Renewable and Sustainable Energy Reviews 161 (2022) 112367

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Regional disparities in steel production and restrictions to progress on global decarbonization: A cross-national analysis

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ARTICLE INFO

Keywords:
Steel production
Carbon neutrality
Energy efficiency
Carbon-intensive
Diffcult to decarbonize sector
Regional disparity

ABSTRACT

Steel production is one of few “difficult-to-decarbonize” sectors that requires strong decarbonization actions. However, the present focus is mainly limited to technical efforts, while regional disparities in steel production and its impacts on energy and carbon efficiency are rarely explored. By integrating environmental extended input-output analysis and material flow analysis, this study, as one of the first attempts, provides an analytical perspective to explore the regional emission performance of steel production across 44 countries and the rest 5 regions from 2000 to 2015, in which the physical indicators such as CO_2 emission, energy use, and carbon intensity are compared. The results show that the CO_2 emission associated with global steel production has increased by 2.5-fold from 2000 to 2015, and the global steel production has only increased by 1.9-fold, indicating a worsening environmental performance with emission intensity increasing from 2.1 tCO_2/t in 2000 to 2.8 tCO_2/t in 2015. This is closely linked to the historical changes in the geographical distribution of steel production as well as the faster increase of steel production in less efficient regions compared to that of more efficient regions. Despite the efficiency improvement in several nations, the carbon intensity of both developed (OECD, from 1.6 t CO_2/t to 2.3 t CO2/t) and developing nations (non-OECD: 2.7 t CO_2/t to 3.0 t CO_2/t) were increasing during the past decade. Thus, there is a need to incorporate regional disparities and inequalities in the designingglobal decarbonization strategies of steel and other heavy industrial sectors.

1. Introduction

Steel is one of the most fundamental metals to underpin nearly every phase of our daily lives [1]. With various properties at an affordable price, steel plays a central role in meeting our basic needs such as shelter, mobility, energy, the delivery of water and food [2]. Thus, such interlinkage makes it essential in tracking global challenges such as climate change, poverty, population growth, water distribution, and low-carbon energy generation [3]. Global steel demand is expected to keep rising over this century, mainly driven by developing nations in Africa, Asia, and South America given the strong need to improve their living standards and lift populations out of poverty [4,5]. However, there is a large regional disparity in steel production across different nations and regions worldwide. Under this ongoing regional shift of steel production, it will be critical to explore such regional disparities and their impacts on the sustainable performance of the global steel industry.

In particular, meeting the greenhouse gas (GHG) emission target is one of the most pressing challenges faced by the global steel industry [6–8] as steel production is inherently energy- and carbon-intensive [9,

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https://doi.org/10.1016/j.rser.2022.112367
Received 19 November 2021; Received in revised form 24 February 2022; Accepted 6 March 2022
Available online 15 March 2022

10]. At present, the global steel industry is the biggest industrial GHG emitter, accounting for around 7% of anthropogenic CO_2 emissions globally [11]. In particular, steel production is identified by one recent study [12] as one of few "difficult-to-decarbonize" sectors where substantial effort must be made on its deep decarbonization. At present, the corresponding measures for the steel industry tend to focus on improving energy efficiency [13–15], the implementation of less carbon-intensive or carbon capture technologies [16,17], and improving resource efficiency associated with its production and consumption [18,19]. However, the progress of those strategies and their effectiveness related to the energy and emission performance of global steel production remains unclear. Indeed, monitoring the carbon emission, energy use, and process efficiency change of steel industries has played an important role in informing further mitigation strategies. Compared to economic indicators, physical efficiency indicators such as energy efficiency or carbon intensity have been found to be more useful and comparable to measure such progress in steel production [20,21].

Various studies have explored the efficiency indicators and their future trends of the global steel industry to inform mitigation strategies. From a global perspective, Hidalgo et al. [22] proposed an Iron and Steel Industry Model (ISIM) to predict the development of the steel industry and its related energy consumption, CO_2 emission, and technology innovation trend until 2030. Milford et al. [6] applied a stock-driven model with different technology options to explore the role of energy efficiency improvement and material efficiency in achieving designed 2050's climate targets. Afterward, Morfeldt et al. [23] integrated the scrap availability into a global energy system model to simulate the feasible technology options and steel flow trends under global climate targets from 2000 to 2100, while Ruijven et al. [24] also applied a global energy model for such projections. Similar approaches have also been used for regional-specific studies [25–28]. However, those studies adopt a high-resolution analysis of the efficiency of different processing technologies while their regional disparities have rarely been considered.

In particular, previous work has already informed there were large disparities in the environmental performance of steel industries across different nations [29,30]. Given that future steel production will occur at a larger geographical scale [31], international comparison and benchmark are critical to clarifying the opportunities and challenges for deep carbonization of steel production. One of the earliest studies is Langley et al. [32] who measured the energy efficiency of steel production in the United Kingdom. Moreover, such analysis has been performed for steel industries in China [33], Poland [34], Thailand [35], India [36], United States [37], Europe [38,39], etc. However, the results from those studies are not comparable as they differed in the system and temporal boundaries, energy/technical mix, greenhouse gas accounting scopes, and accounting methods. Thus, Hasanbeigi et al. [40] with colleagues from Lawrence Berkeley National Laboratory clarifies the boundary setup and methodology preparation in an international comparison with various casa studies for China, Germany, Mexico, and the United States [41,42]. Those previous studies provide a solid foundation to explore the disparities of energy efficiency among different nations, but such process-based analysis requires great efforts in data collection and technical analysis. At present, the comparison of carbon intensity and emission of each region on a global scale has been poorly addressed. In particular, recent studies have revealed a significant amount of indirect emissions and their importance in achieving climate targets for the industrial sector [43,44]. Nevertheless, those indirect emissions from steel production have not been properly reported in previous studies, which has misled technical practice in Brazil's steel production [45].

In our previous study [46], the progress of energy and emission efficiency of steel production have been measured at the global level, indicating its decarbonization progress at the global scale has largely stagnated. However, the detailed analysis of regional progress with comparable indicators is limited by data availability. Here, as one of the first attempts, this study aims to provide such an analysis of the emission performance of steel production across 44 countries and 5 rest-of-world regions from 2000 to 2015, which were measured and compared by physical indicators such as CO_2 emission, energy use, and carbon intensity. The direct and indirect carbon emissions and energy use of the steel industry are estimated by the input-output analysis (IOA) approach with a resolution on two major steel production routes [47], while intensity and efficiency indicators are quantified based on steel production flows. The details of our method are described in Section 2. Section 3 will provide our results regarding regional emissions in steel production and its' disparities, and explore the influential factors on emission changes. Finally, the discussions and conclusions of our work will be presented in Sections 4 and 5.

