

Cross-border emissions in the service sector: A global analysis of environmental and economic linkages

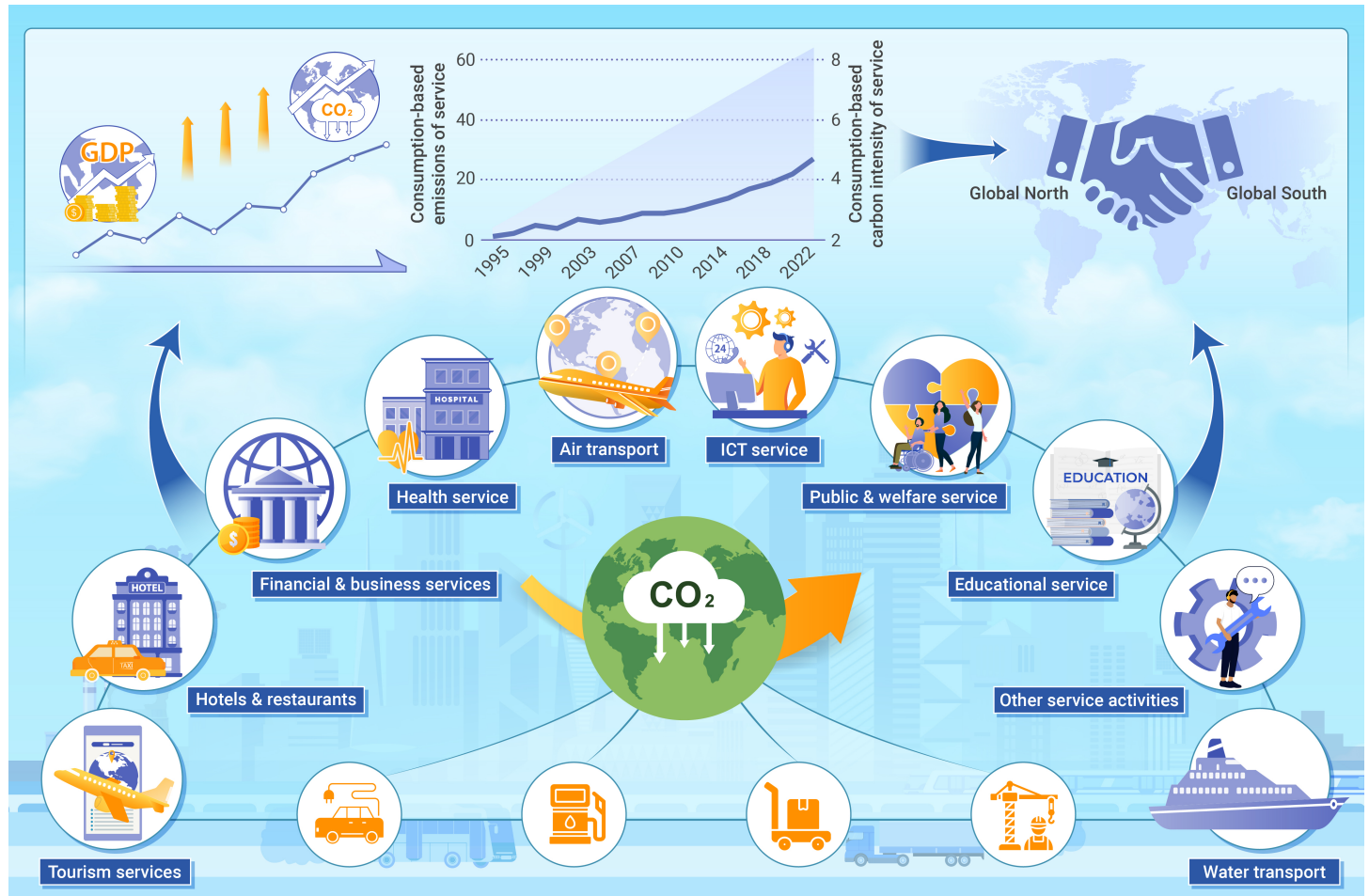
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- The service sector caused 63% of consumption emissions rise, led by public, health, and financial services.
- Developed nations are net importers of service-related emissions, while developing ones are net exporters.
- Enhancing efficiency and green-tech investment in high-impact service sectors are key for cutting emissions.

Cross-border emissions in the service sector: A global analysis of environmental and economic linkages

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The global service industry, commonly perceived as low-carbon, is in fact a significant driver of emissions growth. Yet, traditional emission-accounting-based assessments have overlooked the transmission pathways of emissions in the service industry across regions, thereby making it difficult to uncover its dynamic and complex spatial and industrial interconnections. This study addresses this gap by using multi-regional input-output (MRIO) analysis and structural path decomposition (SPD) to examine consumption-based emissions (CBE) in the service sector across multiple countries from 1995 to 2021, offering new insights for targeted mitigation strategies. Results reveal a steady 63% increase in the global CBE of services, primarily driven by the expansion in public, health, and financial services. While developed countries are net importers of embodied emissions in services, developing nations largely serve as net exporters, with transportation—especially air and water transport—contributing significantly to carbon intensity. China, the United States, and Japan emerge as the top service-sector emitters, highlighting the critical role of both direct and complex intermediate inputs in driving emissions. The study underscores the need for efficiency improvements and green technological investments, particularly in transport and high-impact service sectors, to mitigate emissions while supporting service sector growth. These findings offer insights for policymakers on prioritizing sector-specific and cross-border strategies to achieve sustainable development in the global service industry.

INTRODUCTION

The service industry has evolved into a crucial component of both developed and developing nations' economies. Following the global financial crisis of 2008 and the subsequent pandemic shock, the service industry's contribution to economic outputs has markedly escalated on a global scale, driving global economic growth. The value added by services constituted 74% of GDP in high-income countries and 56.9% of GDP in low- and middle-income regions in 2015.¹ Compared to manufacturing, the service industry's lack of physical presence and its "dematerialization" are emissions-light and producing minimal direct pollution.^{2,3} This is a misperception, though, which directs attention towards the economic benefits of the service industry and away from its environmental implications.

The greenhouse gas (GHG) emissions of the service industry in developed countries have been explored from a production-based perspective, illustrating that the service industry only accounted for a limited share of GHG emissions.^{4,5} However, the service industry's emissions are significantly higher than previously thought when imported inputs are considered from the consumption-based perspective.⁶ Especially in the international transportation sector, which is a high polluted sector and faces the great challenges to net-zero pathway,⁷ it is highly associated with the change in consumption pattern, travel habits and consumption level. In some developing countries, such as China, the growth of carbon emissions in the service industry have surpassed the growth of national economy since 2016.⁸ Thus, it is widely accepted that the production-based emissions of the service industry, which are largely caused by energy use and transportation, are lower than consumption-based emissions (CBE).⁹⁻¹²

Allowing for the identification of cross-border emissions, CBE accounting is critical to emissions reduction in the service industry.^{13,14} Cross-border environmental impacts take place when a country imports pollution-intensive products from other countries to support its service industry; when, however, the final products of the service industry are immaterial and provided to consumers in the form of services, these impacts take the specific form of "cross-border outsourcing". The footprint and bilateral embodied carbon flow in specific service industry, such as tourism, plays a significant role in the ascend of carbon emissions.^{3,15} More importantly, the participation of service industry in global value chains may also affect global emissions as it involves a series of cross-border activities. Thus, it is crucial to clarifying transmission paths and identifying influencing factors for deepening our understanding of the cause of service industry emissions.

Multi-regional Input-output (MRIO) analysis is a suitable method for probing cross-border emissions within the global production network, aiming to examine the interconnectedness of diverse industries across different economies.¹⁶⁻¹⁸ Structural Path Decomposition (SPD) merges Structural Path Analysis (SPA) with Structural Decomposition Analysis (SDA). SPA is a methodology for assessing the contribution of various production pathways to economic and environmental indicators,^{19,20} such as carbon emissions,²¹⁻²³ in specific industry.^{24,25} Combined with SDA, which is usually applied to investigate the driving forces of changes, SPD is used to analyze the contributions of different sectors to overall economic outcomes by breaking down complex interconnections within a system into simpler, identifiable pathways.²⁶ However, one of the shortcomings of SPA is its static use; this study, in comparison, sought for a comprehensive understanding of dynamic changes over the study period. The key driving factors in each transmission layer were assessed by SDA.

