been largely overlooked: international inequality. The future availability of scrap-based EAFs essentially depends on the physical availability of scrap, which can vary widely from region to region. Several studies have shown that in-use steel stocks, or so-called urban mines, which can be recycled in the future tend to be concentrated in certain countries (Müller et al., 2011; Pauliuk et al., 2013b; Watari and Yokoi, 2021). The benefits of scrap recycling are therefore likely to be unevenly distributed globally, with some countries having abundant resources while others lack the necessary resources. Such inequality may create what can be referred to as a “scrap endowment” for certain countries.

The concept of an unequal scrap endowment pertains to the uneven distribution of scrap resources across different regions and countries, leading to certain countries having an advantage over others in the use of recycled steel. This can result in a disadvantage for some countries,

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which may not have opportunities to utilize the benefits of scrap recycling and decarbonization. However, the level of scrap endowment across the world is poorly understood due to fragmented data, hindering the proper discussion of the issue for the global agenda. While previous studies have highlighted regional disparities and inequalities in terms of the current CO_2 emissions performance of steel production (Rasul and Hertwich, 2023; Wang et al., 2022), they have not addressed inequalities in future scrap availability. Although quantitative data on future scrap availability exist (Oda et al., 2013; Pauliuk et al., 2013a; Xylia et al., 2018), there is a lack of information on the levels and trends in scrap endowment in different countries and regions.

This study aims to address this critical gap by providing a comprehensive overview of the levels and trends of scrap endowment across the globe. Our analysis first clarifies the historical inequalities and disparities in global steel use, relying on the most up-to-date data. Subsequently, we investigate the future dynamics of global steel use to calculate future scrap availability by analyzing data from approximately 170 countries. In doing so, this study establishes a crucial foundation for policymakers, civil society, and industrial leaders that will allow them to address this issue in a responsible and effective manner.

2. Methods

2.1. Model overview

To obtain a detailed understanding of the historical growth patterns of in-use steel stocks across the globe, dynamic material flow analysis was performed to trace the production, manufacturing, use, and disposal of materials in the global economy over an extended period of time (Müller et al., 2014). The primary data source used in this study was the Steel Statistics Yearbook published by the World Steel Association (World Steel Association, 2023). The Steel Statistics Yearbook reports steel demand contained in finished products, also known as inflows or true steel use, for about 70 countries through 2019. To compile country-level steel demand data through 2019, we supplemented the dataset from the Steel Statistics Yearbook with additional data from a previous study that was not included in the report (Pauliuk et al., 2013b). The in-use steel stock is then estimated using the lifetime model, assuming the average lifetime of steel-containing products (Müller, 2006). This is a time-cohort-type approach that derives the in-use steel stocks from the sum of the steel inflows embedded in surviving products each year (equations 1 and 2 in Supporting Information). Since the mean lifetime of steel-containing products (i.e., buildings, infrastructure, vehicles, machinery, and consumer goods) varies by region, we assume regionally different mean lifetimes of steel in use, which are expressed as a probability distribution function (see Supporting Information for more details).

The estimated historical stock data for approximately 70 countries provide the basis for exploring the current situation in the remaining approximately 100 countries and future global trends. As reported in previous studies (Hatayama et al., 2010; Müller et al., 2011), there is a strong correlation between per capita stock and GDP, and historical data suggest that stock growth tends to reach a plateau at about USD 20,000 per capita (Fig. 1a). Therefore, we employed curve fitting, assuming a logistic growth function, to estimate both the current in-use stocks for the approximately 100 remaining countries lacking steel demand data and the projected growth of global stocks (Yokoi et al., 2022) (equation 3 in Supporting Information).

In this case, our data demonstrate that countries or regions that industrialized later, such as China, India, and Africa, tend to have faster growth in the in-use stock than regions that industrialized earlier, such as the European Union and North America. Therefore, instead of assuming a growth curve common to all regions, we devise a growth curve for each region based on the following criteria (Fig. 1b): (1) The growth curves for the European Union, North America, and the developed regions in Asia and Oceania, where in-use stock per capita is already showing a saturation trend, are determined by fitting all parameters, including the per capita stock saturation level. (2) For other regions where the in-use stock is experiencing rapid growth, the growth curves are determined using a predetermined average saturation level that is equivalent to that in developed countries (i.e., approximately 12 t/capita).