2. Method and material

2.1. Accounting framework

This study follows the following framework (as shown in Fig. 1) for the quantification and decomposition of physical efficiency indicators (e.g., energy intensity or carbon intensity) of steel production. This study divides the entire world into 44 nations and the rest 5 regions (details can be found in Section S2 in the Supporting information) as the geographic system boundary, and the temporal boundary is set to be 2000 to 2015 due to the input-output data constraints.

As shown in Fig. 1, there are four major steps for this purpose: (a) the total CO_2 emission and energy use of national and regional steel production is quantified through the environmental extended input-output analysis (EIOA) approach, the details of which will be given in Section 2.2; (b) the material flow analysis is applied to trace the steel flows (mainly the ore, scrap, process ratio, and liquid steel flows) associated with steel production in each studied region, the data of which can be directly obtained from world steel yearbook; (c) the energy and emission intensity of steel production can be then obtained by combining the total energy and emission trend from step (a) and production flow from step (b), and the sectoral energy intensity and carbon intensity refer to energy use (GJ) and CO2 emissions per tonne of crude steel produced, which is measured based on the same approach in Ref. [37]; (d) the final step is to explore the key drivers behind the change of total CO2 emission of steel production in each studied region and nations, which will be further explained in Section 2.3.

As for the material flow analysis, we trace the steel flows (measured in steel content) from cradle to gate of steel production, in which the ore flow, scrap flow, ironmaking production flows, and steelmaking flows are quantified. In particular, steel can be produced through two major production routes [48]: the ore-based primary route and the scrap-based secondary route. The primary route, known as the integrated steelmaking route, relies on the use of iron ore and coal for the ironmaking in the blast furnace (BF) and steelmaking in the basic oxygen furnace (BOF). The present steel production is dominated by the primary route with a share of 73% in 2017 [49]. By contrast, the secondary route relies on the use of recycled steel scrap and electricity for the steelmaking in the electric arc furnace (EAF). Notably, these two main routes differ significantly in energy use, carbon emission, and other sustainable performance [26,50]. The secondary route was much environmentally friendlier but limited to available steel scrap generation from societal in-use products [31]. Accordingly, these two routes are further distinguished in our analysis in two separated industrial sectors.

The CO_2 emission of steel production is traced according to the statistical definition of the iron and steel production sector [51], which is not limited to those process-based production activities in previous studies [37,42] but includes all activities involved in steel production. Both the direct and indirect carbon emissions associated with steel production are quantified in this study. The total carbon emission is distinguished into three scopes (i.e., scope 1–3) [52]: Scope 1 accounts for the direct emissions produced by the sources owned or controlled by the emitter. Scope 2 accounts for the indirect greenhouse gas emissions

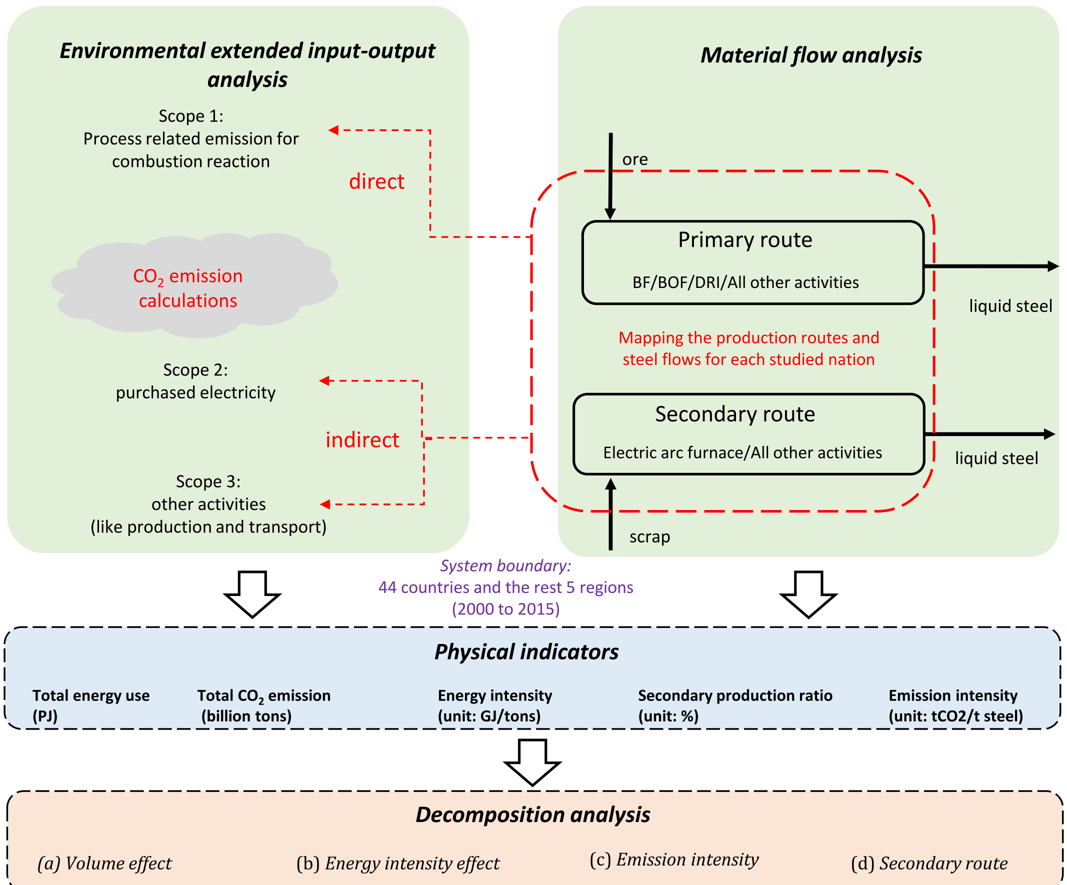

Fig. 1. Accounting framework to quantify the steel production's energy and emission performance.

from the generation of purchased electricity by the emitter, while scope 3 includes all other indirect emissions from activities of the emitter occurring from sources that they do not own or control. Notably, this study only considers the CO_2 emission associated with steel production in our greenhouse gas estimation, while other types of GHG are not included. Notably, the regional coverage of material flow analysis and environmental extended input-output analysis has some mismatches, and we try to harmonize those two according to the above-mentioned geographic boundaries of 44 nations and the rest 5 regions. This uniform boundary can facilitate a relatively fair comparison of the performance of steel industries in different nations.

