Structural Decomposition Analysis of Consumption-based CO_2 Emissions in Major Economies during 2007–2023

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Abstract

This study estimates consumption-based CO_2 emissions across major economies from 2007 to 2023 and evaluates the drivers of emission changes using structural decomposition analysis (SDA), based on multi-regional input-output (MRIO) tables. The differences between consumption-based and production-based emissions reveal emissions embodied in international trade by region and by sector. We use the Asian Development Bank Multi-Regional Input-Output (ADB-MRIO) database, which provides continuous time series including the COVID-19 pandemic period, with IEA CO_2 statistics. We decompose emission changes into three factors: emission intensity, intermediate input structure, final demand effects. This decomposition identifies components related to emission reduction. A sensitivity analysis comparing results with the GTAP database for the benchmark year (2017) evaluates the robustness of findings across different data sources. The study provides updated evidence on consumption-based emissions using the latest available data and offers policy implications for decarbonization in major and global economies.

Keywords: Consumption-based CO_2 emissions, Structural decomposition analysis, Multi-regional input-output analysis, Climate change, International trade

1. Introduction

For addressing climate change, a comprehensive understanding of CO_2 emissions and their underlying drivers is essential. Production-based emission (PE) inventories, which account for emissions from combustion within a country, are the standard for international climate agreements and the GHG statistics. On the other hand, consumption-based emission (CE) accounting provides complementary insights by tracing emissions embodied in international trade (Peters, 2008; Wiedmann, 2009). This approach reveals the extent to which countries are offshoring their emissions through the import of goods and services.

Structural decomposition analysis (SDA) is a well-established framework for identifying drivers of time-series emission changes. By decomposing emission changes into components such as improvements in emission intensity, structural shifts in production, and changes in final demand, SDA provides actionable information for identifying effective components for emission reduction (Hoekstra and van den Bergh, 2003; Su and Ang, 2012).

However, previous studies had several limitations. First, most existing studies rely on data ending before 2020, missing the significant disruptions caused by the COVID-19 pandemic. The pandemic induced irregular changes in economic activity, supply chains, and consumption patterns, leading to a decline of approximately 5% in global CO_2 emissions in 2020 (IEA, 2024). Whether these changes represent temporary shocks or lasting structural shifts remains an important empirical question. Second, comprehensive cross-country comparisons using the latest available data are limited, making it difficult to identify common and divergent patterns across major economies at different stages of development.

This study conducts SDA analysis of consumption-based CO_2 emissions for 26 major economies from 2007 to 2023. We utilize the ADB-MRIO database (ADB, 2024), which provides continuous time-series data covering the COVID-19 pandemic and subsequent years, with IEA CO_2 statistics (IEA, 2024). Our analysis aims to: (1) quantify the contributions of different factors to consumption-based emission changes in major economies; (2) identify distinct patterns across country groups; and (3) assess the robustness of results by comparing with the GTAP database.

2. Methodology

2.1 Consumption-based CO_2 Emissions Accounting

Consumption-based CO_2 emissions are estimated using the multi-regional input-output (MRIO) framework. This approach is consistent with the methodology developed by the OECD for their trade in embodied CO_2 indicators (Yamano and Guilhoto, 2020). The basic MRIO formulation is given by:

$$x = (I - A)^{-1} y = Ly$$

where x is the total output vector, A is the inter-regional input coefficient matrix, I is the identity matrix, $L = (I - A)^{-1}$ is the Leontief inverse matrix, and y is the final demand vector. The consumption-based CO_2 emissions are then expressed as:

$$CE = e' L y$$

where e is the vector of direct CO_2 emission coefficients (emissions per unit of output) and y is the final demand vector for consumption of goods and services. This formulation evaluates both domestic emissions and indirect emissions embodied in imports. The emissions embodied in net imports (CE − PE) indicate the extent to which a country offshores its emissions through international trade.

2.2 Structural Decomposition Analysis

To identify the drivers of emission changes, we decompose consumption-based emissions into four factors (Dietzenbacher and Los, 1998; Su and Ang, 2012):

$$CE = E \cdot L \cdot Y$$

where E is the diagonal matrix of sectoral emission intensity, L is the Leontief inverse matrix capturing intermediate input structure, and Y is total final demand. The change in emissions between time 0 and T is decomposed as:

$$\Delta CE = CE^T - CE^0 = \Delta E + \Delta L + \Delta Y$$

Each factor corresponds to a distinct driver. ΔE captures changes in emission intensity reflecting technological improvements and fuel switching. ΔL reflects changes in supply chain structure, including shifts in industrial intermediate input patterns. ΔY represents demand growth effects, primarily driven by economic growth. Following the approach of Dietzenbacher and Los (1998), we use the average of polar decompositions to address the non-uniqueness problem inherent in SDA.