Finally, future steel demands (i.e., inflows) are calculated using a simple mass balance of stock changes plus outflows (Pauliuk et al., 2013a). Population and GDP data are based on Shared Socioeconomic Pathway 2, which represents a middle-of-the-road scenario with moderate population and GDP growth (Fricko et al., 2017). We do not consider so-called hibernation or missing stock, which remains after it is no longer used or is left to mix with soil without being removed from a demolition site (Daigo et al., 2015). Our scrap availability estimates therefore consider the maximum end-of-life scrap that could theoretically be recovered.

3. Scenarios

Currently, steel is abundant and relatively affordable, leading to its wasteful use (Allwood and Cullen, 2012). However, several studies have shown that product designers, architects, urban planners, and manufacturers, as well as general consumers, have significant potential to use steel more efficiently (Milford et al., 2013; Pauliuk et al., 2021). Therefore, in addition to the baseline scenario, which represents a world in which steel products are used as inefficiently as in the past, we create a material efficiency scenario, which represents a world in which steel products are used more efficiently. Specifically, we assume that per capita stocks converge to approximately 7 tonnes instead of an average of approximately 12 tonnes, and that the average lifetime of steel

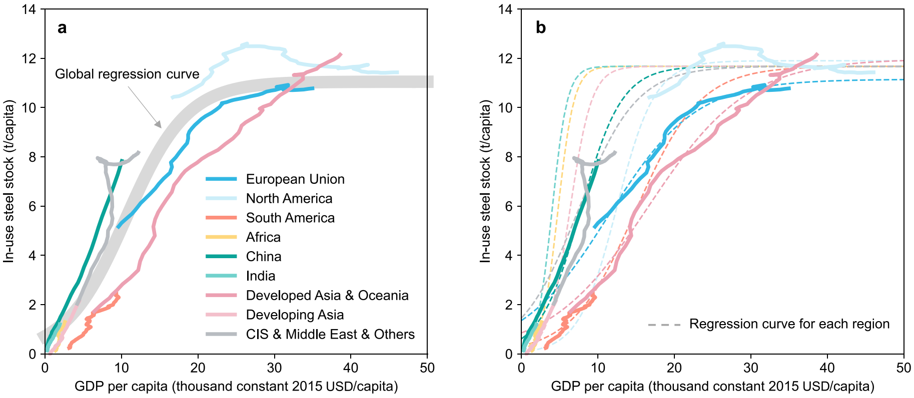

Fig. 1. In-use steel stock per capita in relation to GDP per capita (constant 2015 USD) 1960–2019, showing (a) regression analysis for all regions and (b) regression analysis for each region.

products is extended by 50%. Such a significant gain in service efficiency of in-use steel stock comes primarily from buildings and vehicles. Based on available evidence (Table S2 in Supporting Information), the in-use steel stock in the form of buildings and vehicles could provide the same level of service with approximately 60% less stock than that used today through reducing overdesign, downsizing, and promoting sharing. The potential for improving service efficiency for other uses is relatively small: approximately 30% for infrastructure, approximately 20% for machinery, and approximately 10% for consumer goods. This is a type of sensitivity analysis, which aims to assess the sensitivity of scrap availability to different future steel demands, rather than to assess the maximum potential of material efficiency.

We validate our assumptions in this domain by comparing our scenarios with the Low Energy Demand scenario of Grubler et al. (2018), which considers the most ambitious material efficiency, and the IEA's Sustainable Development scenario (IEA, 2020), which uses more conservative assumptions. Note that the future scenarios are shown as starting in 2021 because there may be a sharp spike or dip in the connection between our projections and historical data.

4. Results

4.1. Unequal global steel use

Historically, in-use steel stocks have been distributed unequally across the world, with significant disparities between the Global North and the Global South (Fig. 1). In 2019, the Global North, which includes areas such as the European Union, North America, and developed Asia and Oceania, has an average of 10–12 tonnes of steel stock per capita supporting daily life in the form of infrastructure and products. Conversely, in the Global South, which comprises Africa, South America, India, and developing Asia, the average is only 1–2 tonnes per capita. China's in-use steel stocks are approaching the levels of wealthier countries, with a remarkable five-fold increase in the past two decades resulting in in-use steel stocks reaching approximately 8 tonnes per capita in 2019.