Previous research on the emissions of service sectors has confined to a production-based perspective and a limited range of aspects. First, few studies have tackled the CBE of the service industry, thus neglecting a comprehensive analysis of the environmental footprint of the service sector. Second, while the emissions of specific service sectors have been investigated at the country and region levels, few studies have tracked the embodied emissions flows of the entire industry. Third, the extensive utilization of both scenario analysis and the Logarithmic Mean Divisia Index in studying the driving forces behind service industry emissions has caused scholars to neglect the industrial connections among different regions. To fill these knowledge gaps, this study attempts to apply an MRIO analysis and SPD in order to investigate (1) the evolutionary change of CBE of the service industry; (2) the transfer networks of emissions embodied in the service industry (EESI); and (3) the detailed industrial paths of emission changes and the outcomes of different determinants on each path in the service industry. Our research seeks to explore additional dimensions by: (1) investigating sector-specific decarbonization challenges within the service sectors of major countries, such as the United States and China; (2) quantifying the embodied emissions of the service sector at the transmission layer level; and (3) analyzing the environmental spillover effects of China's service sector, which significantly influence the emissions of the global service industry at both national and sectoral scales.

MATERIALS AND METHODS

CBE of the service industry

Assuming there are n regions globally, the structure of the MRIO can be depicted as:

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix} = \begin{bmatrix} a^{11} & a^{12} & \cdots & a^{1n} \\ a^{21} & a^{22} & \cdots & a^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a^{n1} & a^{n2} & \cdots & a^{nn} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix} + \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} \quad (1)$$

Furthermore, the equation (1) can be rewritten in matrix form with the Leontief matrix, as shown in equation (2):

$$X = AX + Y = (I - A)^{-1}Y = BY \quad (2)$$

The B matrix is the Leontief inverse matrix, illustrating the direct and indirect sectoral linkages; here, $f = (f_1^1, f_1^2, \dots, f_1^n, f_2^1, f_2^2, \dots, f_2^n, \dots, f_n^1, f_n^2, \dots, f_n^n)$ is defined using the sectoral carbon intensity coefficient in each region—that is, the proportion of sectoral carbon emission in each region to its total output—and “diag (.)” denotes the diagonalization of a matrix. Thus, the carbon emissions that are induced by final demand (CBE) can be illustrated as:

$$EC = \text{diag}(f)BY \quad (3)$$

where $EC = (EC_1^1, EC_1^2, \dots, EC_1^n, EC_2^1, EC_2^2, \dots, EC_2^n, \dots, EC_n^1, EC_n^2, \dots, EC_n^n)$.

To demonstrate carbon emissions' incorporation into international trade flows, the embodied emissions triggered by final demand can be introduced and described by means of equation (4):

$$\begin{bmatrix} EC^{11} & EC^{12} & \cdots & EC^{1n} \\ EC^{21} & EC^{22} & \cdots & EC^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ EC^{n1} & EC^{n2} & \cdots & EC^{nn} \end{bmatrix} = \begin{bmatrix} f^1 & 0 & \cdots & 0 \\ 0 & f^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & f^n \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1n} \\ B^{21} & B^{22} & \cdots & B^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ B^{n1} & B^{n2} & \cdots & B^{nn} \end{bmatrix} \begin{bmatrix} Y^{11} & Y^{12} & \cdots & Y^{1n} \\ Y^{21} & Y^{22} & \cdots & Y^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y^{n1} & Y^{n2} & \cdots & Y^{nn} \end{bmatrix} \quad (4)$$

In our model, EC^{rs} represents the carbon emissions exports from region r to region s , indicating the transfer of emissions embodied in the service sector (EESI). Therefore, the embodied emissions of region r 's service industry to region s can be written in the matrix form:

$$EC_i^{rs} = \text{diag}(f_i)B_iY^s \quad (5)$$

which reflects the carbon emissions resulting from the service industry required to meet a nation's demand for goods and service. In this study, consumption-based emissions (CBE) within the service sector are defined as the total carbon emissions produced by consumption activities related to services. Emissions embodied in the service industries (EESI), on the other hand, pertain to the emission flows embodied within the service sector.

Moreover, the aggregated embodied intensity (AEI) of the service industry is introduced to evaluate the emission performance of the service sector. According to Koopman et al. (2014),²⁷ the value added of various sectors of each country from the consumption-based view can be approximated as:

$$VA = \text{diag}(v)BY = HY \quad (6)$$

where $VA = (VA_1^1, VA_1^2, \dots, VA_1^n, VA_2^1, VA_2^2, \dots, VA_2^n, \dots, VA_n^1, VA_n^2, \dots, VA_n^n)$ is the sectoral value added in various regions. $v = (v_1^1, v_1^2, \dots, v_1^n, v_2^1, v_2^2, \dots, v_2^n, \dots, v_n^1, v_n^2, \dots, v_n^n)$ is the sectoral value-added coefficient in each region—that is, the proportion of sectoral value added in each region to its gross output. H denotes the input-output structure matrix. In contrast to B , H is the matrix showing the coefficients of the economic value required by a standard factor H_{ij}^s , i.e., the value added induced by sector i in region r to satisfy per final consumption of sector j in region s . Therefore, the AEI of the service industry can be formulated as:

$$AEI_i = \frac{EC_i}{VA_i} = \frac{\text{diag}(e_i)H_iY}{I^sH_iY} = \frac{\sum EC_{is}}{\sum VA_{is}} = \sum \left(\frac{VA_{is}}{VA_i} \right) \left(\frac{EC_{is}}{VA_{is}} \right) = \sum w_{is}AEI_{is} \quad (7)$$

In the above equation, e_i represents the direct emission intensity—the

proportion of sectoral carbon emission in each country to its total value added; EC_i is the CBE of the service industry; and H_i is the value chain coefficient matrix of the service industry's consumption for other industries. $w_{is} = VA_{is}/VA_i$ is the share of value added embodied in service sectors. The contribution of specific service sector to the AEI of the service sector in aggregate can be calculated as $(w_{is}AEI_{is})/AEI_i$.

In input-output analysis, two approaches are used for measuring sectoral carbon emission intensity: f_i is the ratio of carbon emissions to its gross output^{28,29} and e_i is the proportion of carbon emissions to its value added.³⁰ The results from these two approaches differ. The former measures total carbon emissions based on total output, while the latter evaluates environmental efficiency at the consumption level, specifically CBE per unit of value added. We adopted the second definition to calculate AEI, ensuring sectoral-level consistency. In equation (7), I denotes a unit vector.

Structural path analysis of the EESI

In the principle of SPA, the Leontief inverse matrix in Equation (2) is transformed into the Taylor expansion form, which can be shown as:

$$(I - A)^{-1} = I + A + A^2 + A^3 + \cdots = I + A + A^2 + A^3 + A^{(>3)} \quad (8)$$

Therefore, the path decomposition of the EESI can be formulated as equation (9):

$$EC = f(I - A)^{-1}Y = \underbrace{fIY}_{1st\ layer} + \underbrace{fAY}_{2nd\ layer} + \underbrace{fA^2Y}_{3rd\ layer} + \underbrace{fA^3Y}_{4th\ layer} + \underbrace{fA^{(>3)}Y}_{other} \quad (9)$$

In modern industrial structures, sectoral linkages extend infinitely in upstream and downstream directions, captured by SPA.³¹ Equation (9) facilitates the analysis of higher-order environmental contributions through upstream production structures. The total environmental impact encompasses direct impacts from manufacturing (1st layer) and indirect impacts from upstream processes (e.g., 2nd layer).

The 1st layer (fIY) indicates direct emissions within the service industry—that is, it measures the intermediate environmental impact of final demand on the service industry. For more complex service activities, other sectors need to invest in AY , resulting in embodied emissions in the 2nd layer (fAY). The greater the number of sectors that are regarded as inputs, the greater the increases to A^2Y , leading to indirect emissions in the 3rd layer (fA^2Y). Likewise, $fA^{(>3)}Y$ is the emissions of other layers, and its industrial path has witnessed more than three times of inputs transfer to achieve higher complexity of the service industry. The first 4 layers generally cover over 80% of the environmental footprint, and the results after the higher layers are less explanatory.³² Thus, this paper investigates the first four transmission layers and higher layers are aggregated into the category “other.”