2.3 Data Sources

This study uses the ADB-MRIO database at constant 2010 prices (ADB, 2024), which contains national input-output tables, international trade flows, and value-added data for 26 world regions and 18 industry sectors covering 2007–2023. For CO_2 emissions, we use IEA sectoral CO_2 emission statistics (IEA, 2024). In our production-based CO_2 emissions, emissions from electricity and heat production are allocated to respective demand sectors based on the IEA energy balance tables. Consistent with IEA CO_2 statistics and UNFCCC inventories, emissions from international bunkers (international aviation and maritime transport) are excluded from national emission totals. It should be noted that the OECD estimates (Yamano and Guilhoto, 2020) include international bunker emissions in their analysis.

To assess the robustness of our findings, we compare results from the ADB-MRIO database with the GTAP database for overlapping years. Since the GTAP database provides only limited benchmark years, we conduct a static comparison for 2017. This analysis identifies regions and sectors where database choice significantly affects results and provides guidance for data improvement priorities.

3. Results

3.1 Emissions Embodied in Trade: Global Patterns

Figure 1 shows the emissions embodied in net imports (EET) for major economies over the study period. The results illustrate how international trade shifts embodied CO_2 emissions across economies. Major developed regions, including the United States, the European Union, and Japan, are net importers of CO_2 emissions, while China is the largest net exporter. Most other emerging economies also show net export patterns in recent years, reflecting their roles as manufacturing hubs in global supply chains. The level of emissions embodied in trade grew steadily until 2019. A temporary decline in embodied emissions was observed in 2020, reflecting the decrease in global trade during the COVID-19 pandemic. In the subsequent years, a recovery trend was estimated.

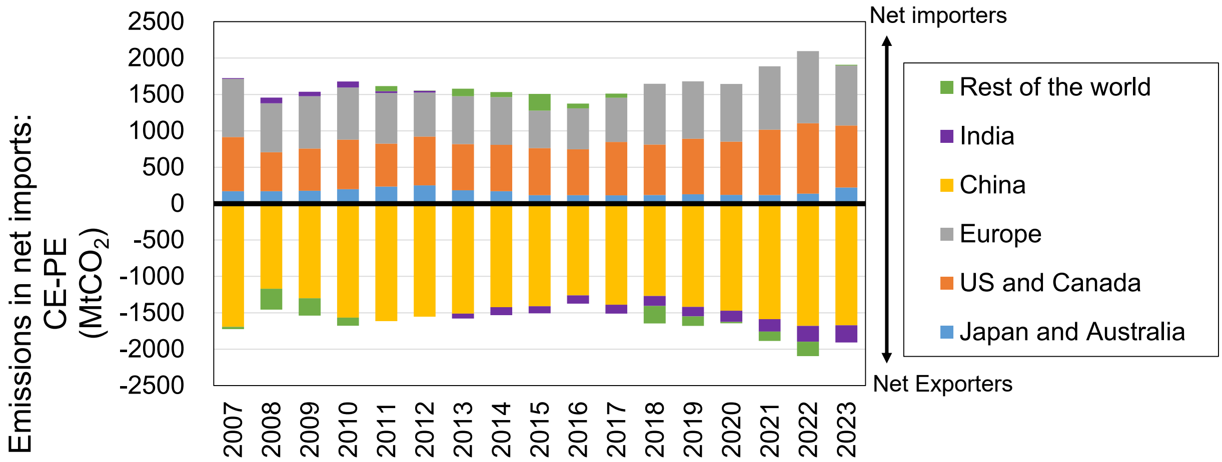

Figure 1 Emission embodied in trade

3.2 Regional Emissions Embodied in Trade

Among Asian economies, the analysis reveals an asymmetric emission transfer structure. Japan and Australia are net importers of CO_2 emissions (EET > 0), while Indonesia, Vietnam, and Thailand are net exporters (EET < 0), with these patterns continuing and slightly expanding in recent years. This reflects the broader global tendency for CO_2-intensive manufacturing to shift from developed to developing countries.

For Japan, the country-level analysis shows that China is the largest source of emissions embodied in imports, particularly in energy-intensive sectors such as the metals industry (including steel). This suggests a pattern of production relocation from Japan to China.