The magnitude of this unequal distribution of steel use is best represented through a world map, with clear boundaries demarcating the Global North and Global South (Fig. 2). Almost all of the countries in Africa, South America, and developing Asia have lower in-use steel stocks per capita than their wealthier counterparts, reflecting the disparity in the use of steel in products and infrastructure worldwide. The Global North possesses valuable urban mines that can be recycled in the future, while the Global South has, historically, emitted relatively little carbon and has limited urban mines.

4.2. Significant growth in steel demand in the Global South

The current inequality in global steel use determines where significant demand growth will occur and, consequently, where emissions mitigation efforts should be focused. In a world where steel is used as inefficiently as it was in the past, global steel demand is projected to increase by about 50% by 2050 (Fig. 3a). The main drivers of this growth are Africa, South America, India, and developing Asia, which together will account for about 70% of total annual demand in 2050, up from about 20% currently. The generation of end-of-life scrap is estimated to double by 2050 to about 40% of annual demand. However, due to the long service life of steel products, end-of-life scrap generation from Africa, South America, India and developing Asia is expected to remain limited, at approximately 10% of their annual demand in 2050.

The situation remains the same if steel products are used more efficiently. Assuming that there is an increase in service efficiency of in-use steel stock and an extension in product lifetimes, global steel demand is projected to be halved from baseline levels by 2050, or about 70% of current levels (Fig. 3b). The estimated 2050 demand of about 1200 Mt/yr falls well within the range of about 530–1700 Mt/yr for the Low Energy Demand scenario of Grubler et al. (2018) and the IEA's Sustainable Development scenario (IEA, 2020). Given this significant reduction in demand, end-of-life scrap generation is projected to reach more than 70% of annual global demand by 2050. However, this is not the case in Africa, South America, India, and developing Asia, where significant demand growth persists, and the end-of-life scrap is projected to meet only about 20% of their annual demand by 2050.

4.3. Scrap endowment in the Global North

The scrap availability ratio, which can be expressed as the ratio of cumulative end-of-life scrap to cumulative demand through 2050, clearly shows the disparity between the Global North and the Global South (Fig. 4a). By 2050, the European Union, North America, and developed Asian and Oceania could theoretically hold enough end-of-life scrap to equal their entire steel demand, if they chose to do so. China could also have domestic end-of-life scrap for about half of its cumulative demand. However, in the absence of international trade, other developing countries would have extremely limited end-of-life scrap available to meet their demand. For South America and developing Asia, the scrap availability ratio is less than 30%, and for Africa and India, where demand is expected to rise more rapidly, the ratio is estimated to be less than 5%.

Such regional disparities are robust, irrespective of potential improvements in the efficiency of steel use (Fig. 4b). Indeed, assuming that steel-containing products are used efficiently, developed countries can

