Energy Proceedings
Vol 64, 2026
ISSN 2004-2965

From Mining to Downstream Products: Multi-Regional Carbon Flows and Drivers in the Global Iron and Steel Sector#

Eugene Haochen Yu[1,2], Fu Yuning[1,2], Yang Xingyuan[1,2], Ma Linwei[1, 2*], Li Zheng [1, 2], Ni Weidou[1]

1 State Key Laboratory of Power Systems, Department of Energy and Power Engineering, Tsinghua University, Beijing, 100084, China

2 Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy and Sustainable Development, Laboratory for low carbon energy, Tsinghua University, Beijing, 100084, China

ABSTRACT
The iron and steel supply chain is a high energy consuming sector spanning mining, steelmaking, and downstream product use. This study integrates material flow analysis, complex network modeling, and multi-regional LMDI decomposition to assess CO_2 emissions and their drivers across major regions from 2000 to 2020. Results show a structural shift toward a China-centered supply chain, with economic growth contributing +3.15 $GtCO_2$ as the dominant driver, while cleaner energy (ΔCOE, -0.22 $GtCO_2$) and efficiency gains (ΔEI, -0.55 $GtCO_2$) increasingly offset emissions. These findings highlight the redistribution of emissions along the global supply chain and support region-specific strategies for low-carbon transitions in the steel sector.

Keywords: carbon emission, driving forces, MFA, complex network model, LMDI model, iron and steel supply chain

NONMENCLATURE

Abbreviations	
ISSC	Iron and steel supply chain
LMDI	logarithmic mean Divisia index
SP	Steel product
ICP	Iron-containing end-use product
SDA	Structural decomposition analysis
IDA	Index decomposition analysis
Symbols	
A	Adjacent matrix
V	Nodes
E	Edges
m	Quantity of iron & steel products
γ	Grade of product
y	Export country
z	Import country
o	Iron ore
p	Pig iron
s	Steel scraps
c	Crude steel
sp	Steel products
i	Energy type
j	Country
k	Type of iron and steel industry
C	CO_2 emission
E	Energy consumption
Y	Iron-content based output
P	Population

1. INTRODUCTION

In the context of global warming, carbon neutrality becomes more and more crucial, attention must be given to high-emission industries such as the iron and steel supply chain (ISSC)[1,2]. The ISSC is a supply chain that stretches from upstream mining and raw material extraction to downstream manufacturing and consumption of iron-containing products (ICP). This supply chain is inherently international due to regional differences[3]. Resource-exporting countries, manufacturing hubs and consumers each play a distinct role within the chain, meaning the decarbonization of iron and steel supply chain is a global matter which requires joint effort across countries and regions[2].

Over the last 20 years, the manufacturing hub of ISSC has shifted. This geographical shift in manufacturing hub has been accompanied by major changes in global consumption and trade[4]. These changes have reshaped the patterns of carbon emission across the entire iron and steel supply chain, raising the question of what caused these emission patterns to shift.

Existing research on ISSC has largely concentrated on individual countries or regions, such as China[5], USA[6]. The common methodology for these research is MFA or a combination of MFA with Input-output model to construct iron and steel supply chain, other research tend to also focus on single country's CO_2 emission using logarithmic mean Divisia index (LMDI) approach[7]. These research provide valuable insight at a regional level, but is insufficient on a global level. At a multi-

This is a paper for the 17th International Conference on Applied Energy - ICAE2025, Dec. 8-12, 2025, Bangkok, Thailand.

regional level, current studies tend to focus on carbon emissions of a single steel product[8], or the physical flows of multiple steel products without considering the carbon emission producing these products[9]. Therefore, there is a gap for comprehensive analysis of carbon emissions across the entire global iron and steel supply chain, together with their driving factors.

Therefore, this study seeks to bridge the gap. Based on MFA and complex network models, we mapped the global multi-regional iron flow, together with multi-regional LMDI model, this study provides a comprehensive assessment of carbon emissions and their driving forces across the iron and steel supply chain. This study makes three key contributions to the literature. First, it introduces a material flow-based perspective to characterize the global multi-regional iron and steel supply chain, offering a more detailed physical representation of iron flows compared to previous studies that primarily relied on macroeconomic models. Second, it is the first to apply a multi-regional LMDI decomposition to the international iron and steel supply chain, enabling a systematic assessment of the driving forces behind carbon emission changes across mining, steel production, and downstream product consumption at the global scale. Third, by explicitly capturing regional and national heterogeneity, this research provides novel insights into how emission drivers vary across different economies, thereby offering more accurate evidence to design region-specific low-carbon transition policies for the global steel industry.