2.2. Energy use and carbon emission quantification

As introduced in Ref. [53], the primary production of steel is captured by the sector of "manufacture of basic iron and steel and of ferro-alloys group" which includes activities such as direct reduction of iron ore, production of pig iron, conversion of pig iron into steel, manufacture of ferroalloys and manufacture of steel products, while the secondary production of steel is captured by the sector of "reprocessing of secondary steel" which includes the production of secondary steel through the EAF method to create new steel products.

Then, the total (direct and indirect) carbon emissions associated with the primary and second steel production are quantized by Environmental Input-Output Analysis, widely accepted and employed to illustrate the total environmental repercussions triggered by production activities. First, the monetary balance relation in an input-output system (Suppose there are m regions and each region has n sectors) by

$$\mathrm{X} = \mathrm{AX} + \mathrm{Y} \tag{1}$$

where X $= [x_j^s]_{mn\times1}$, x_i^r is the total economic output of sector s in region j; The technical coefficient matrix A $= [a_{ij}^{rs}]_{mn\times mn}$ is given by $a_{ij}^{rs} = Z_{ij}^{rs}/x_j^s$, in which Z_{ij}^{rs} is the inter-sector monetary flow from sector i in region r to sector j in region s; Y $= [y_i^{rs}]_{mn\times1}$, y_i^{rs} is the final demand of region s for goods or services of sector i from region r.

Then transforming equation (1) to

$$\mathrm{X} = (I - A)^{-1} Y \tag{2}$$

where $(I - A)^{-1}$ is the Leontief inverse matrix, which captures both direct and indirect economic inputs to satisfy one unit of final demand in monetary value; I is the identity matrix.

To calculate the total direct and indirect carbon emissions to produce a unit of final demand (E), the input-output table is extended with a vector of sectoral carbon emission coefficients (F) for all regions

$$\mathrm{E} = \mathrm{F}(I - A)^{-1} \tag{3}$$

where F is given by F $= \mathrm{K}\widehat{X}$, in which K $= [k_i^r]_{1\times mn}$ is a vector of sectoral direct carbon emission for all regions, the hat indicates a diagonal matrix.

Thus, the total direct and indirect carbon emissions to production primary/second steel for all regions (TC) can be calculated by

$$\mathrm{TC} = \widehat{E}X' \tag{4}$$

where X' is the economic total output matrix with zeros for all sectors' total output other than primary/second steel production. The indirect carbon emission (scope 2 plus scope 3) can be obtained by subtracting direct emissions from total emissions. TC shows the level of emissions that primary/second steel sectors have agency over along the full upstream supply chain. Electricity and other sectors' scope 1 emissions can be regarded as primary/second steel sectors' scope 2 and scope 3 emissions, respectively. If the direct emissions of other sectors are zero, implying that the indirect emissions of the primary/second steel sectors are all from electricity sectors. Thus, the carbon emission associated with the production of electricity (scope 2) can be obtained by adjusting equation (4), i.e. adjusting E so that carbon emissions of all sectors except for the electricity production sector are zero.

2.3. Decomposition analysis method

In this study, a decomposition analysis has been used to explain the effects of key components on CO_2 emission of national and global steel production. Four major factors that could influence CO_2 emission and emphasize the emission of primary production are considered: (a) *Volume effect*- $\Delta E_{P,Pri}$: the steel production volume of the primary route; (b) *Energy intensity effect*-$\Delta E_{En,Pri}$: the energy use per ton of primary production; (c) *Emission intensity effect*-$\Delta E_{E,Pri}$: Represents the CO_2 emission per ton of energy use in primary production; (d) *Secondary route effect*-ΔE_{Sec}: the CO_2 emission of secondary production of steel.

Total CO_2 emission of steel production in each country can be represented by:

$$E_t = E_{Pri,t} + E_{Sec,t} = P_{Pri,t} \times \frac{En_{Pri,t}}{P_{Pri,t}} \times \frac{E_{Pri,t}}{En_{Pri,t}} + E_{Sec,t} \tag{5}$$

where $E_{Pri,t}$ and $E_{Sec,t}$ is the CO_2 emission of primary and secondary production of steel in *t* year. $P_{Pri,t}$ represents the primary production of steel, $En_{Pri,t}$ represents the energy use in primary production.

The aggregate change in total emission of steel production can be calculated by:

$$\Delta E_t = \Delta E_{P,Pri} + \Delta E_{En,Pri} + \Delta E_{E,Pri} + \Delta E_{Sec} \tag{6}$$

where $\Delta E_{P,Pri}$, $\Delta E_{En,Pri}$, $\Delta E_{E,Pri}$, ΔE_{Sec} denote the CO_2 emission change associated with primary production (*P*), energy intensity (*En*), emission intensity (*E*), and secondary emission (*Sec*), respectively. These four factors can be further calculated by:

$$\Delta E_{P,Pri} = \frac{E_{Pri}^T - E_{Pri}^0}{\ln E_{Pri}^T - \ln E_{Pri}^0} \ln\left(\frac{P_{Pri}^T}{P_{Pri}^0}\right) \tag{7}$$

$$\Delta E_{En,Pri} = \frac{E_{Pri}^T - E_{Pri}^0}{\ln E_{Pri}^T - \ln E_{Pri}^0} \ln\left(\frac{En_{Pri}^T}{En_{Pri}^0}\right) \tag{8}$$

$$\Delta E_{E,Pri} = \frac{E_{Pri}^T - E_{Pri}^0}{\ln E_{Pri}^T - \ln E_{Pri}^0} \ln\left(\frac{E_{Pri}^T}{E_{Pri}^0}\right) \tag{9}$$

$$\Delta E_{Sec} = E_{Sec}^T - E_{Sec}^0 \tag{10}$$

where T and $T = 0$ represent the last year and base year of the period, respectively.

2.4. Data sources

The results in this paper are calculated based on Exiobase version 3.4. Exiobase is a large dataset that describes the economic relationships between 163 sectors over 49 regions (countries or groups of countries). The EXIOBASE MRIO data used to produce the results is from http://exiobase.eu/, while the production data is mainly from the world steel yearbook [49] which documents the crude steel production, EAF steel production, and other production flows from 2000 to 2015 among nations. Those flow datasets are synergized to similar geographical boundaries.