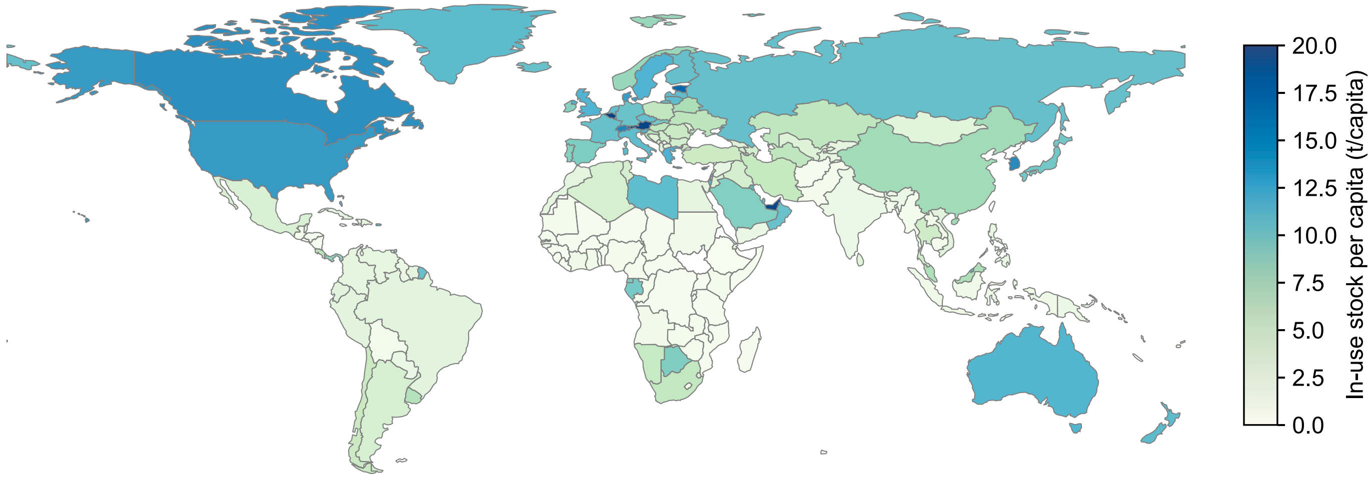

Fig. 2. Global distribution of in-use steel stock per capita in 2019.