At the same time, it should be noted that the study involves certain simplifications. Sectoral energy consumption data are approximated, the coverage is limited to the major steel-producing and consuming countries, and downstream consumption is primarily represented by machinery and transport equipment. Detailed limitations and uncertainties will be discussed in the conclusion part.

2. METHODOLOGY

2.1 Research framework

Figure 1 presents a comprehensive research framework to investigate CO_2 emission alongside the international iron and steel supply chain. This framework consists of three major layers. The top layer represents the physical flow of iron element across the chain, including upstreaming mining and quarrying industry that produces iron ore, midstream iron and steel industry that produces steel products (SP), and downstream end-use that consumes iron-containing end-use products (ICP). These flows occur domestically and across borders, reflecting the globalized nature of the iron and steel supply chain.

The middle layer highlights the energy consumption with each production stage. Energy carries including coal, coke, natural gas, LNG and electricity are consumed in different stages of production, causing major CO_2 emission.

The bottom layer reflects the resulting energy-related carbon emissions, which is a result from direct fuel combustion and electricity use. Process emissions are not considered in this study. By combining material together with energy, this framework allows the quantification of energy-related CO_2 emissions embodied in production, trade, and end use.

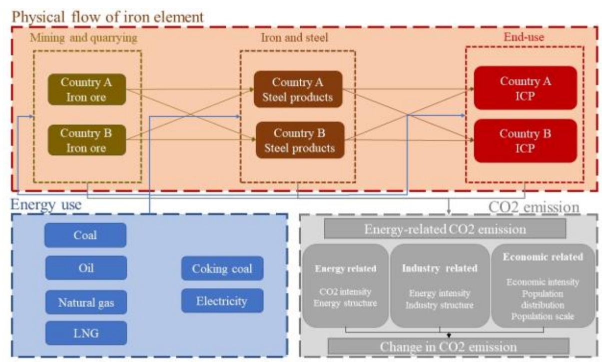

Fig. 1 Research framework

2.2 Research scope

The research scope for this study is defined in terms of special, temporal and sectoral. Spatially, this study focuses on the world's major steel-producing and consuming regions, namely the EU27, North America (United States, Canada, Mexico), Australia, China, Japan, Korea, India, Brazil, and other European countries (Russia, Norway, Switzerland, Türkiye, United Kingdom). Together, these regions account for the majority of global iron ore mining, steel production, and downstream steel consumption, making them representative of the global steel supply chain, as figure 2 shows.

Temporally, this study covers five benchmark years: 2000, 2005, 2010, 2015, and 2020. These years capture key stages in the evolution of the global steel industry, including the relocation of production capacity from developed to emerging economies, and the associated shifts in trade and consumption patterns.

Sector wise, the entire iron and steel supply chain, including iron ore extraction, crude steel and finished steel production, and downstream iron-containing products use. Energy use and energy-related carbon emissions are consistently tracked across all sectors.

2.3 MFA and complex network model

Complex network model is used to map the flow of iron and steel products between different countries/regions. An Adjacent matrix A=(V,E), containing nodes V (in this case countries/regions), and edges E (flow of iron and steel products between countries/regions) is used to show the international iron and steel supply chain, as equation below shows:

$$A = (V, E) = \begin{bmatrix} A_{1,1} & A_{1,2} & \cdots & A_{1,n} \\ A_{2,1} & A_{2,2} & & A_{2,n} \\ \vdots & & \ddots & \vdots \\ A_{n,1} & A_{n,2} & \cdots & A_{n,n} \end{bmatrix}$$

Where for example $A_{1,2}$ would represent the trade of product A from country 1 to country 2.

On this basis, MFA is applied to connect all iron & steel products together, from iron ore to iron containing end-use products. The MFA of iron & steel is based on the principle of iron element quality balance. The basic calculation formula used for this study is shown below:

$$\sum_{y,z} m_o\gamma_o = \sum_{y,z} m_p\gamma_p$$

$$\sum_{y,z} m_s\gamma_s + \sum_{y,z} m_p\gamma_p = \sum_{y,z} m_c\gamma_c$$

$$\sum_{y,z} m_c\gamma_c = \sum_{y,z} m_{sp}\gamma_{sp} = \sum_{y,z} m_{icp}\gamma_{icp}$$

Where m is the quantity of the iron & steel product, γ is the grade of certain product. Subscript y, z, o, p, s, c, sp, and icp represents export country, import country, iron ore, pig iron, steel scraps, crude steel, steel products, and iron containing end-use products, respectively.