3. Results

3.1. Growing CO_2 emissions from global steel production

As shown in Fig. 2, the CO_2 emission associated with global steel production has increased by 2.53-fold from 1.8 B t/yr (billion tons per year) in 2000 to 4.5 B t/yr in 2015, while the growth ratio of global steel production only stays at 1.9-fold. In contrast to a previous study [6], our results indicate a worsening environmental performance of the global steel industry with emission intensity increasing from 2.1 tCO_2/t steel in 2000 to 2.8 tCO_2/t steel in 2015. Furthermore, a substantial increase in the CO_2 emission is found from both scope 1, 2, and 3. The direct CO_2 emission has grown by 2.2-fold from 0.8 B t in 2000 to 1.4 B t in 2015, accounting for around 45% of the total emission, while the emission from electricity use (scope 2) is much smaller with a share of 10%. Notably, the indirect emissions (scope 3, excluded scope 2) associated with steel production has gained their share in total CO_2 emission, rising from 44% (0.8 B t/yr) in 2000 to 50% (2.2 B t/yr) in 2015, which implies that the production of intermediate resource poses a higher impact on steel's emissions ever before. Given the indirect emission has surpassed the direct sources as the main contributor to total emission, the carbon management of steel production should move beyond the plant level to the upstream supply chain.

Such CO_2 emission increase is closely linked to the historical changes in the global distribution of steel production and the regional carbon intensity. For a better presentation, this study divided the world into OECD and non-OECD regions. Their historical trends of steel production and CO2 emission are presented in Fig. 2b and c, respectively. It is noted that the global center of steel production has rapidly shifted from OECD region to the non-OECD region. In 2000, OECD region produced around 498 Mt/year steel, which is 1.4 times that of non-OECD region. Afterward, the steel production of OECD region kept stable at about 490 Mt/year. By contrast, the growing steel demand (from both OECD and non-OECD regions [54]) is mainly supported by non-OECD region, and it has surpassed OECD region as a global production center since 2005 to reach 1130 Mt/year in 2015, which is around 2.3 times higher than that of OECD region. As OECD region owns more efficient technologies and operations in steel production [41,42], the average carbon intensity of non-OECD region during the studied period was 2.8 t CO_2/t steel, which is around 50% higher than that of OECD region (1.9 t CO_2/t steel). Thus, such a "race to bottom" trend (i.e. higher steel production in less efficient regions) made global steel production less CO_2 emission efficient, contributing significantly to its total CO_2 emission increase. More seriously, despite various climate mitigation efforts [55], there is a continuing increase in CO_2 intensity in both the OECD region (i.e. from 1.6 t CO_2/t steel to 2.3 t CO_2/t steel) and non-OECD region (i.e. 2.7 t CO_2/t steel to 3.0 t CO_2/t steel) from 2000 to 2015, indicating limited historical progress in decarbonizing steel production on the global level.

3.2. Regional disparities in steel production and CO_2 emission

There are large regional disparities in production amount and route mix, emission and energy intensity in global steel production as presented in Fig. 3. In general, the entire Asian and Pacific region dominated global steel production (70%) and emissions (86%) in 2015. At present, China is the global largest steel producer (Fig. 3a), rising from 145 Mt/yr (global share: 17%, second after EU-28) in 2000 to 825 Mt/yr (global share: 51%) in 2015, while its share in total CO_2 emission also increased from 33% to 60% during the past 15 years. India, of specific notice, accounted for around 5% of global total steel production but was responsible for 8% of total global emission in 2015 (Fig. S3). As the second-largest steel producer after China, EU's steel production stayed at around 170 Mt/yr during the studied period, but its share in global production decreased from 23% in 2000 to 10% in 2015 (Fig. S2) due to the production growth in other regions. Consequently, its emission share sharply reduced from 13% in 2000 to 4% in 2015. The United States is

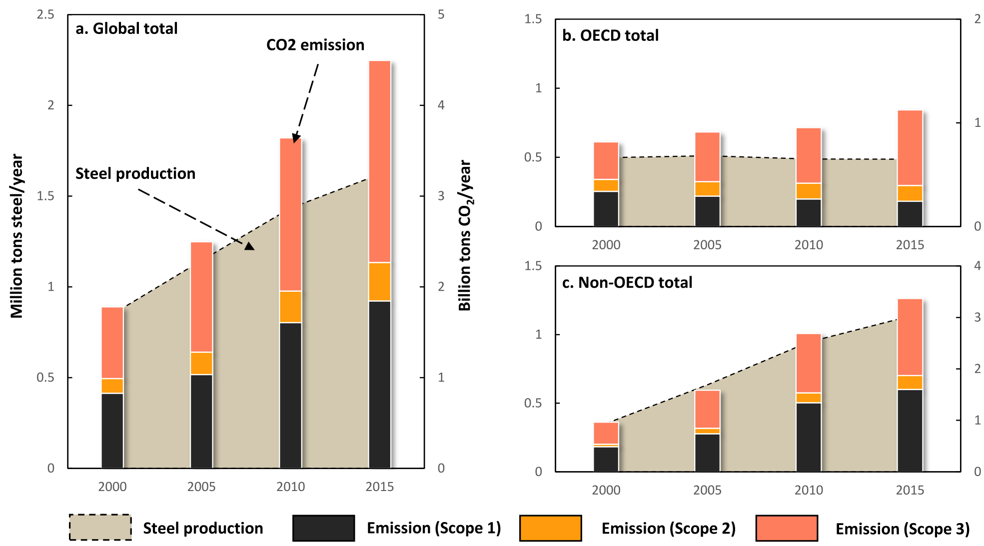

Fig. 2. Emission and production trend of global steel production from 2000 to 2015 (a indicates how the CO_2 emission from scope 1 to scope 3 and steel production changes with time. b gives the results for OECD region, while c is mapped for that of non-OECD region. Those three figures share the same unit for the left and right y-axis.).

another noticeable steel producer with annual production decreasing from 101 Mt/yr to 79 Mt/yr, and its total CO2 emissions followed the same trend from 0.19 B t/yr in 2000 to 0.15 B t/yr in 2015 (Fig. S4).