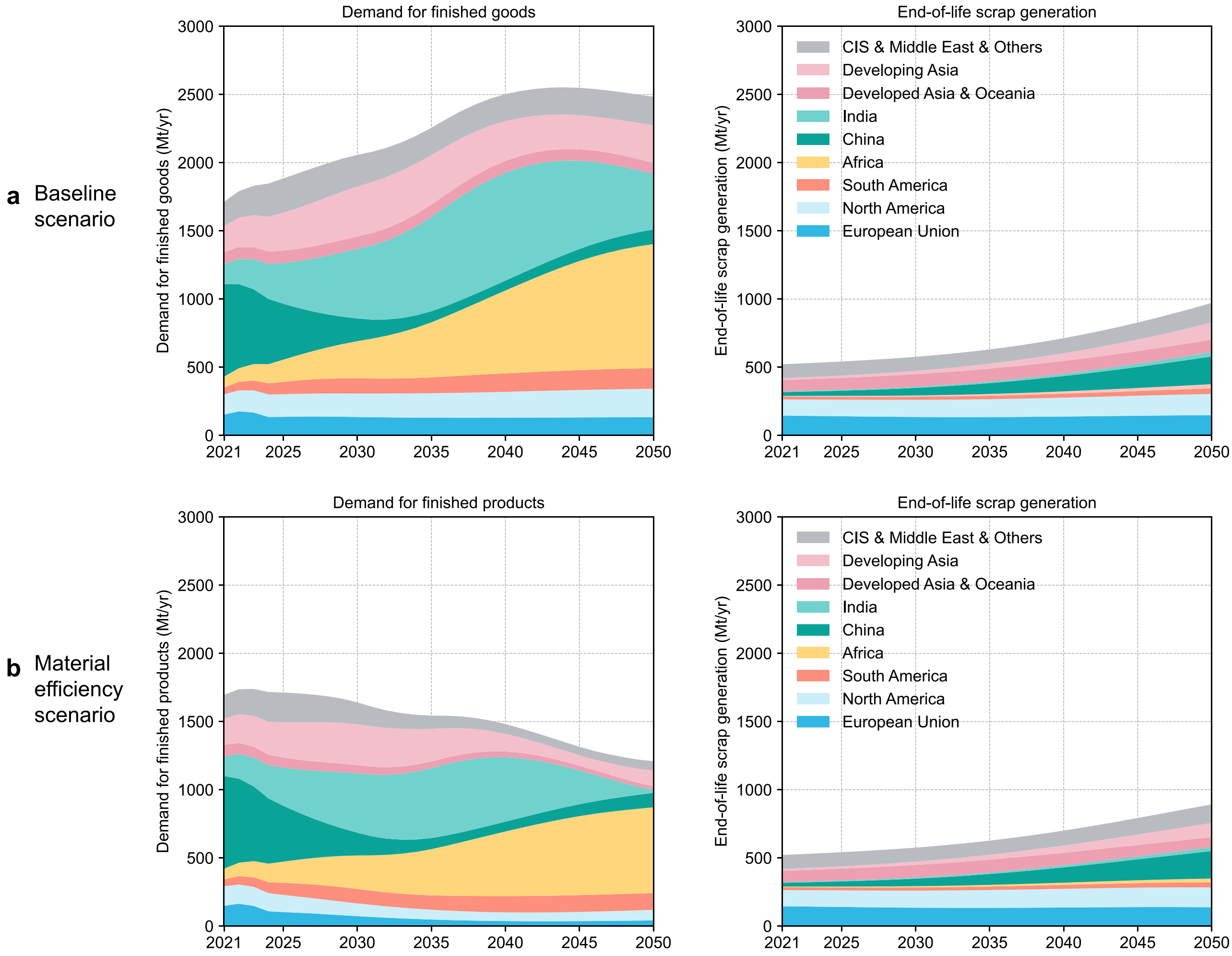

Fig. 3. Global steel demand and scrap generation through 2050, showing (a) baseline scenario and (b) material efficiency scenario.

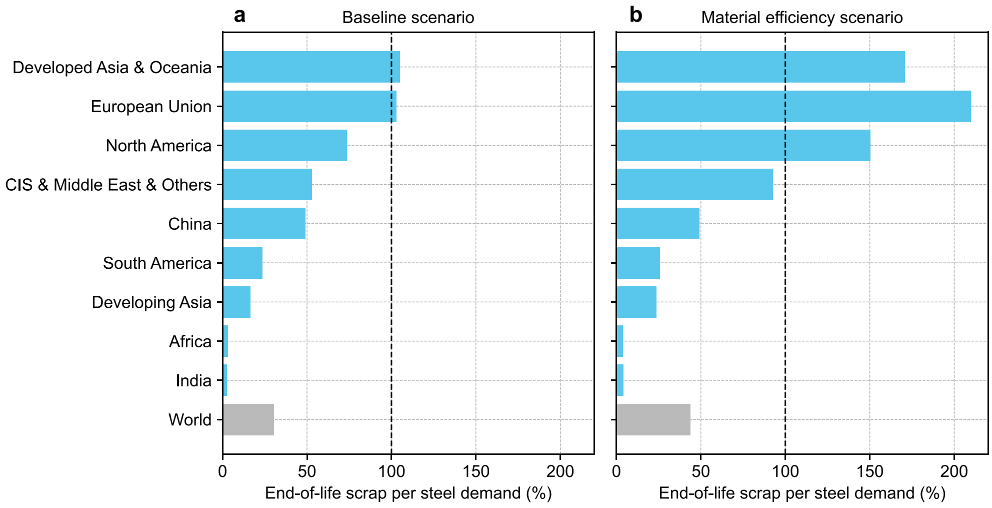

Fig. 4. Scrap availability ratio derived from end-of-life scrap generation relative to cumulative demand from 2021 to 2050, showing (a) baseline scenario and (b) material efficiency scenario. In panel (b), the generation of end-of-life scrap significantly exceeds the demand for steel in some regions, implying a decline in in-use steel stock. We assume that per capita stocks converge to approximately 7 tonnes instead of the observed average of approximately 12 tonnes, mainly due to the increased service efficiency of steel stocks in the form of buildings and vehicles (Table S2 in the Supporting Information).

cumulatively generate surplus end-of-life scrap. However, scrap availability in developing countries remains relatively limited. Clearly, estimates of future steel demand and scrap generation are subject to uncertainty, but what this sensitivity analysis confirms is that the regional disparities in future scrap availability are valid, irrespective of future demand growth trends. This is because most of the end-of-life scrap generated by 2050 will come from steel already in use today. This observation indicates that present disparities in global steel use are likely to shape future availability of scrap resources, conferring advantages to countries in the Global North.

Importantly, the presence of end-of-life scrap equivalent to the total steel demand does not necessarily imply that such demand can be fulfilled exclusively through the utilization of end-of-life scrap alone. Scrap recovery and processing almost always result in some degree of mass loss (Pauliuk et al., 2017). Furthermore, converting end-of-life scrap into steel requires dilution of impurities, especially copper (Daehn et al., 2017), and adjustment of the concentration of alloying additives, which in turn requires a certain amount of virgin material, including pig iron, directly reduced iron, or relatively “clean” scrap (e.g., forming and fabrication scrap) (Harvey, 2021). Therefore, the estimated end-of-life scrap availability does not necessarily correspond to the scrap-based steel supply on a one-to-one basis. What the analysis shows is the relative scale of the unprocessed resources that can be recovered and recycled compared to the steel demand – the higher the scrap availability ratio, the greater the potential for meeting demand with scrap that is properly processed.