2.4 Bottom-up CO_2 calculation

The carbon emission for the ISSC is calculated based on a bottom-up accounting framework, shown below:

$$C = Energy\ type\ \times Carbon\ emission\ factor$$

2.5 LMDI decomposition

LMDI method is a common method for revealing the driving forces of energy consumption[10-12], CO_2 emission[13-16] at a regional or global level. Two common and popular decomposition methods are structural decomposition analysis (SDA) and index decomposition analysis (IDA). The main difference between the two methods is that SDA's data input relies on input-out framework, whereas IDA is not limited to this framework. Hence IDA has lower data requirement[17], making it a common choice of decomposition method for multi-regional studies. The

Fig. 2 Spatial boundary of this research

driving forces of international iron and steel supply chain CO_2 emission are identified by the equation below:

$$C = \sum_i \sum_j \sum_j = \frac{C_{ijk}}{E_{ijk}} \times \frac{E_{ijk}}{E_{jk}} \times \frac{E_{jk}}{Y_{jk}} \times \frac{Y_{jk}}{GDP_j} \times \frac{GDP_j}{P_j} \times \frac{P_j}{P} \times P \equiv COE \times ES \times EI \times G \times ECI \times PD \times P$$

Where C is the total CO_2 emission of international iron and steel supply chain; Cijk is the CO_2 emission caused by caused by energy type i consumed by the steel industry k in country j; Eijk is the energy type i consumed by the steel industry k in country j; Ejk is the total energy consumed by steel industry k in country j; Yjk is the iron-content-based total output of steel industry k in country j; GDPj is the GDP of country j; Pj is the population of country j; P is the total population. In addition, COE is CO_2 intensity effect which represents the changes in carbon emission caused by the consumption of different types of energy; ES is the energy structure effect which represents the influence of the composition of different energy types consumed; EI is the energy intensity effect which represents the efficiency of energy use; G is the industry structure effect which refers to the contribution of changes in output of the iron and steel supply chain relative to the country's GDP; ECI is the economic intensity effect which is the relationship between a country's GDP and its population; PD is the population distribution effect which accounts for the differences in population shares among countries; P is the population scale effect which represents the impact of total population on overall CO_2 emission. The multipliers, meaning of each abbreviation and decomposition formula are shown in Table 1.

Table 1. Multipliers, abbreviation, and decomposition formula

Multiplier	Abbreviation	Driving forces	Decomposition formula

C_{ijk}/E_{ijk}	COE	CO_2 intensity effect	$\Delta COE = \sum_{ijk} \frac{C^T - C^0}{\ln C^T - \ln C} \cdot \ln(\frac{COE^T}{COE^0})$
E_{ijk}/E_{jk}	ES	Energy structure effect	$\Delta ES = \sum_{ijk} \frac{C^T - C^0}{\ln C^T - \ln C} \cdot \ln(\frac{ES^T}{ES^0})$
E_{jk}/Y_{jk}	EI	Energy intensity effect	$\Delta EI = \sum_{ijk} \frac{C^T - C^0}{\ln C^T - \ln C} \cdot \ln(\frac{EI^T}{EI^0})$
Y_{jk}/GDP_j	G	Industry structure effect	$\Delta G = \sum_{ijk} \frac{C^T - C^0}{\ln C^T - \ln C} \cdot \ln(\frac{G^T}{G^0})$
GDP_j/P_j	ECI	Economic intensity effect	$\Delta ECI = \sum_{ijk} \frac{C^T - C^0}{\ln C^T - \ln C} \cdot \ln(\frac{ECI^T}{ECI^0})$
P_j/P	PD	Population distribution effect	$\Delta PD = \sum_{ijk} \frac{C^T - C^0}{\ln C^T - \ln C} \cdot \ln(\frac{PD^T}{PD^0})$
P	P	Population scale effect	$\Delta P = \sum_{ijk} \frac{C^T - C^0}{\ln C^T - \ln C} \cdot \ln(\frac{P^T}{P^0})$

Based on the driving forces, the change in CO_2 emission from time 0 to time T can be divided into the effects of change in the 7 driving forces, as the equation below:

$$\Delta C^T = C^T - C^0 = \Delta COE + \Delta ES + \Delta EI + \Delta G + \Delta ECI + \Delta PD + \Delta P$$

2.6 Data input

The major difficulties in terms of international studies is the collection of data. Different countries have different statistical coverage and scope. Table 2 shows the data source of this study.