The scrap-based secondary steel production is much less emission-intensive than ore-based primary production, making the secondary ratio (i.e. secondary/total steel production) an important indicator to measure the sustainable performance of national steel production [56,57]. Despite the increase of secondary production (from 286 Mt/yr to 408 Mt/yr), on the global level, the secondary ratio decreased from 34% in 2000 to 25% in 2015, partly because of the low secondary share (i.e., 11%) in China. In 2015, there is still various regions' steel production dominated by scrap-based secondary route, including North America (60%), India (65%), Middle East (79%), Rest Asia and Pacific (64%), and Africa (65%), while many developed nations have owned lower secondary ratio, such as Japan (22%), EU-28 (42%). This contrasts previous studies [58] presuming the developed nations may have higher secondary ratios given their mature steel stocks. The infrastructure lock-in effect [58] caused by the long lifetime of primary production facilities (around 60 years), as pointed out by Ref. [31], can stop the production route shift with the scrap availability. Meanwhile, the scrap trade, which was always neglected by previous projection studies [23,24], can play a critical role in decarbonizing national and global steel production, such as India, Africa, and other developing Asia [59].

3.3. Worsening CO_2 emission efficiency of regional steel production

The historical changes of CO_2 emission intensity of each region from 2000 to 2015 is presented in Fig. 4, which are categorized into three groups (group I-good performance: <2.5 tCO_2/t steel; group II-medium performance: 2.5–3.5 tCO_2/t steel; group III-poor performance: >3.5 tCO_2/t steel). At present, the lowest practical emission intensity of regional steel production, according to our estimations in Fig. 4, can reach 1.03–1.07 tCO_2/t steel in EU-28 and the Middle East. Such good performance in the Middle East is mainly due to its high secondary ratio, while EU-28 benefits from its efficient processing technologies and strong policy support [38,60]. The steel production in South America and rest EU is performing excellent in its emission intensity, staying at 1.5 tCO_2/t steel, but their impacts on the global trend are quite limited given their low production shares. Thanks to its high secondary ratio, North America has good performance with a relatively higher intensity at 1.7 tCO_2/t steel. Still, there is no substantial improvement in the emission intensity of regions in the "good performance" group, indicating such a level of emission efficiency as a practical limitation for global steel production.

As the largest steel producer and CO_2 emitter, China has made the largest improvement in its emission intensify, decreasing from 3.8 tCO_2/t steel in 2000 to 3.2 tCO_2/t steel in 2015, which is still two times more than the practical lowest levels. Such improvements, through technical efficiency improvement and out-of-date factifies elimination [28,33], help China shifting from group III to group II as shown in Fig. 3b. Nevertheless, China's emission intensity has stagnated since 2005. Meanwhile, the emission reduction driven by this efficiency improvement fails to offset the production increase's effect in emission increase, causing China's total emission increase from 0.55 B t/yr in 2000 to 2.6 B t/yr in 2015. As one of the largest steel potential consumers [4] with a higher secondary ratio, India remains at group III during the studied period with emission intensity staying at 3.99 tCO_2/t steel. If its production increase with a lower secondary ratio, the environmental performance of India could worsen if no further actions are taken.

Of serious concern for steel decarbonization, the carbon intensity of most key producers is worsening. As the second-largest steel producer in Asia, Japan is witnessed with the highest increase in its emission intensity from 1.8 tCO2/t steel in 2000 to 4.2 tCO2/t steel in 2015, turning from group I to group III. As one of the largest steel producers, South Korea also dropped to group III from group II with 4.1 tCO_2/t steel in 2015. Thus, as the home of many global largest steel companies such as Nippon Steel, Posco, HYUNDAI Steel, those two nations ranked as the worst steel producer with the highest emission intensity calls for more attention.

3.4. Influential factors on CO_2 emission changes of steel production

In this study, the historical changes of CO_2 emission are decomposed by the factors of production flow, energy intensity and emission intensity changes from primary production route and secondary production route for each studied region. As presented in Fig. 4a, the rapid growth of steel production both on primary and secondary production routes in Asia and Pacific countries (like China and India) are the dominant influences of global CO_2 emission growth, which reflects the aggressive expansion on steel production capacity in these nations contributed more than 2320 Mt CO_2 emission growth and offsets the technology innovation's benefits on CO_2 emission reduction. However,