5. Discussion

The evidence for scrap endowment is clear. Our analysis showed that developed countries can hold abundant scrap, if they choose to do so. However, without international trade, developing countries lack the necessary scrap to meet their future demand. This unequal distribution in future scrap availability poses challenges to achieving a just transition to a decarbonized global steel industry, as it constrains the range of viable options. While various methods for near-zero emissions steel production are available, their associated levelized costs differ substantially (Fig. 5). The levelized cost of iron ore-based steel production (e.g., blast furnace with CCUS, direct reduction with green hydrogen, and iron oxide electrolysis) is approximately twice that of scrap-based production. This implies that countries in the Global North, with its substantial scrap endowments derived from significant historical carbon emissions (Fanning and Hickel, 2023), possess the capability to produce zero-emission steel at a relatively low cost. Conversely, in the absence of such endowments, countries in the Global South would not have this option without international trade. As a result, countries without scrap endowments would be forced to produce zero-emission steel at a higher cost, depending on the trade market. The difference in future scrap availability could therefore pose a moral issue, as the Global South is still developing its infrastructure, and this phase of development is inherently more energy- and carbon-intensive than later phases of development. If the Global South were to decarbonize at the same time as the Global North, this would place a greater burden on the Global South.

To mitigate this potential challenge, we propose that strategic initiatives be developed that focus on the responsible sourcing of scrap steel and the establishment of robust international trading frameworks. The transfer of scrap from the Global North to the Global South remains a subject of considerable debate, encompassing a spectrum of advantages and disadvantages (Liu et al., 2018). On the one hand, exporting scrap can provide the Global South with access to valuable resources that it may not have locally. These resources could be used to support the development of manufacturing industries in the Global South. On the other hand, there are concerns about the environmental and social impacts of exporting scrap, including pollution, hazardous waste, and worker exploitation. To ensure that the export of scrap steel from the Global North to the Global South is undertaken in a responsible and equitable manner, we propose that the following factors need to be considered.

First, regarding quality standards, regulatory measures should be implemented to ensure that exported scrap steel satisfies requisite criteria for contamination and hazardous substances. Additionally, the processing methods employed should be designed to mitigate negative impacts on workers and the environment. Second, regarding fair trade practices, the export of scrap steel should be undertaken in a way that is fair and transparent, with appropriate pricing and compensation for all parties involved. Third, regarding technology transfer, international organizations and developed countries should support developing countries in building their recycling infrastructure through technical assistance and capacity-building initiatives.

The framework of mineral resource governance has potentially much to teach us in this domain. Mineral resource governance refers to the management and regulation of mineral resources by governments or other governing bodies (IRP, 2019). It involves licensing, permitting, fiscal policy, impact assessments, transparency, and accountability to ensure that resources are exploited in a sustainable and responsible manner. Although this framework is increasingly being implemented in