Table 2. Main data source of this study

	Main data source		
Country/region	Energy	CO_2 emission	Iron and steel flow
EU27	EURO Stat Complete energy balances [18], IEA World Energy Statistics [19]	2006 IPCC guidelines for national greenhouse gas inventories [25]	WSA steel statistical yearbook [26], USGS [27], UN Comtrade [28], Steelonthenet [29]
Other European countries	IEA World Energy Statistics [19]		
North America	IEA World Energy Statistics [19], eia Manufacturing Energy Consumption Survey [20]		
Australia	IEA World Energy Statistics [19]		
China	NBSC China energy statistical yearbook [21], IEA World Energy Statistics [19]		
Japan	Nippon steel Fact book 2022[22],		

	METI Statistical yearbook [23], IEA World Energy Statistics [19]		
Korea	KEEI Yearbook of energy statistics [24], IEA World Energy Statistics [19]		
India	IEA World Energy Statistics [19]		
Brazil	IEA World Energy Statistics [19]		

3. RESULTS AND DISCUSSIONS

3.1 International iron and steel supply chain iron flow

Figures 3 to 5 presents the chord diagram of iron ore, steel products (SP), and iron containing end-use products (ICP), respectively. For example Figure 3(a) 2000 ore means the flow of iron ore in terms of iron element including both trade between countries/regions and domestic consumption, Figure 3(b)2000 ore trade means the flow of iron ore in terms of iron element between countries/regions only trade.

For iron ore, the year 2000 was characterized by relatively balanced global flows. With the exception of major mining countries, most nations relied primarily on domestic extraction for local use. In terms of trade, limited resource endowments made Japan and the EU27 the dominant importers. By 2020, however, global iron ore flows became heavily concentrated in China. Although demand in other countries continued to increase, their global shares declined. China also emerged as the leading importer, consolidating its central position in the global iron ore trade.

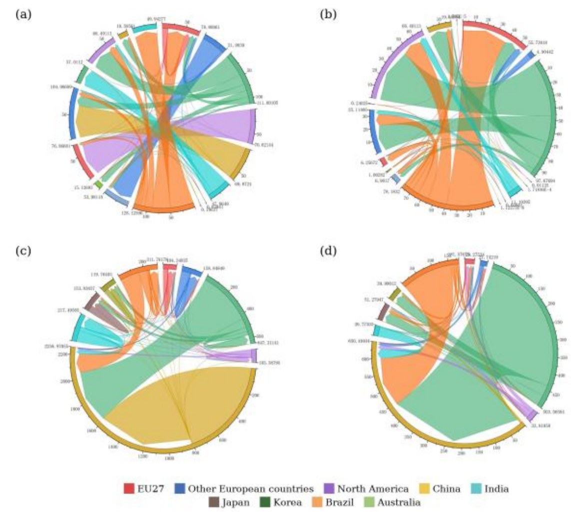

Fig. 3 (a) 2000 ore, (b)2000 ore trade, (c) 2020 ore, (d)2020 ore trade unit:Mt

For SP, production in 2000 was more evenly distributed among the EU27, North America, China, and Japan. Steel trade patterns exhibited clear regionality, with exchanges concentrated within Western countries and, separately, among Asian countries. By 2020, over half of global steel production was concentrated in China, while the remainder was shared more evenly among the EU27, North America, other European countries, India, and Japan. Trade flows remained regionally clustered, though China's growing share

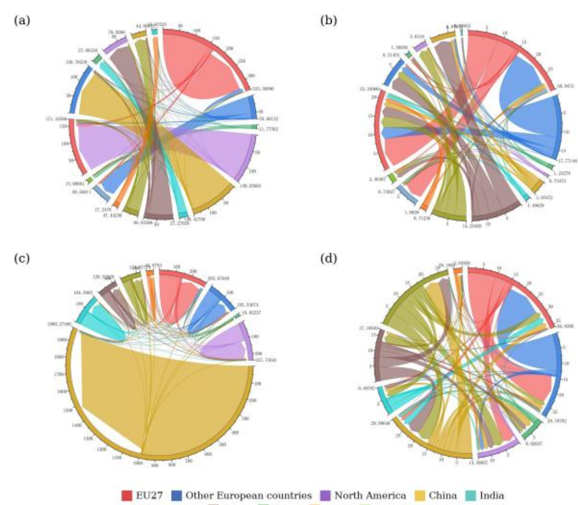

Fig. 4 (a) 2000 SP, (b)2000 SP trade, (c) 2020 SP, (d)2020 SP trade unit:Mt reflected its increasing influence, while the EU27 continued to act as the world's largest exporter.