Structural path decomposition of the EESI

SPD can be used to apply the crucial transmission layers and driving factors involved in the change of emissions in each layer. According to Equation (5), the change of EESI can be divided into several influencing factors:

$$\Delta EC_i = EC_i^1 - EC_i^0 = \text{diag}(f_i^1)B_i^1Y^1 - \text{diag}(f_i^0)B_i^0Y^0 = \Delta fBY + \Delta f\Delta BY + \Delta B\Delta Y \quad (10)$$

where ΔEC_i is total change in the EESI. Δf , ΔB , and ΔY show changes in EESI that are affected by changes in emission intensity, the input-output structure, and final demand, respectively. Final demand can be disentangled into demand structure (ΔY_{str}) and demand level (ΔY_{lev}). The subscripts 0 and 1 stand for the base period and end year. Specifically, change in the technical coefficient structure indicates change in the production structure.

Based on Su et al. and Li et al.,^{33,34} various factors can be further disintegrated into different transmission layers, and Equation (10) can be expanded as:

$$EC = \Delta(fY) + \Delta(fAY) + \Delta(fA^2Y) + \Delta(fA^3Y) + \Delta(fA^{(>3)}Y) = \underbrace{\frac{1}{2}\Delta f(Y_0 + Y_1)}_{1st\ layer} + \frac{1}{2}(f^1 + f^0)\Delta Y$$

$$\begin{aligned}
& + \frac{1}{6} \Delta f [A_0(2Y_0 + Y_1) + A_1(2Y_1 + Y_0)] + \frac{1}{6} [f^0 \Delta A(2Y_0 + Y_1) + f^1 \Delta A(2Y_1 + Y_0)] \\
& + \frac{1}{6} \underbrace{[(2f^0 + f^1)A_0 \Delta Y + (2f^1 + f^0)A_1 \Delta Y]}_{\text{2nd layer}} \\
& + \frac{1}{6} \Delta f [A_0 A_0(2Y_0 + Y_1) + A_1 A_1(2Y_1 + Y_0)] \\
& + \frac{1}{6} [f^0 \Delta A A_1(2Y_0 + Y_1) + f^1 \Delta A A_1(2Y_1 + Y_0)] \\
& + \frac{1}{6} [f^0 A_0 \Delta A(2Y_0 + Y_1) + f^1 A_0 \Delta A(2Y_1 + Y_0)] \\
& + \frac{1}{6} \underbrace{[(2f^0 + f^1)A_0 A_0 \Delta Y + (2f^1 + f^0)A_1 A_1 \Delta Y]}_{\text{3rd layer}} \\
& + \frac{1}{6} \Delta f [A_0 A_0 A_0(2Y_0 + Y_1) + A_1 A_1 A_1(2Y_1 + Y_0)] \\
& + \frac{1}{6} [f^0 \Delta A A_1 A_1(2Y_0 + Y_1) + f^1 \Delta A A_1 A_1(2Y_1 + Y_0)] \\
& + \frac{1}{6} [f^0 A_0 \Delta A A_1(2Y_0 + Y_1) + f^1 A_1 \Delta A A_0(2Y_1 + Y_0)] \\
& + \frac{1}{6} [f^0 A_0 A_0 \Delta A(2Y_0 + Y_1) + f^1 A_1 A_1 \Delta A(2Y_1 + Y_0)] \\
& + \frac{1}{6} \underbrace{[(2f^0 + f^1)A_0 A_0 A_0 \Delta Y + (2f^1 + f^0)A_1 A_1 A_1 \Delta Y]}_{\text{4th layer}} \\
& + \underbrace{\Delta f A^{(>3)} Y + f \Delta A^{(>3)} Y + f A^{(>3)} \Delta Y}_{\text{higher layer}}
\end{aligned} \tag{11}$$

We analyze EESI drivers at the supply-chain level using SPD, suitable for micro-level analysis. The first layer reflects service sector emissions directly linked to final consumption, influenced by emission intensity and final demand (structure and level). The second layer incorporates the first-order technical coefficient structure A , illustrating inter-sectoral product and emission flows. The third and fourth layers include second- and third-order technical coefficient structures, respectively, capturing changes in complex input structures affecting EESI. Results of SPD for the first four layers are presented in this study.

Data

The analysis uses data from EXIOBASE3, a comprehensive EE-MRIO database covering 44 countries, 5 regions, and 163 sectors from 1995 to 2021. EXIOBASE3's high-resolution sector classification aligns well with the System of Environmental Economic Accounting (SEEA).³⁵ To address price comparability, a GDP deflator from the World Bank was applied to convert data to 2015 constant prices, consistent with current GDP calculations. Following Huo et al.³⁶, 28 service sectors from EXIOBASE3 were selected and aggregated into 10 categories for comparability and consistency (Table S1).

RESULTS

CBE and AEI of the service industry

The CBE of the global service industry were found to have increased steadily by 63% between 2021 (8,758 million tons) and 1995 (5,369 million tons), indicating an increasing environmental impact (Figure 1A). We found a significant increase in emissions during 1999–2000 and 2009–2010, with 9% and 5% increments. Moreover, the CBE of the global service industry accounted for approximately 30% of global emissions. In contrast, the value added by the global service industry represented nearly two-thirds of global value added during 1995–2021. The service industry is thus shown to be environmentally benign and critical to global economic growth.

Additionally, public and welfare services were shown to have driven CBE of a magnitude of 1,866 million tons, representing over 21.3% of the global EESI in 2021 (Figure 1A & Table S2). Health services and financial and business services were the second and third most significant drivers, accounting for 19.0% and 18.6% of the global EESI, respectively, in 2021. Public and welfare services sector typically involves large-scale infrastructure construction, energy consumption (such as in hospitals, schools, and government services), and the provision of extensive social services. These activities

require significant amounts of energy, resources, and materials, resulting in carbon emissions that are notably higher than those of other service sectors. The higher the share of these service sectors, the higher the public demand for public services and welfare, reflecting the contribution of human activities to carbon emissions in a service-oriented economy. Importantly, emissions from health services and ICT services both experienced significant growth (146.5% and 146.6%, respectively) between 1995 and 2021 (Table S2).

The AEI of the global service industry improved significantly, decreasing from 17.4 to 10.4 ton/thousand euro (−67.3%) during the study period, well below the global average (Figure 1B). This trend mirrored global patterns, declining gradually from 1995 to 2001, doubling during 2001–2008, and then falling by 43.3% from 2008 to 2021. Transport services—air, water, and inland transport—were key contributors to AEI. In 2021, water and air transport accounted for 24.4% and 23.7% of service industry AEI, respectively, followed by financial and business services (14.2%) (Table S3). According to Equation (7), the contribution of transport services to the AEI of the service sector in aggregate could be ascribed to the AEI of transport services and the share of value added in transport services. Transport services exhibited the highest AEI among all the service sectors, but the share of value added embodied in transport services accounted for less than 10% of the service sector in aggregate. In other words, high AEI of the transport sectors played an inhibited role in decreasing the AEI of the service sector in aggregate. Public and welfare services, education, and health services had minimal contributions, each accounting for less than 6%.

Significant spatial disparities in CBE and AEI are evident across national economies (Figures 2 & S1). EESI constituted a substantial portion of national CBE, particularly in European countries (Figure S1). Advanced economies like the United States, Canada, and Australia exhibited lower AEI compared to developing nations such as China and India. In 2021, Estonia, South Africa, Russia, Greece, and China had the highest service industry AEI, at 1087.8, 175.4, 150.4, 132.1, and 121.6 tons/thousand euro, respectively. In 1995, Bulgaria, China, Russia, Estonia, and Romania led with AEI of 611.7, 580.4, 517.6, 461.8, and 429.8 tons/thousand euro. Most countries, except Estonia and Japan, significantly reduced their AEI through energy efficiency improvements (Figure 2), a trend consistent in 2004 and 2013 (Figure S2).