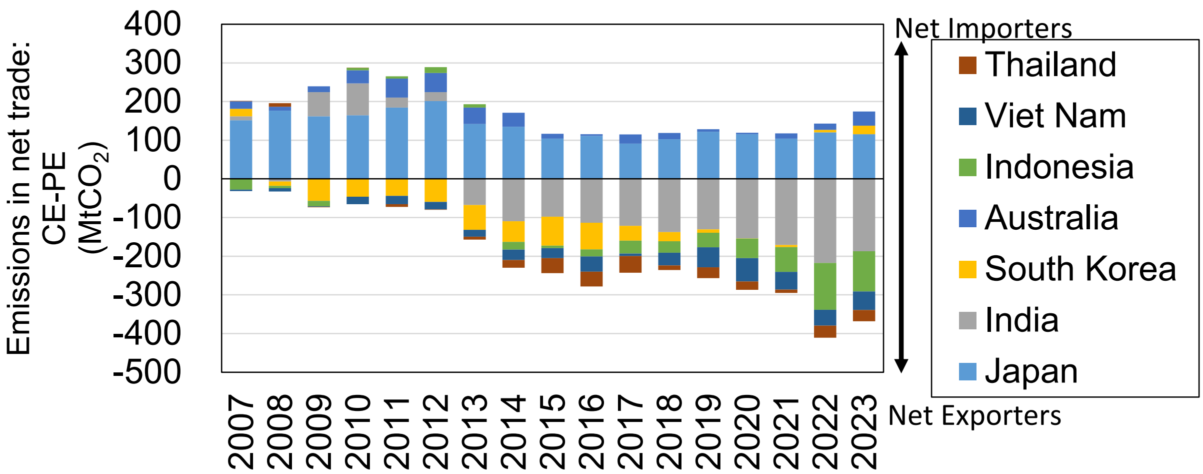

Figure 2 Emission embodied in trade for major Asian regions (except for China)

3.3 Decomposition of Emission Changes

The decomposition analysis of emissions embodied in trade, following the approach of Xu and Dietzenbacher (2014), decomposes changes in trade-embodied CO_2 emissions into three factors: CO_2 intensity effects, production structure (Leontief structure) effects, and final demand effects. Preliminary results for selected Asian economies indicate that no single factor dominates the annual changes in EET across the countries examined. All three factors contribute to varying degrees, suggesting that emission reduction in the context of international trade requires a multi-faceted policy approach combining technological improvement, industrial restructuring, and demand-side management.

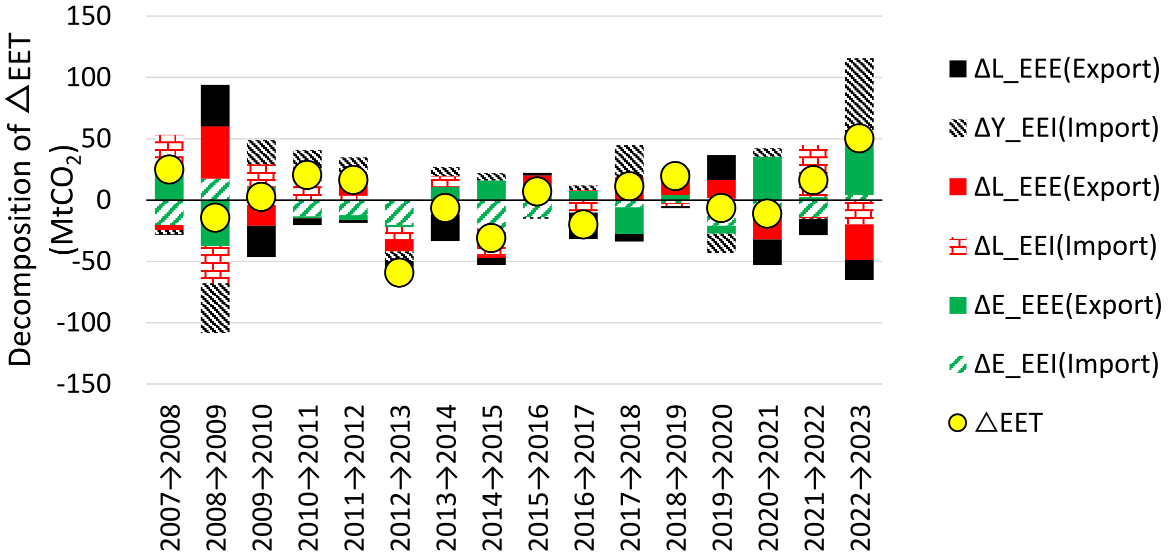

Figure 3 Decomposition of annual changes in EET in Japan

4. Expected Contributions

This study is expected to make several contributions. First, we provide updated estimates of consumption-based emissions for major economies from 2007 to 2023, covering the most recent period including the COVID-19 pandemic and subsequent recovery, and analyze their drivers using structural decomposition analysis.

Second, the cross-country comparison across 26 regions identifies patterns at different stages of economic development. The analysis reveals asymmetric emission transfer structures among economies, particularly highlighting the role of energy-intensive industries in shaping trade-embodied emission patterns. As a policy implication, the decomposition results identify influential components for emission reduction.

Third, the database comparison between ADB-MRIO and GTAP provides useful insights into the sensitivity of consumption-based emission estimates to data source choices, contributing to database development efforts and helping quantify uncertainty ranges.

5. Concluding Remarks

This study provides an updated and comprehensive analysis of consumption-based CO_2 emissions in major economies from 2007 to 2023, using the ADB-MRIO database combined with IEA CO_2 statistics. The structural decomposition analysis framework enables the identification of key drivers behind emission changes, including technological improvements, industrial restructuring, demand growth. The results indicate that international trade plays a significant role in redistributing CO_2 emissions across economies, with developed countries generally being net importers and emerging economies being net exporters of embodied emissions. The decomposition analysis suggests that no single factor dominates emission changes, underscoring the need for comprehensive policy approaches to decarbonization that address multiple dimensions simultaneously.

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