For ICP, global patterns in 2000 resembled those of steel. However, in trade, the EU27 and North America played more dominant roles, with stronger exchanges involving Japan compared to steel trade. By 2020, ICP flows again mirrored steel distribution, with China's output increasing substantially. In trade, the EU27 remained the leading exporter, but China's share rose rapidly, while North America's export role diminished significantly.

Together, these results highlight the shift in the global iron and steel supply chain over the past two decades: from relatively balanced and regionally segmented patterns to a more China-centered system, with trade still retaining strong regional characteristics.

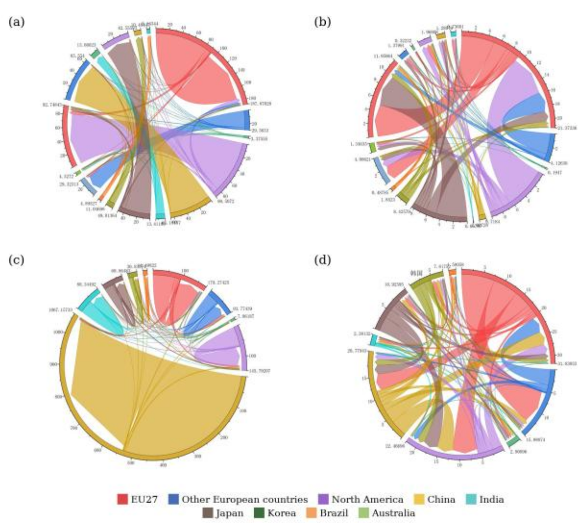

Fig. 5 (a) 2000 ICP, (b)2000 ICP trade, (c) 2020 ICP, (d)2020 ICP trade unit:Mt

3.2 Energy and CO_2 emission from 2000 to 2020

Between 2000 and 2020, global energy consumption of the international steel supply chain (ISSC) increased from 15.66 EJ to 33.74 EJ, an absolute rise of 18.08 EJ (+115%), while CO_2 emissions grew from 1.62 Gt to 3.43 Gt, corresponding to an increase of 1.82 Gt (+113%). Most of this expansion occurred during 2000–2010, when energy use rose by 13.11 EJ (+84%) and CO_2 emissions by 1.55 Gt (+96%).

After 2010, growth dynamics shifted. From 2010 to 2015, global energy consumption increased only marginally (+1.15 EJ, +4%), while CO_2 emissions declined slightly (−0.13 Gt, −4%), indicating a temporary decoupling between energy use and emissions. Between 2015 and 2020, energy consumption rebounded to 33.74 EJ (+13%), accompanied by a renewed increase in CO_2 emissions (+0.40 Gt, +13%), though at a slower pace than in the pre-2010 period.

China dominated both absolute and relative growth, with energy consumption rising from 4.56 EJ to 20.58 EJ (+16.02 EJ, +350%) and CO_2 emissions from 0.54 Gt to 2.25 Gt (+1.71 Gt, +315%), accounting for the vast majority of global increases. India emerged as a secondary growth pole, as its energy use expanded from 0.32 EJ to 2.78 EJ (+760%) and emissions from 0.03 Gt to 0.30 Gt (+1,050%), albeit from a much smaller base.

In contrast, traditional industrial regions experienced sustained declines. The EU27 reduced energy consumption by 17% and CO_2 emissions by 38%, while North America achieved reductions of 20% and 41%, respectively, reflecting efficiency gains and structural shifts. Overall, the data reveal a pronounced reallocation of energy use and emissions toward emerging economies, with post-2010 trends suggesting growing constraints on emission growth relative to energy consumption.