In 2021, China, the United States, and Japan led in service industry CBE, with 2,466.4, 1,583.9, and 314.2 million tons respectively (Figure 2 & Table S4). China's CBE quadrupled from 561.5 million to 2,466.4 million tons during the study period. Sectoral contributions to CBE varied significantly across countries. In the USA, public and welfare services, financial and business services, and health services were dominant, with minimal changes over time (Figure 2). In China, public and welfare services contributed 19.5% to EESI in 1995, while financial and business services accounted for 17.5% and hotels and restaurants for 12.9% (Figure 2 & Table S4). By 2021, health services dominated at 37.4%, followed by public and welfare services (18.1%) and financial and business services (13.3%) (Figure 2 & Table S5). In Indonesia, water transport contributed 20% of emissions in 1995, but by 2021, public and welfare services accounted for one-third, reflecting increasing public health awareness in developing societies. These results indicate that China and Indonesia need to develop more effective carbon reduction strategies targeting the service sector, particularly in the areas of health and public welfare, in order to address the growing challenges of emissions.

The flows of EESI by region

Between 1995 and 2021, most developed countries were the net importers of EESI, such as the United States, the UK and Japan (Figures 3–4). In 2021, the EESI in the United States, the UK and Japan imported 141.8, 53.6 and 51.1 million ton, respectively. Air and water transport accounted for a significant proportion of the EESI, up to 40% in most net importing countries (Figure 3). This is partly owing to the increasing demand for international transport induced by prosperous international trade. Emissions embodied in imports from air transport and water transport accounted for 73%, 72% and 70% in Japan, the UK and Australia in 2021.

Russia, South Korea, and Germany were the main net exporters of EESI in 2021, while in 1995, Russia, Canada and China were the net exporters (Figure 3). However, the industrial composition of the emission embodied in the export varied across different countries. In Russia, other service activities

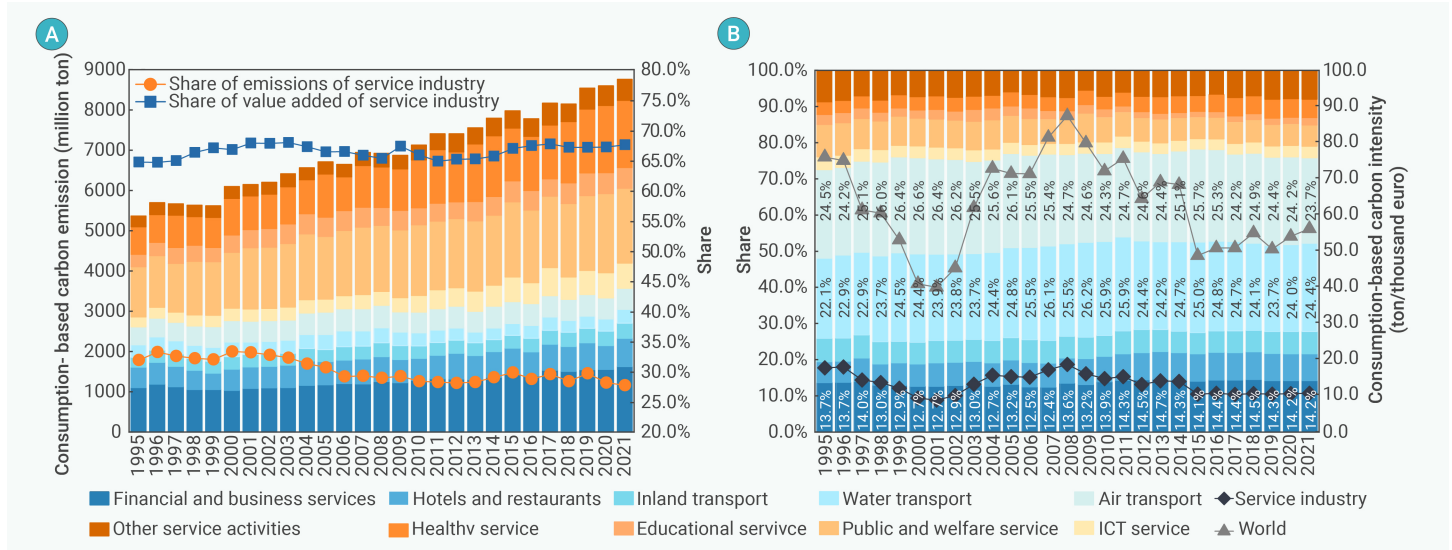


Figure 1. The CBE, AEI and value added of the service industry, 1995–2021 A. The CBE and value added of the service industry during 1995–2021. The percentage indicates the service industry's share of total emissions or total value added. B. The AEI of the service industry during 1995–2021. The percentage indicates the share of AEI by different service categories. The grey line and black line represent the AEI of the global economy and the global service industry.

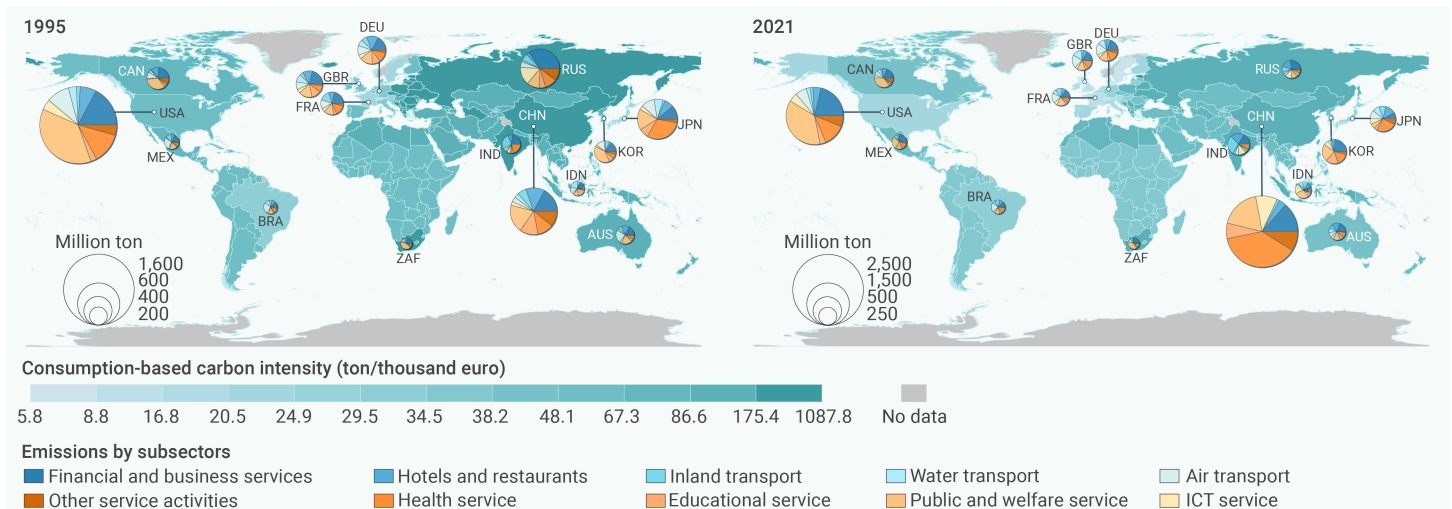


Figure 2. The CBE and AEI of the service industry by country in 1995 and 2021 The shading indicates the CBE of the service industry in each region. The pie charts represent the value of the CBE of the service industry and proportions of different categories in the top 15 countries with the highest CBE in 2021.

accounted for over 50% of the emissions exported, followed by air transport and water transport. In Indonesia, water transport and financial and business services were the two main categories of the emissions exported (Figure 3). Hotels and restaurants played a key role accounting for an increasing share of emissions embodied in trade, especially in advanced economies.

China changed from a net exporter of emissions to a net importer of emissions between 1995 and 2021. In 1995, China was a net exporter of emissions with 3.5 million ton, whilst it was a net importer of emissions with 17.9 million ton in 2021. Water transport and air transport were the main parts of emissions embodied in trade, together accounting for 70% and 55.7% in exports and imports, respectively in 2021. Financial and business services have become one of the most significant categories of emissions embodied in trade, accounting for 14.6% and 11.6% of emissions embodied in trade in 2021 (Figure 3).

The bilateral trade patterns in EESI significantly changed from 1995 to 2021 (Figure 4). Russia was the most important exporter to the UK's emissions, though the emissions exported from Russia to the UK declined from 9.9 million ton in 1995 to 5.3 million ton in 2021. However, the EESI exported from Russia to China experienced a significant increase from 2.4 million ton to 15.6 million ton during 1995–2021. WWA (RoW Asia) played a progressively significant role in shaping the EESI in China. The emissions exported from WWA (RoW Asia) to China increased by almost seven times from 2.3

million ton to 16.5 million ton during the study period. The USA has become one of the most significant importing destinations for EESI in China.