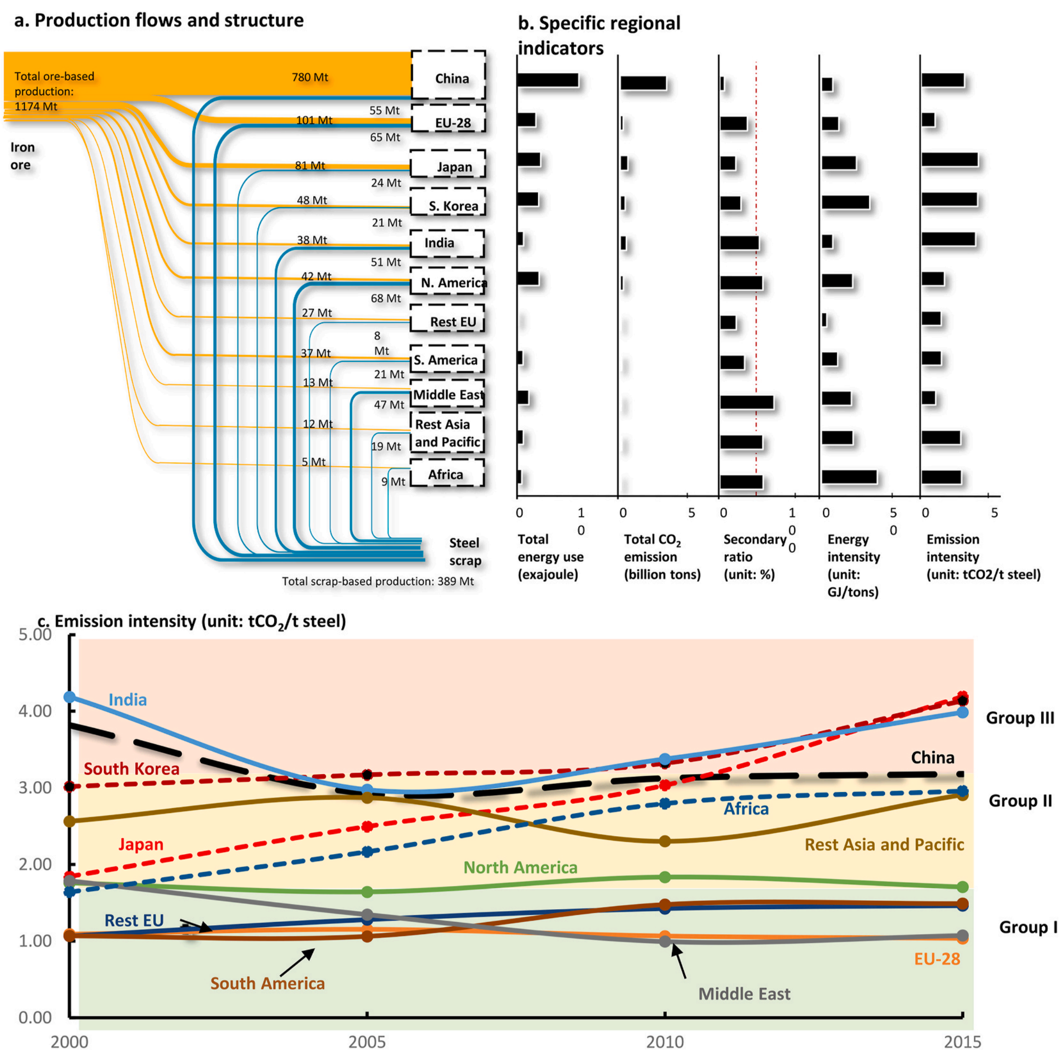

Fig. 3. Production flows and key indicators of steel production (a is Sankey diagram of primary and secondary production flows into each region in 2015, and the results for other regions are in Fig. S2-4. b presents the specific regional performance indicator for each region. C presents the historical change of emission intensity of each region).

we should not ignore China's efforts on steel decarbonization which are shown in Fig. 4b. Compared with other Asia and Pacific countries (Fig. 4e), China's steelmaking capacity expansion slowed, especially in 2010–2015. Under the influence of this and decreasing energy intensity caused by energy conservation policies, China's CO_2 emission only increased 566 Mt CO_2 emission in 2010–2015, which was 42% of China's CO_2 emission growth in 2005–2010. As shown in Fig. 4c and d, EU and America (North America and South America) nations with high-efficiency technologies decreased 118 Mt CO_2 by decreasing primary route's steel production, but due to the lack of effective carbon and energy reduction management, only 10 Mt CO_2 emission reduction contributed by energy and emission intensity changes on these nations. The worst performance on steel decarbonization is from the rest Asia and Pacific nations contributed a 683 Mt CO_2 emission growth in 2000–2015 by its' increasing steel production and energy/emission intensity (Fig. 4e). Due to the lack of sustainable industry development planning, these nations' steel production both on primary and secondary production routes increased by 50% in 2000–2015, and the CO_2 emission increment on these nations in 2010–2015 has increased by 68% compared with that in the last five years.

4. Discussion

4.1. Global cooperation and mitigation strategies for steel decarbonization

For steel decarbonization, the major steel producer, like China, Europe, India, Japan and the US, has set the ambitious decarbonization roadmap and implemented a range of measures, like restricting steel capacity expansions, investing in EAFs capacity and technological improvement (see Table 1). The emerging steel producers, like India and nations in the Middle East, have been encouraged to expand steel scrap trade (see Fig. 5). As a result, 56% of steel production in India and 94% of that in the Middle East was from the EAF-scrap route in 2020. Meanwhile, as the largest steel producer, China has eased the ban on steel scrap imports since 2019 and removed its import tax since 2022. However, brisk steel demand led to continued growth in domestic steel production (especially in China, India and other Asia nations). During 2015–2020, the global primary steel production has increased by 13% and its direct emission has increased by 27%. More effective measures and wider cooperation are necessary to reach net-zero steel worldwide (see Table 1).

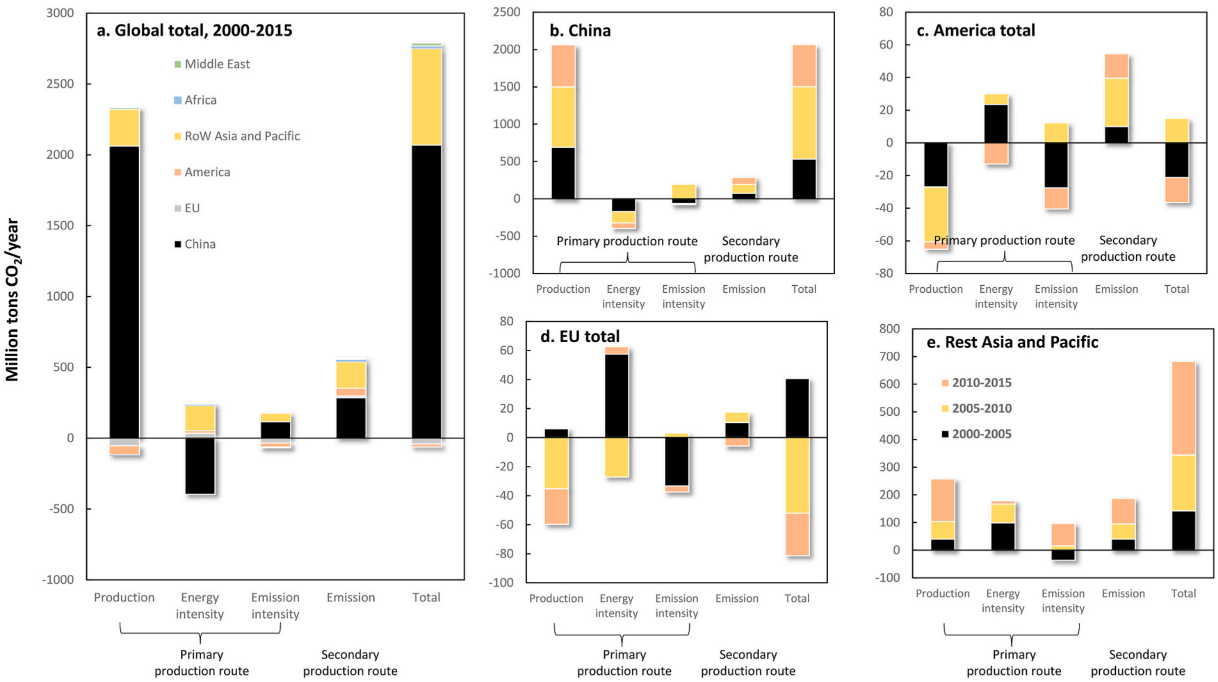

Fig. 4. Results of decomposition of total CO_2 emission of steel production during 2000–2015 (a explain the effects of four major factors on CO_2 emission changes of each region. b, c, d and e give the results for China, America (North America and South America), EU, and rest Asia and Pacific, respectively. Those figures share the same unit, and b, c, d, e share the same legend).