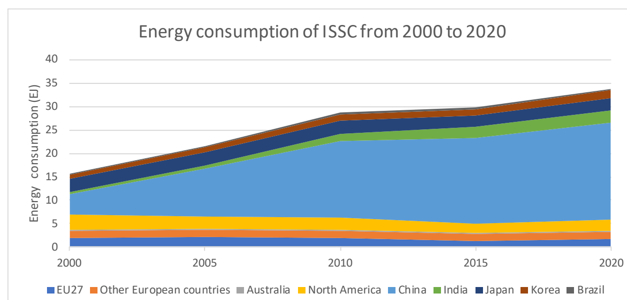

Fig. 6 Energy consumption from 2000 to 2020

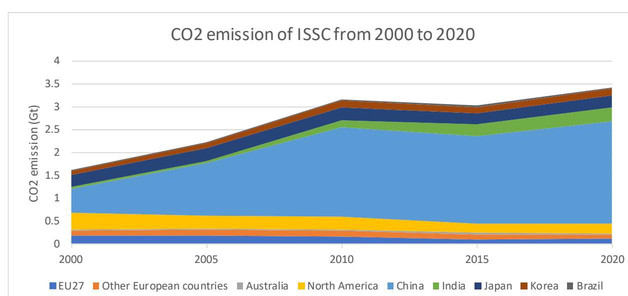

Fig. 7 CO_2 emission from 2000 to 2020

3.3 Results of LMDI decomposition

Figure 8 presents the LMDI decomposition of energy-related CO_2 emissions in the global iron and steel supply chain over the period 2000–2020. The results indicate that changes in emissions are driven by a combination of scale expansion and mitigating effects associated with efficiency improvements and structural adjustments, with the relative importance of each factor varying substantially across sub-periods.

From 2000 to 2005, global CO_2 emissions increased by 0.61 Gt. This rise was primarily driven by the economic intensity effect (ΔECI, +0.76 $GtCO_2$), reflecting rapid expansion of steel-related economic activity. A smaller positive contribution was also observed from the CO_2 intensity effect (ΔCOE, +0.12 $GtCO_2$). These growth effects were partially offset by improvements in energy intensity (ΔEI, −0.12 $GtCO_2$), energy structure (ΔES, −0.05 $GtCO_2$), and industry structure (ΔG, −0.05 $GtCO_2$). However, the combined mitigation effects were insufficient to counterbalance the scale-driven increase in emissions.

During 2005–2010, CO_2 emissions rose further by 0.93 Gt, representing the fastest growth phase in the study period. The economic intensity effect (ΔECI, +1.86 $GtCO_2$) overwhelmingly dominated emission growth, indicating an unprecedented expansion of industrial output. At the same time, substantial mitigation effects emerged, particularly from industry structure adjustment (ΔG, −1.08 $GtCO_2$), suggesting shifts toward less carbon-intensive production structures. Additional reductions were contributed by energy intensity improvements (ΔEI, −0.08 $GtCO_2$) and energy structure changes (ΔES, −0.03 $GtCO_2$). Despite these efforts, the magnitude of scale expansion outweighed all mitigating effects, leading to a net increase in emissions.

Between 2010 and 2015, global CO_2 emissions declined slightly by 0.13 Gt, marking a critical turning point in the emission trajectory. Although the economic intensity effect remained positive (+0.75 $GtCO_2$), it was more than offset by combined mitigation effects. The largest reduction stemmed from industry structure effects (ΔG, −0.56 $GtCO_2$), followed by significant contributions from energy intensity improvements (ΔEI, −0.29 $GtCO_2$) and energy structure optimization (ΔES, −0.10 $GtCO_2$). In addition, a decline in the CO_2 intensity effect (ΔCOE, −0.06 $GtCO_2$) further reduced emissions, indicating cleaner energy use and technological progress. Together, these effects resulted in an absolute reduction in emissions during this period.

From 2015 to 2020, CO_2 emissions increased again by 0.40 Gt, though at a considerably slower pace than during the pre-2010 expansion. Emission growth was once more driven by the economic intensity effect (ΔECI, +0.59 $GtCO_2$). Nevertheless, mitigation effects persisted, including reductions from industry structure adjustment (ΔG, −0.12 $GtCO_2$), energy intensity improvements (ΔEI, −0.06 $GtCO_2$), and CO_2 intensity changes (ΔCOE, −0.13 $GtCO_2$). The energy structure effect (ΔES, +0.03 $GtCO_2$) played a relatively neutral role in this period. These results indicate that while emission growth resumed, its magnitude was substantially constrained by ongoing efficiency and structural improvements.

Taken together, the period-by-period decomposition reveals a clear evolution in the drivers of CO_2 emissions within the global iron and steel supply chain. Over the entire study period, economic intensity (ECI) consistently emerges as the dominant positive driver, underscoring the central role of production scale expansion in shaping long-term emission trends. In contrast, mitigation is primarily achieved through a combination of industry structure adjustment (G),

Fig. 8 LMDI decomposition result

energy intensity improvement (EI), and energy structure optimization (ES), with their relative effectiveness strengthening over time.

The results further suggest a distinct transition after 2010. While emissions increased rapidly prior to 2010 as scale effects overwhelmingly dominated, the 2010–2015 period represents a unique phase in which mitigation effects collectively outweighed scale expansion, resulting in an absolute decline in emissions. After 2015, emissions resumed growth; however, the magnitude of increase was markedly lower than during the earlier expansion phase. This indicates not a failure of mitigation mechanisms, but rather a shift toward constrained emission growth under renewed industrial expansion, reflecting the increasing influence of efficiency gains, structural upgrading, and cleaner energy use within the steel supply chain.