Figure S3 shows that advanced countries such as the United States, Canada, and western countries experienced the main transfer of EESI in 1995. However, the EESI shifted their center to China, Russia, and other emerging countries over the study period. This shift can be seen in the increases witnessed in the EESI flows from China to the United States and the rest of the world between 1995 and 2021.

Structural path analysis of the EESI

Based on Equation (10), the emissions contribution of the global service sector through transmission layers from 1995 to 2021 were calculated. The global EESI primarily stem from transmission structures comprising three layers or fewer (Figures 5 & S4).

The EESI of the first three layers occupied more than 70% of the CBE (Figure 5A). The emissions of global service sector are primarily derived from the three types of pathways, i.e., service sector → final consumption, intermediate input → service sector → final consumption, and intermediate input → intermediate input → service sector → final consumption, respectively. It is mainly ascribed to the direct role for service sector providing the service consumption for households.³⁷ As a significant contributor to EESI, transportation—encompassing water, air, and land transport—directly satis-

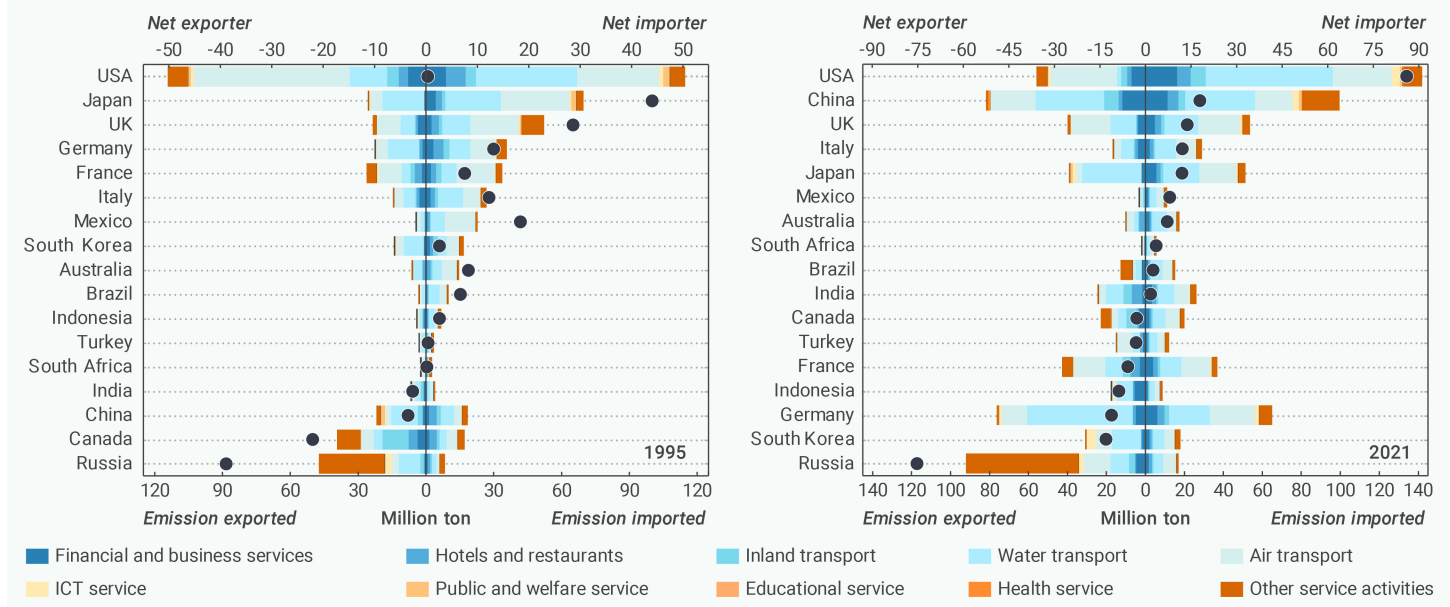


Figure 3. The carbon emission embodied in international trade of services, by subsector, of the 17 major countries in 1995 and 2021 The bars show the emissions embodied in ten service sectors of 17 major countries. The circles denote net imports or exports of EESI.

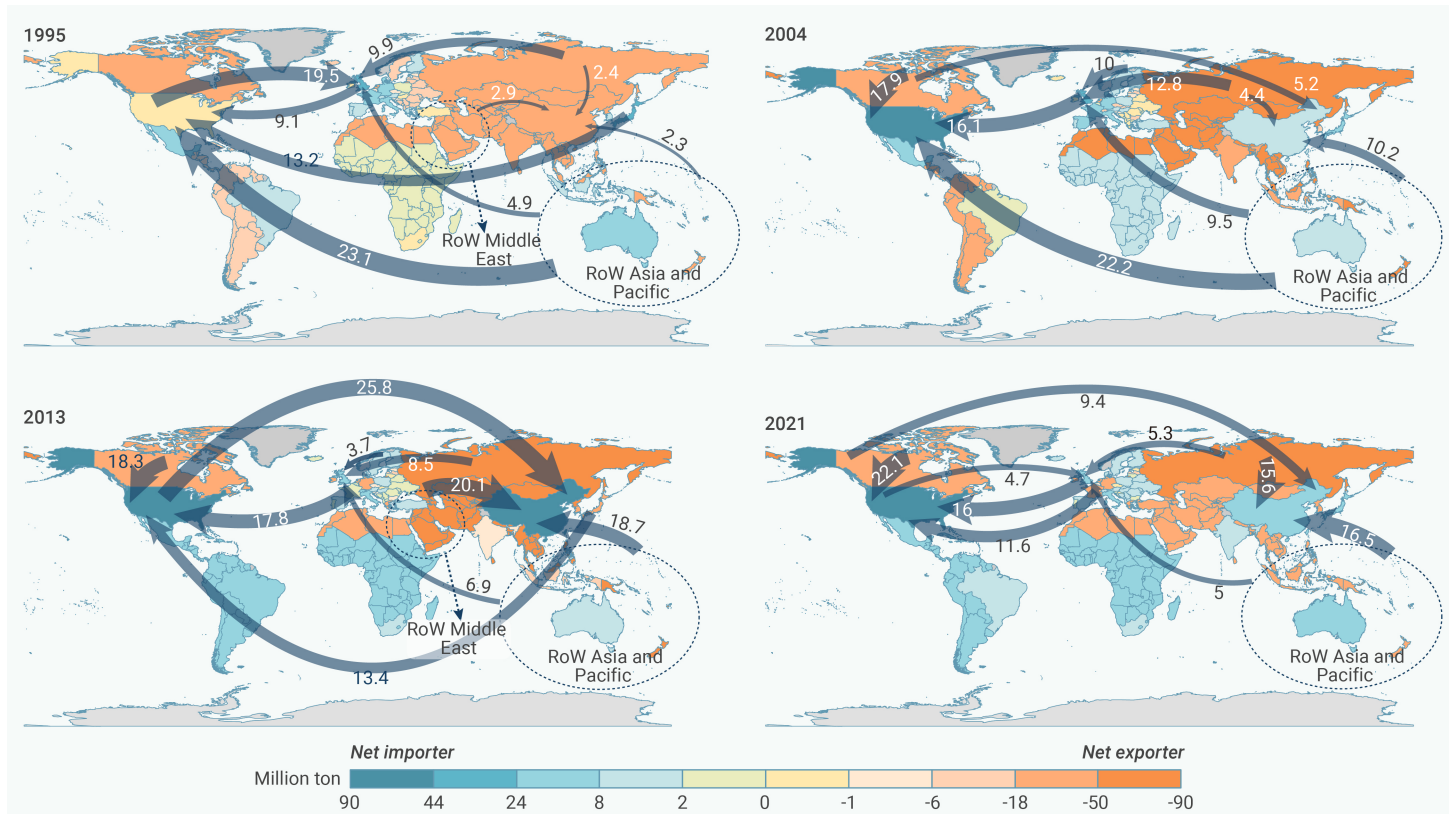


Figure 4. Global distribution of EESI in trade Net EESI in trade for each region (shading) and the emission inflow of the UK, the USA and China in 1995, 2004, 2013 and 2021. The shading illustrates the scale of net emissions embodied in trade, with net exporters depicted in red and net importers in blue. The UK, the USA, and China emerge as the top three net importers of EESI.

fies household service demands, thereby leading to carbon emissions directly triggered by households and making a single-layer transmission pattern (i.e., transport → final consumption). As a focal point in the low-carbon evolution of transportation,³⁸ electric vehicles have introduced a pathway wherein electric inputs → transport → final consumption, effectively shifting transport-related carbon emissions to the power industry.