4.2. Changes in regional disparitiesand impacts on decarbonization

The current focus is mainly limited to the low-carbon production of iron and steel [62–66], including strategies like hydrogen-based production, electrolysis-based steelmaking, carbon capture and storage (CCS), biomass-based options, blast furnace improvement, zero-carbon electricity and others. For example, green hydrogen produced with renewable energy can effectively replace fossil fuels in steel production. Renewable electricity from wind, solar, and water can lead to zero-carbon emissions in electricity production [67,68]. However, aside from those technology-based factors, our study highlights that production flows-based factors have a key impact on global steel production's energy and emission performance. Corresponding, this study provides a regional perspective on such production flows-based factors and finds that increasing steel production and the expansion of regional disparities are the major drivers of growing global carbon emissions in steelmaking. During the past fifteen years, steel production has increased 1.9-fold on the global level, in which most of those steel production increases have occurred in emerging economies. Combined with the production technology disparities, such regional changes have caused the transfer of these steel production from low carbon intensity nations (like North America and EU-28) to high carbon intensity nations (like China and India), inducing around 250% growth in carbon emissions. Thus, our study urges the consideration of regional disparities and inequalities in designing global strategies toward climate mitigation.

4.3. Potentials of steel production route transition are conditional

As production routes (ore-based primary vs. scrap-based secondary) matter to steel production's overall performance [26,69–71], our study further reveals the production route mix in different regions, as another important production flow-based factor, would further impede the decarbonization in global steel production. When the economic development of some developing nations starts to soars, their demand for iron and steel will experience a fast increase period [4,72]. Due to the lack of available steel scrap generation from societal in-use products [31,73], those developing nations with high carbon intensity will also fail to obtain the steel from the scrap-based secondary production routes, although they are less energy- and carbon-intensive [74]. Hence, these nations would rely heavily on the use of iron ore for their steel productions with the large scale of steel production facilities construction. Such route changes exacerbate the decarbonization difficulty in developing nations. For instance, China has made great achievements in decreasing its energy and carbon intensity, but its overall performance remains less efficient. Meanwhile, given the heavy initial capital investment and long lifespan of those primary steel production facilities such as BF/BOF (60–100 years) [31,75], some nations with high primary production route share will start to export their steel products to meet other nations' steel demand when their steel demand matures [4,72]. This will also compound the difficulties in the decarbonization of global steel production. Clearly, a more open and green international steel market is needed to realize low-carbon steel production.

4.4. Continuing regional expansion and transition may raise carbon emissions

Along with the steel production boom, the global steel industry has also experienced a grand shift from advanced capitalist countries to late industrializing countries (e.g., the center of steel production shifts from the United Kingdom, the United States, Japan, to China) [76]. For instance, China has taken over steel capacity from developed countries and became the world's largest steel-producing country in 1996 [77]. At present, China contributes over 50% of total production but plans to cut its steel production capacity under the expected decrease in steel demand and the strong environmental and carbon constraints. Looking to the future, India, as the world's second-largest steel producer, is expected to double its capacity in the 2030s [55] and offset the contraction of steel production in China [78]. Meanwhile, the steel demand of Middle East, Latin America, and developing Asia will also increase rapidly to 2050 [31]. Due to the lack of steel scrap and economic intensive to adopt decarbonization technology, the development of low-carbon steel production in these emerging nations is retarded, compounding the difficulty of decarbonization. Meanwhile, these nations' strong increase in steel demand calls for cost-effective emerging

Table 1
Current production capacity and decarbonization strategy in future in major steel producers.

Region	Emission intensity in 2015 (t CO_2/t steel)	Production capacity and share in 2020			Decarbonization target and strategy in future	
		Steel production (Mt)	Proportion in global production	Primary/ Second steel production	Decarbonization target for each country and its major steel enterprises	Key priorities for steel decarbonization [61]
China	3.16	1064.8	57%	91%/9%	• A peak emission by 2025 and a 30% reduction from the peak level by 2030 in the steel industry • A 30% reduction by 2035 of GHG emissions on 2020 levels in the steel industry **(Baowu Group)**	• Ramping up the identification and closure of excess steelmaking capacity • Retrofitting the remaining BF-BOF capacity • Using of lower carbon steel in public projects • Scaling up scrap sorting and recycling • Accelerating the inclusion of steel and cement in the emissions trading system
Europe	1.15	279.4	15%	57%/43%	• A 55% reduction by 2030 of GHG emissions on 1990 levels • A 30% reduction by 2030 of GHG emissions in the steel industry **(ArcelorMittal Europe)**	• Ramping up the expansion of renewable energy infrastructure • Focusing deployment of renewable-based hydrogen in steel sectors • Seeking complementary approaches to carbon tariffs, product standards, subsidies and public procurement with trade partners
India	3.99	100.3	5%	45%/55%	• A 33–35% reduction by 2030 of GHG emissions on 2005 levels • A 23% reduction by 2030 of GHG emissions on 2020 levels in the steel industry **(JSW Steel)**	• Ensuring that new steel plants built under the planned capacity expansion are "net-zero ready" • Investing in EAFs and DRI capacity • Developing a robust assessment of the infrastructure expansion required to shift from coal-based to hydrogen-based DRI
Japan	4.19	83.2	4%	75%/25%	• A 46% reduction by 2030 of GHG emissions on 2013 levels • A 30% reduction by 2030 of GHG emissions on 2013 levels in the steel industry **(Nippon Steel)**	• Mapping out power sector and CCUS infrastructure needs for steel sector decarbonization and integrating steel within plans to establish a hydrogen economy • Introducing ambitious green steel public and private procurement goals • Coordinating efforts to pool and scale up investments in research, pursuing partnerships with developing countries
South Korea	4.14	67.1	4%	69%/31%	• A 24% reduction by 2030 of GHG emissions on 2017 levels • A 20% reduction by 2030 of GHG emissions on 2017–2019 levels in the steel industry **(POCOS Steel)**	• Introducing targeted regulation to improve incentives for scrap retrieval, sorting and decontamination • introducing green steel private procurement requirements for the auto-sector and appliance industry to drive demand for cleaner solutions • Introducing policies to ensure no new investment in coal-based steelmaking facilities
United States	1.92	72.7	4%	29%/71%	• A 50–52% reduction by 2030 of GHG emissions on 2005 levels • A 35% reduction by 2030 of GHG emissions on 2015 levels in the steel industry **(Nucor Corporation)**	• Introducing policies to ensure no new investment in coal-based steelmaking facilities • Enabling transition finance for steel decarbonization in emerging and developing economies via multilateral development banks • Expanding technology and policy partnerships on near-zero-emissions steel with developing countries via the B3W partnership

low-carbon technology and decarbonization policies, which are not feasible in the short term. Such continuing steel production shift is a critical challenge in the future decarbonization of steel production. Hence, how to achieve decarbonization of steel production in these emerging nations should be deeply discussed. Otherwise, the carbon emission of steel production will increase rapidly and jeopardize the carbon neutrality target [46,58,79].