4. LIMITATIONS

Several limitations of this study should be acknowledged. First, the estimation of upstream mining energy use involves simplifications. Specifically, we approximated the energy consumption of iron ore extraction by using the “Mining and quarrying” sector data from the IEA database. However, this sector also includes other mining activities beyond iron ore, which may over-estimate energy use and consequently introduce bias in the calculation of carbon emissions. Future work will address this issue by adopting a bottom-up approach, combining country-level iron ore production statistics with more detailed energy intensity estimates to isolate iron ore–specific energy consumption.

Second, our analysis is limited to major steel-related countries, which together account for roughly 85% of global production and consumption. While this coverage captures the vast majority of the global steel system, it still excludes some smaller producers and consumers. As a result, the total carbon emissions estimated in this study are slightly lower than the actual global emissions. Expanding coverage to additional countries will be an important next step to enhance completeness.

Third, on the downstream side, we primarily considered machinery and transport equipment as the main consuming sectors. While these account for the majority of direct steel use, indirect consumption driven by other sectors was not fully captured. Future work can improve this limitation by incorporating input–output tables and applying a Leontief consumption matrix to better reflect the indirect demand for steel across the global economy.

5. CONCLUSION

This study provides a comprehensive assessment of energy-related carbon emissions and their driving forces along the global iron and steel supply chain, covering upstream mining, midstream steel production, and downstream iron-containing products. This study enriches the literature by introducing a material flow-based approach and applying multi-regional LMDI decomposition for the first time to the global iron and steel sector. By highlighting regional and national differences in emission drivers, it provides more accurate evidence for designing differentiated low-carbon transition strategies worldwide.

The results highlight a profound transformation: from 2000 to 2020, global iron ore, steel, and ICP flows shifted from relatively balanced regional patterns to a more China-centered structure, while trade remained strongly regionalized. In terms of carbon emissions, economic growth consistently exerted the largest positive impact across all periods, reflecting rising demand for steel and iron-related products. In contrast, efficiency improvements, structural changes, and declining carbon coefficients from cleaner energy use played increasingly important roles in offsetting growth-driven emissions, particularly after 2010.

Building on these findings, several policy implications emerge for a regionally differentiated approach to decarbonizing the steel industry. For resource-exporting countries such as Australia and Brazil, policies should focus on reducing emissions in mining and transport, while aligning export strategies with global low-carbon demand. For major steel producers like China, India, and the EU27, accelerating the deployment of breakthrough technologies (e.g., hydrogen-based direct reduction, CCUS, and electrification of heat) will be critical to reducing production-related emissions. In advanced economies with declining steel demand, such as Japan and North America, efforts should emphasize demand-side strategies, including material efficiency, product recycling, and extending the lifetime of steel-intensive goods. Finally, stronger international coordination is needed to address carbon leakage and ensure fair competition, for example through mechanisms like CBAM or harmonized carbon accounting standards.

ACKNOWLEDGEMENT

The authors are grateful for the support of the Carbon Neutrality and Energy System Transformation (CNEST) Program led by Tsinghua University, the Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy and Sustainable Development and the support from BP through the Phase IV Collaboration between Tsinghua and BP.

REFERENCE

[1] IEA (2023), World Energy Outlook 2023, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2023, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

[2] Kim, J., Sovacool, B. K., Bazilian, M., Griffiths, S., Lee, J., Yang, M., & Lee, J. (2022). Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. Energy Research & Social Science, 89, 102565.

[3] Wang, P., Zhao, S., Dai, T., Peng, K., Zhang, Q., Li, J., & Chen, W. Q. (2022). Regional disparities in steel production and restrictions to progress on global decarbonization: A cross-national analysis. Renewable and Sustainable Energy Reviews, 161, 112367.

[4] Pei, M., Petäjäniemi, M., Regnell, A., & Wijk, O. (2020). Toward a fossil free future with HYBRIT: Development of iron and steelmaking technology in Sweden and Finland. Metals, 10(7), 972.

[5] Yang, H., Ma, L., & Li, Z. (2023). Tracing China's steel use from steel flows in the production system to steel footprints in the consumption system. Renewable and Sustainable Energy Reviews, 172, 113040.

[6] Mapping the annual flow of steel in the United States. Environmental science & technology, 53(19), 11260-11268.

.