Moreover, the transmission pattern with two layers (i.e., intermediate input → service sector → final consumption) made the greatest part to the global EESI (Figure 5A). Apart from renewable energy technologies, thermal

power generation predominates in many regions. Recently, renewable energy and clean technology have been the focus of financial and business services, health services, and republic welfare services. For instance, green and clean financial services require the input of green financial products and establishment of clean energy industry cluster, making the EESI develop a transmission pattern with two layers, i.e., green financial products → service sector → final demands. Therefore, enhancing the consumption-side emission reduction performance of the global service industry is crucial, with particular emphasis on optimizing the key transmission structures.

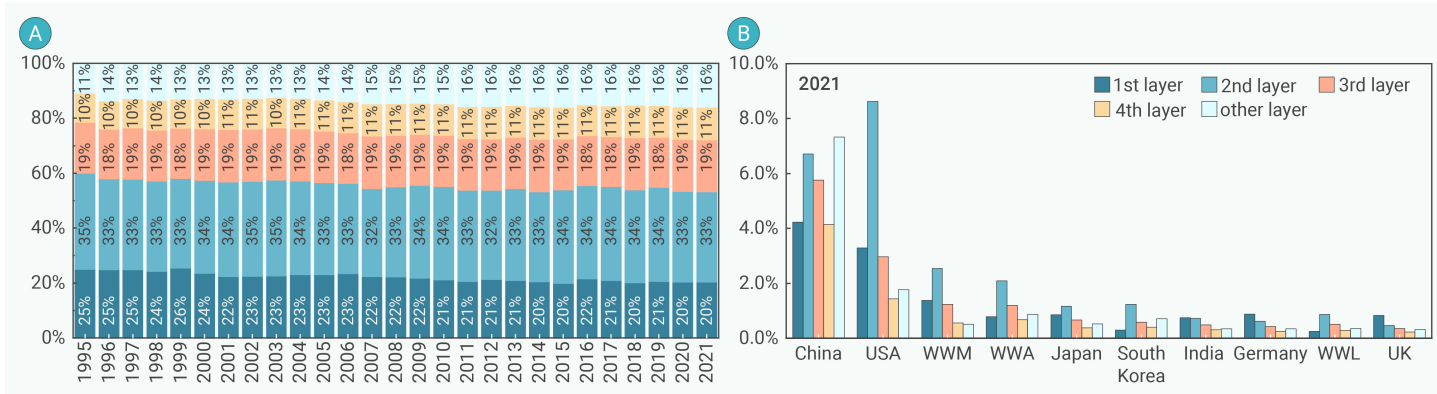


Figure 5. Contribution of each layer to the CBE of the service industry at the global and country levels.

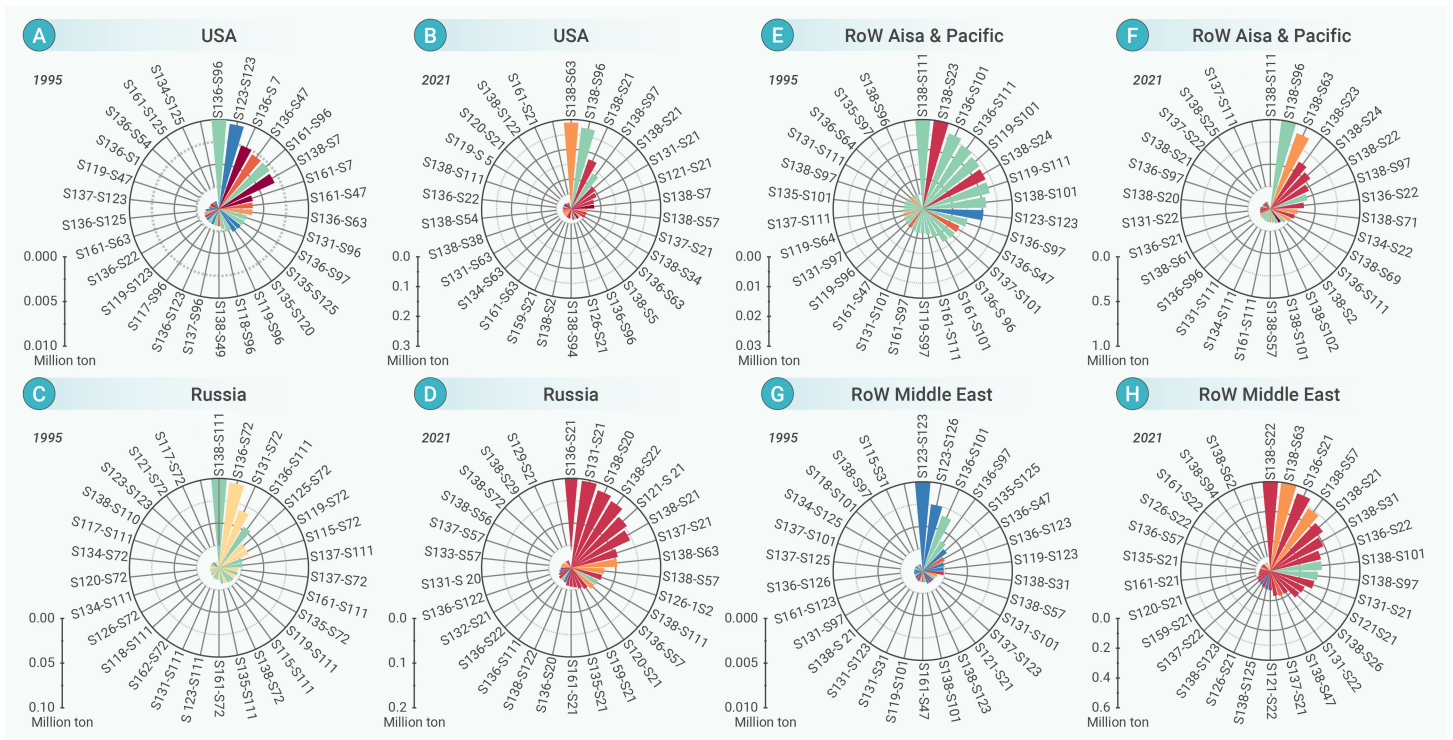


Figure 6. The sectoral impact of Chinese service industry on the USA, Russia, RoW Asia & Pacific and RoW Middle East at the second layer in 1995 and 2021. The preceding industry codes correspond to China's service sectors, while the subsequent codes represent industries in other countries. For example, in the upper right figure, S138-S96 indicates the environmental impact of China's S138 industry on the United States' S96 industry through the second layer. The full term of sector code is presented in Table S1.

The global service industry's emissions are driven primarily by the top 10 countries, which accounted for over 70% of total emissions in 2021 (Figure 5B). These countries—China, the United States, WWM (RoW Middle East), WWA (RoW Asia and Pacific), Japan, South Korea, India, Germany, WWL (RoW America), and the UK—collectively contributed 74.5%. Emissions impacts from China, WWM, WWL, India, and South Korea are rising, while those from the United States, Russia, Japan, the UK, France, and Germany were declining (Figure S2). Emerging economies, with their rapidly growing domestic service sectors, are playing an increasingly significant role in global emissions, necessitating greater attention to their escalating influence.

China, the United States, and Japan have always been the primary countries affecting the emissions of the global service industry. China's contribution to CBE rose from 10.5% in 1995 to 28.2% in 2021 (Figure 5B & S4). Since China acceded to the WTO, the breadth and depth of the global division of labor has been strengthened, as has China's role in accelerating the process of globalization. In recent years, under the "Belt and Road" strategy and boost of bilateral trade mechanism, China vigorously has deepened financial opening-up and strengthened financial services for real economy. The effect of China on the global EESI is therefore examined further below (Table S5).