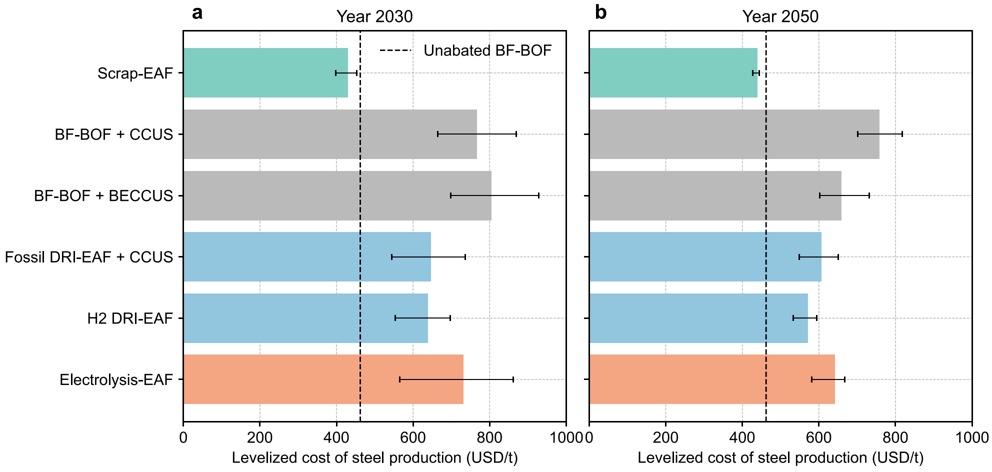

Fig. 5. Levelized cost of zero-emission steel production, showing (a) year 2030 and (b) year 2050. Error bars indicate the range of country-level figures for each technology, with the low and high ends representing costs in the most and least favorable locations, respectively. Data adopted from the Mission Possible Partnership (2022). EAF: Electric arc furnace, BF: Blast furnace, BOF: Basic oxygen furnace, BECCUS: Bioenergy with carbon capture and storage or utilization, CCUS: Carbon capture and storage or utilization, DRI: Direct reduced iron.

an industrial context, its main focus is on extractive industries (Ali et al., 2017). Our analysis suggests that effective resource governance will also be required for scrap steel recycling in order to ensure that the transition to a decarbonized global steel industry is fair and just. Integrating the concept of scrap endowment into the ongoing debate on resource governance could be an effective way to achieve these aims.

At a more practical level, there are several potential measures that can be adopted to address equity concerns in the context of scrap endowment. One approach is to explore the concept of Official Development Assistance (ODA) that includes zero-emission resources (e.g., recycled steel, green hydrogen-based steel, or high-quality scrap) for development in the Global South (Iacobuţă et al., 2022). Instead of providing development assistance in the form of money or foreign aid, donor countries could establish a quota of zero-emission resources as part of their ODA commitments. Such an approach would facilitate equitable access to zero-emission resources and help recipient countries leapfrog traditional carbon-intensive infrastructure development.

Another possible mechanism to address equity concerns is the establishment of a 'climate club' that brings together donor countries providing zero-emission resources, and recipient countries committed to sustainable infrastructure development. This climate club would foster inclusive membership, facilitate technology and knowledge sharing, and facilitate collective advocacy (Hermwille et al., 2022). Given the global nature of the steel industry, with its complex supply chains and diverse stakeholders, such a climate club could play a crucial role in promoting equitable access to zero-emission resources through collective action.

Overall, the key message of this study is the importance of recognizing the unequal scrap endowment when formulating decarbonization and circular economy strategies for the global steel industry. There is growing recognition of the need to consider regional disparities and inequalities in decarbonization strategies, particularly in terms of the current emissions performance of steel production (Wang et al., 2022). There is also an argument supporting the deployment of hydrogen-based technology and CCUS in the steel industry through instruments such as financial support, technology transfer, and climate clubs, with a focus on the Global South (Sovacool et al., 2023). We endorse these perspectives as they emphasize the significance of scrap endowment. The scrap endowment in the Global North, identified in this study, underscores the importance of equity-focused discussions and instruments. Current circular economy strategies often focus too much on the economic benefits and resource security of individual countries, particularly those in the Global North, by keeping as much waste as possible at home (Barrie et al., 2022; Kirchherr et al., 2017). We challenge this practice and argue for the need to place equity concerns at the heart of industrial decarbonization and circular economy strategies at a global scale.

Interestingly, Devlin et al. (2023) highlighted the potential energy and cost advantages for specific countries, including those in the Global South, in green hydrogen-based iron and steel production. This perspective raises intriguing questions: Where, how and to what extent should iron and steel be produced and utilized given the unequal distribution of various resources, including iron ore, scrap, energy, human resources, and technology? Is there an optimal and equitable supply configuration? Can modern societies, confronted with significant geopolitical risks, accept such an optimal and equitable supply configuration? We call for further research to address these questions, with an emphasis on equity.

CRediT authorship contribution statement

Takuma Watari: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Damien Giurco:** Conceptualization, Writing – review & editing. **Jonathan Cullen:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139041.

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