[7] Huang, J.-B., Luo, Y.-M., & Feng, C. (2019). An overview of carbon dioxide emissions from China’s ferrous metal industry: 1991–2030. Resources Policy, 62, 541–549.

[8] Li, Q., Wen, B., Wang, G., Cheng, J., Zhong, W., Dai, T., ... & Han, Z. (2018). Study on calculation of carbon emission factors and embodied carbon emissions of iron-containing commodities in international trade of China. Journal of Cleaner Production, 191, 119-126

[9] Zhong, W., Dai, T., Wang, G., Li, Q., Li, D., Liang, L., Sun, X., Hao, X., & Jiang, M. (2018). Structure of international iron flow: Based on substance flow analysis and complex network. Resources, Conservation and Recycling, 136, 345–354.

[10] Mousavi, B., Lopez, N. S. A., Biona, J. B. M., Chiu, A. S. F., & Blesl, M. (2017). Driving forces of Iran's CO_2 emissions from energy consumption: An LMDI decomposition approach. Applied Energy, 206, 804–814.

[11]Laporte, J. P., Román-Collado, R., & Cansino, J. M. (2024). Key driving forces of energy consumption in a higher education institution using the LMDI approach: The case of the Universidad Autónoma de Chile. Applied Energy, 372, 123797.

[12]Yang, X., Wang, S., Zhang, W., Li, J., & Zou, Y. (2016). Impacts of energy consumption, energy structure, and treatment technology on SO_2 emissions: A multi-scale LMDI decomposition analysis in China. Applied Energy, 184, 714–726.

[13] Xu, S.-C., He, Z.-X., & Long, R.-Y. (2014). Factors that influence carbon emissions due to energy consumption in China: Decomposition analysis using LMDI. Applied Energy, 127, 182–193.

[14] Miao, Y., Lu, H., Cui, S., Zhang, X., Zhang, Y., Song, X., & Cheng, H. (2024). CO_2 emissions change in Tianjin: The driving factors and the role of CCS. Applied Energy, 353, 122122.

[15] Liu, Y.-Z., Su, C., & Zhang, W.-W. (2024). A multi-region analysis on drivers of energy related CO_2 emissions in India from 2013 to 2021. Applied Energy, 355, 122353.

[16] Yang, X., & Su, B. (2019). Impacts of international export on global and regional carbon intensity. Applied Energy, 253, 113552.

[17] Hoekstra, R., & van den Bergh, J. C. J. M. (2003). Comparing structural decomposition analysis and index. Energy Economics, 25(1), 39–64.

[18] Eurostat. (2025). Complete energy balances [Data set]. Eurostat. https://doi.org/10.2908/nrg_bal_c

[19] International Energy Agency. (2023). World energy statistics [Data set]. IEA. https://www.iea.org/data-and-statistics

[20] U.S. Energy Information Administration. (2025). Manufacturing energy consumption survey (MECS) — Manufacturing energy consumption [Data set]. EIA. https://www.eia.gov/consumption/manufacturing/

[21] NBSC. China energy statistical yearbook 2021. Beijing: China Statistics Press; 2023

[22] Nippon Steel. (2022). Nippon Steel Factbook 2022 [Factbook]. Nippon Steel. Retrieved 2025-08-03, from https://www.nipponsteel.com/en/factbook/2022/

[23] Ministry of Economy, Trade and Industry (METI). (n.d.). METI statistics [Data portal]. Government of Japan. Retrieved 2025-08-03 from https://www.meti.go.jp/english/statistics/index.html

[24] Korea Energy Economics Institute. (2023). KEEI statistics database: Energy board [Data set]. KEEI. Retrieved 2025-07-29, from https://kesis.keei.re.kr/board.es?mid=a20301020000&bid=0047

[25] Intergovernmental Panel on Climate Change (IPCC). (2006). 2006 IPCC guidelines for national greenhouse gas inventories (Vols. 1–5). IGES. https://www.ipcc-nggip.iges.or.jp/public/2006gl/

[26] World Steel Association. (2022). Steel Statistical Yearbook 2022 [Statistical publication]. Retrieved 2025-08-23 from https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2022.pdf

[27] USGS, 2023. Iron Ore Statistics and Information. Retrieved 2025-08-23 from https://www.usgs.gov/centers/nationalminerals-information-center/iron-ore-statistics-and-information

[28] United Nations, 2021. UN Comtrade Database. Retrieved 2025-06-20 from https://comtrade.un.org/

[29] Steelonthenet.com. (n.d.). Steel industry intelligence platform [Data & market intelligence]. Retrieved 2025-06-26, from https://www.steelonthenet.com/