China's global EESI influence primarily operates through the 2nd and higher layers (Figure 6). In 2021, China's service sector significantly affected Russia's fossil energy and mining industries, while impacting the Asia-Pacific region's hydroelectric and steam power industries. Between 1995 and 2021, these spillover effects shifted notably. In 1995, China's service sector primarily influenced the Middle East's service sector, but by 2021, its impact shifted to the mining industry. Overall, China's service sector exerts diverse industrial spillover effects across regions.

The 8 sectors in Table S6 are the sectors with the highest share of China's influence on the global EESI in each layer. In 1995, S113 (Construction), S86 (Manufacture of machinery and equipment nec) and S87 (Manufacture of office machinery and computers) were the main sectors on the 2nd layer, while in 2021, S113 (Construction), S86 (Manufacture of machinery and equipment nec) and S138 (Health and social work) were the main sectors on the 2nd layer. S113 (Construction) exhibited a growing significance within the first layer, while its impact on other layers declined.

Most of China's EESI originated from the United States, transmitted through heavy chemical and machinery manufacturing industries, including S1-Petroleum, chemicals & non-metallic mineral products, S3-Electrical & machinery, and S6-Transport equipment (Figure S5). In 2021, over half of

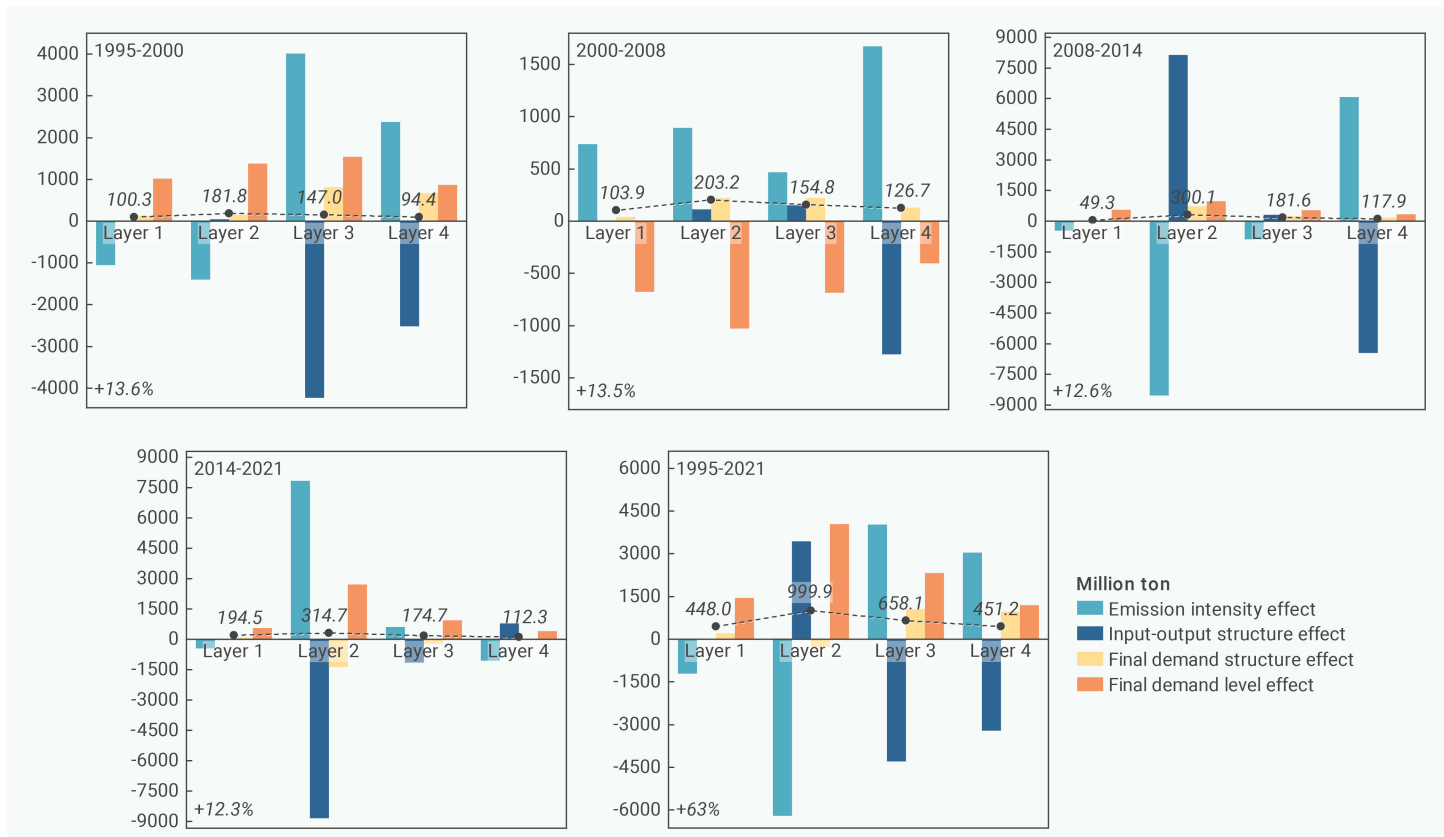


Figure 7. Changes in the emissions of the global service industry from 1995 to 2021.

emissions embodied in China's financial and business services were imported from the USA Electrical & machinery sector, while one-third came from the USA Petroleum, chemicals & non-metallic mineral products sector. These industries emerged as the primary channels for interregional emissions linkages between China and the United States.

Structural path decomposition of the EESI

According to Equation (12), we decomposed changes in the CBE of the global service industry in each layer from 1995 to 2021 into emission intensity, technical coefficient structure, demand structure, and demand level (Figure 7). The global economy has been substantially impacted by the global financial crisis in 2008, leading to a profound downturn in both the total global trade and investment and recovering in 2014.³⁹ Thus, the research period was separated into four stages with 2000, 2008 and 2014 as the nodes, namely 1995–2000, 2000–2008, 2008–2014 and 2014–2021, and the inter-temporal changes of the global EESI was compared in these four periods. The global EESI increased by 63% in 1995–2021, which increased by 13.6% from 1995 to 2000, increased by 13.5% from 2000 to 2008, increased by 12.6% from 2008 to 2014 and increased by 12.3% from 2014 to 2021 (Figure 7).

From 1995 to 2021, sectoral emission intensity effect emerged as the primary driver of emission reductions in the first and second layers, accounting for 90.1% and 330.2% decreases, respectively (Figure 7). However, it contributed to emission increases in the third and higher layers. The reductions in the first and second layers highlight the effectiveness of improvements in energy efficiency and cleaner technologies. Conversely, the rise in higher layers suggests potential unintended consequences, such as emission leakage or shifts in production practices. This increase may result from the relocation of high-emission activities to less regulated sectors or regions, undermining global reduction efforts. Enhanced emission reduction techniques also play an intermediary role in the service sector's direct fulfillment of final consumption, as supported by Su et al. (2019).³³

Increasing consumption level effect was the prominent factor driving the growth of emissions in all the layers. This suggests that merely improving emission intensity (i.e., carbon emissions per unit of economic activity) may

not be adequate to attain overall carbon reduction targets, and it is imperative to also manage consumption growth. High levels of consumption not only drive economic growth but also impose significant environmental pressures, particularly concerning carbon emissions embodied within the service sector. The input-output structure exerts its most significant inhibitory effect on the reduction of global EESI within the third and subsequent layers. The current economic structure may present inherent barriers that constrain the further reduction of global EESI. Overcoming these limitations requires optimizing the industrial chain layout and strengthening cross-tier cooperation.

During 1995 and 2000, the directions of all the effects were similar to the period from 1995 to 2021. When it comes to 2000–2008, sectoral emission intensity always inhibited the decline of emissions in all the layers. It doesn't indicate that emission efficiency decreased. It can be attributed to the unreasonable energy structure with higher proportion of coal use. Nevertheless, the global EESI was reduced greatly because of the final demand level effect. The impact of both the final demand structure and input-output structure on EESI change was modest. From 2008 to 2015, the input-output structure effect contributed to emissions reduction in the third and fourth layers but led to an ascend in EESI in the second layer. Consequently, the improvement of energy conservation, energy efficiency and the decline in global EESI can be achieved by perfecting the input-output structure of countries at higher layers.

DISCUSSION

Our analysis investigated inter-temporal changes in EESI at the global and country levels. The findings concern the environmental performance of the service sector and help explore alternative strategies for achieving sustainable growth in the service industry.