4.5. High importance of emerging producers' decarbonization efforts

The mitigation strategies and roadmaps for emerging steel producers, such as India, Middle East, and others, should be planned and promoted urgently along with their fast production increase. Standing at regional disparities, two main suggestions are summarized: (a) Expanding the trade of steel scrap and green steel products. There is a key regional mismatch of scrap generation and steel consumer in the coming decade, making the future trade of scrap critical to balance such regional disparities. The corresponding global cooperation is needed to facilitate developing nations to import recycled steel scrap originating from developed nations, and encourage the consumer to use green steel manufactured through steel scrap by environmental product declaration. (b) Limiting the expansion of carbon-intensive primary production facilities. It is expected that global steel demand will increase by more than a third through 2050. Meanwhile, as predicted by Pauliuk et al. [31], the steel scrap will increase rapidly by 2~3-fold by 2050, and the predicted rise of global steel demand can be met by increasing secondary production if that old scrap is well recycled. Historically, the rapid build-up of steel production capacity (mainly in China) has led to global excess capacity, leading to a severe carbon lock-in effect [80]. In case of exacerbating such effect, the development of carbon-intensive primary production capacities should be utterly cautious, and global cooperation is needed to promote such capacity balance.

5. Conclusion

The global steel industry is the biggest industrial carbon emitter and one of few "difficult-to-decarbonize" sectors with large disparities in major steel production routes, efficient technologies, and environmental performance across different nations. By Using comparable physical indicators such as direct and indirect CO_2 emission, energy use, and

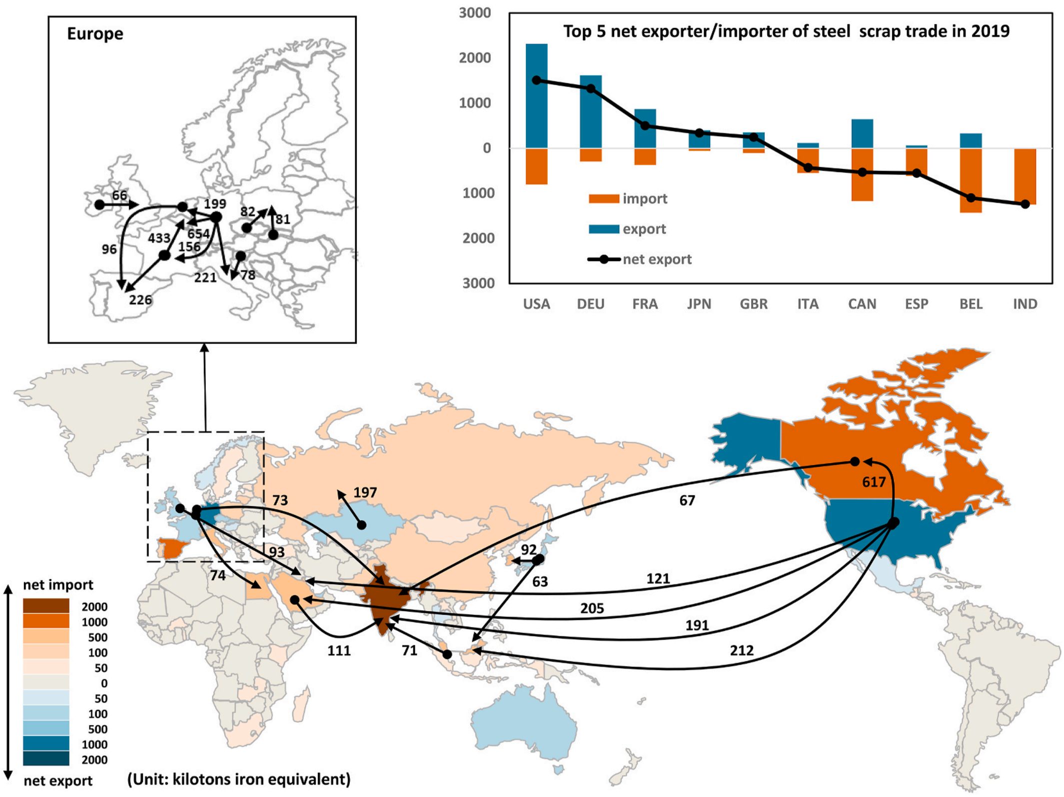

Fig. 5. Net trade flow of steel scrap in 2019 (The line in Fig. 5 represents the top 25 flows of steel scrap net-trade between two nations. The background map shows the net trade weight in each country.).

carbon intensity, our analysis provided an analytical perspective to demonstrate the emission performance and decarbonization potential of regional steel production and highlights the production flows-based factors that have exerted a key impact on the energy and emission performance. The results show the worsening energy use efficiency, emission efficiency and environmental performance of regional steel production driven by the regional disparities in steel production and the "race to bottom" trend. Those results indicated that global cooperation between different countries along the entire steel supply chain should be promoted. Mitigation strategies from both production and consumption in emerging nations are critical in the decarbonization of steel production while satisfying their steel demand. Furthermore, this study provides a global analytical tool and perspective to demonstrate regional steel production's emission performance and decarbonization potential across different countries with comparable physical indicators. Similar studies at the global level should be carried out in other carbon-intensive industries such as aluminum and cement industries, which are also under mounting mitigation pressure with high regional disparities.

Credit author statement

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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.

Acknowledgment

This study is supported by the National Natural Science Foundation of China (Nos.71904182 and 71961147003), Key Program of Frontier Science of the Chinese Academy of Sciences (No. QYZDB-SSW-DQC012)>, the National Social Science Fund of China (No. 21ZDA065), and the Dalian National Laboratory for Clean Energy Cooperation Fund (No.DNL202024).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112367.

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