Enhancing the environmental sustainability of the service industry

The service industry plays a pivotal role in the contemporary industrial framework. The service sector dominates modern economies (up to 75% in developed nations). Though traditionally viewed as cleaner than manufacturing,⁴⁰ its emissions are rising despite lower global EESI shares and declining AEI.^{41,42} However, this study accords with earlier observations that the EESI have increased substantially.^{43,44} The EESI continues to grow, which differs

from the common understanding that the service industry is environmentally benign. Thus, balancing service sector expansion with emission control is a critical sustainable development challenge.

The trends in service industry emissions vary among different countries. Our analysis concluded that China, the United States, and Japan were the top 3 countries with the highest service industry emissions. Undoubtedly, according to UNCTAD, the value added in the service industry of these three countries accounted for over 50% of the total value added in the global service industry in 2021. Hence, these countries might shoulder more emission reduction responsibilities in the service industry. China experienced an ascend in the EESI but a substantial decrease in the AEI of the service industry, which can be attributed to significant progress in environmental protection and ecological remediation, including the optimization and agglomeration of producer services.⁴⁵

The transport sector, particularly air and water transport, dominates service industry emissions due to high energy intensity, as noted by Van et al. (2018).⁴⁶ This can be attributed to the large amount of energy consumption in air transport and water transport, resulting in substantial emissions.⁴⁷ This also underscores the dependence of global trade on energy-intensive modes of transportation, particularly for rapid transport demands and the shipment of bulk goods.⁴⁸ Transport accounts for ~25% of emissions, projected to double by 2050.⁴⁹ Although the transport sector accounted for a relatively small share of overall economic activity within the service industry, its substantial energy consumption and low carbon efficiency resulted in a disproportionately large impact on the total emissions. Decarbonizing the service industry hinges on improving transport's energy efficiency and accelerating clean energy adoption.

In developed countries, service-sector emissions primarily arise from public/welfare services, financial/business services, and healthcare. The service industry represents over 70% of the GDP in developed countries, which possess a well-developed healthcare system, financial institutions, and education system. Driven by high public demand, these sectors rely on energy-intensive infrastructure (e.g., hospitals, schools), resulting in disproportionately high emissions compared to other service industries. This underscores the environmental impact of a service-dominated economy. As societal focus on health and welfare grows, balancing economic, social, and environmental priorities becomes critical. Future mitigation strategies should focus on promoting green building practices, renewable energy adoption, and process optimization.

China's service sector shows evolving carbon emission spillover effects across regions and industries. First, its impact on Russia's fossil energy and mining industries contrasts with its focus on Asia-Pacific's hydroelectric and steam power sectors, highlighting region-specific emission transfers linked to energy trade. Second, from 1995 to 2021, spillover effects shifted from intra-service sector impacts in the Middle East to mining-dominated influences, reflecting changing industrial strategies to support China's service sector expansion. These findings emphasize the need for international collaboration to address interconnected emissions, ensuring decarbonization efforts in one region do not increase emissions elsewhere. This insight informs targeted policies to mitigate China's service-sector carbon footprint through strategic trade and industry interventions.⁵⁰

Driving factors of EESI

In most net importing countries, air and water transportation constituted a substantial portion of the EESI, representing up to 40%. This is attributable to the growth of international trade, the energy-intensive modes, changes in logistics demands, limitations in technology and infrastructure, the high dependency of the service industry on cross-border transportation, as well as the influence of policies and regulations. To effectively reduce the carbon emissions from these transportation methods, a multifaceted approach is required. This approach should encompass technological innovation, policy guidance, industry regulation, and international cooperation, thereby promoting the transportation sector towards a more green and sustainable direction.

The global EESI is primarily derived from the first three layers, especially the transmission pattern with two layers (i.e., intermediate input → service sector → final consumption). This suggests that global EESI primarily serve final demands directly, with limited intermediate input transmission, reducible

through improved fuel efficiency and production technology.^{37,38} China's growing role in global EESI stems from the rapid opening of its service sectors post-WTO accession. At the sectoral level, China's construction and machinery manufacturing are pivotal. Its expanding trade and investment networks have deepened global ties, positioning it as a major goods exporter, with trading partners amplifying its impact on global EESI.⁵¹

The decline of the global EESI was primarily ascribed to the emission intensity enhancement. The inhibitory effect of sectoral emission intensity is much stronger in the process of service sector directly providing demands for households. This phenomenon underscores the necessity for comprehensive emission reduction strategies that encompass all layers of the economy. Policies must not only focus on improving emission intensity in primary sectors but also address the structural and economic factors that drive emissions in higher layers. Additionally, fostering sustainable consumption patterns and promoting cross-sectoral collaboration are essential for achieving holistic and sustainable carbon reductions. Future research should aim to unravel the underlying mechanisms of emission intensity effects across different layers and develop integrated approaches that prevent emission leakage, thereby ensuring that carbon reduction efforts are both effective and equitable.

In contrast, increasing final consumption substantially drives increases in such emissions, underscoring the significant environmental impact of rising consumer demand. Also, the final consumption pattern has a promotive effect on increasing emissions, indicating that current economic and industrial configurations hinder effective carbon emission reductions at these levels. This dual dynamic suggests that while improvements in emission intensity within certain sectors can lead to significant emission reductions, the overall increase in consumption can offset these gains, particularly in more complex economic layers. Moreover, the inhibitory role of the input-output structure may reflect emission leakage or the shifting of high-emission activities to less regulated layers or regions. To address these challenges, it is imperative to adopt comprehensive carbon reduction strategies that not only enhance emission intensity but also manage consumption growth and optimize input-output relationships. Policies should focus on promoting sustainable consumption patterns, fostering green supply chains, and encouraging cross-sectoral collaboration to mitigate the adverse effects of the current economic structure on global carbon emissions.⁵² Future research should delve deeper into the mechanisms driving these layer-specific effects and explore integrated approaches that ensure emission reductions are consistent and sustainable across all economic layers.

While existing studies examine emission transmission layers in specific regions or global frameworks,^{24,38} such approaches may inadequately address global service-sector decarbonization. This study establishes a comprehensive global analytical framework covering transport, healthcare, and financial services, identifying critical emission transmission layers. The findings enable policymakers to design differentiated regulations targeting EESI transmission variations for enhanced mitigation.

CONCLUSION

This study analyzed the spatial distribution and long-term trends of EESI across the world employing MRIO framework and SPD. From 1995 to 2021, the global service industry's CBE rose sharply while its AEI declined. China, the U.S., and Japan were the top emitters. Developed countries were net importers of EESI, while developing countries were net exporters. Industrial pathways in the first and second layers accounted for half of the CBE. The decline in global EESI was primarily driven by emission intensity, while its increase was largely due to final demand levels. This study highlights key practical implications. First, prioritizing public welfare, health, financial, and transportation services through green technologies and improved transport efficiency is essential. Second, trade relationships, especially China's, significantly impact global EESI. Third, reducing global EESI requires adjusting national trade structures. Lastly, aligning service industry consumption with upstream supply industries is crucial, achievable by enhancing technological efficiency and reducing high-emission product use.

This study offers valuable insights but has limitations. First, the input-output model assumes linearity and a static economic system, neglecting nonlinear interactions and temporal dynamics, which may overlook struc-

tural economic changes. Second, data constraints exclude many African and Latin American countries, despite their recent advancements in producer services supporting manufacturing.⁵³ Third, while the MRIO framework uses 2015 constant prices, significant service cost disparities between developing and developed countries may affect AEI comparability. Future research could incorporate purchasing power parity (PPP) adjustments and conduct sensitivity analysis to address these price differences.

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AUTHOR CONTRIBUTIONS

J. L. and S. W. designed research; J. L. and S. W. performed research; J. L., S. W. and Y. Z. analyzed data; J. L., S. W., C. F. and K. F. wrote the paper; J. L., S. W., Y. Z. S. W., C. F.

K. F. and K. H. contributed to the final draft. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

All data used in this study are available in the public domains as follows. (1) EXIOBASE version 3.8 is publicly available at <https://zenodo.org/record/5589597>. (2) The GDP deflator originated from World Bank Open Data at <https://data.worldbank.org.cn/indicator/NY.GDP.MKTP.CD?view=chart>. (3) The code is performed in R Language, and it will be made available on request.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-geo.2025.100133>