Pathways to decarbonizing the global service industry

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Abstract

While the service industry is generally considered a low-carbon sector, it contributes significantly to global carbon emissions. However, such emissions have typically relied on production-based evaluations without accounting for emissions embodied in international trade. Here, this paper estimates the consumption-based emissions (CBE) of the service industry and investigates the flows of embodied emissions globally using a Multi-regional Input-output model. Structural path analysis (SPA) and decomposition (SPD) methods are used to explore emission reduction paths and the driving factors. Our results show that the CBE of the global service industry not only increased by 63% but now comprised approximately over 30% of global total emissions, with the public and welfare services, health services sectors contributing the most to emissions growth. The consumption-based carbon intensity of the global service industry declined markedly, or nearly one-quarter of global carbon intensity. Advanced countries such as Japan, the UK, and the USA, were identified as the leading net importers of embodied service industry emissions, with air transport and water transport being the primary sources of carbon inflow. Russia was the principal net exporter of emissions. China altered from a net exporter of emissions to a net importer. The results reveal that the second layer had a more pronounced influence on the emissions than other layers, although the contribution of higher layers to emissions steadily increased. Emission intensity effect promoted emissions declines, while the increasing consumption level restrained such decreases. This study aims to provide valuable insights into reducing the emissions of the global service industry.

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Key Points:

- Emissions of the global service industry grew steadily at 63% during 1995-2021, accounting for nearly one-third of global total emissions.
- Developed countries such as Japan, the UK, and the USA, were regarded as the leading net importers of embodied service industry emissions.
- China changed from a net exporter of emissions to a net importer and was the centre of embodied emissions transfers in the service sector.
Abstract

While the service industry is generally considered a low-carbon sector, it contributes significantly to global carbon emissions. However, such emissions have typically relied on production-based evaluations without accounting for emissions embodied in international trade. Here, this paper estimates the consumption-based emissions (CBE) of the service industry and investigates the flows of embodied emissions globally using a Multi-regional Input-output (MRIO) model. Structural path analysis (SPA) and decomposition (SPD) method is used to explore emission reduction paths and the driving factors. Our results show that the CBE of the global service industry not only increased by 63% over the period 1995-2021 but now comprised approximately over 30% of global total emissions, with the public and welfare services, health services sectors contributing the most to emissions growth. The consumption-based carbon intensity of the global service industry declined markedly, by 67.3%, or nearly one-quarter of global carbon intensity. Advanced countries such as Japan, the UK, and the USA, were identified as the leading net importers of embodied service industry emissions, with air transport and water transport being the primary sources of carbon inflow. Russia was the principal net exporter of emissions. China altered from a net exporter of emissions to a net importer during the time. The results of SPA reveals that the second layer had a more pronounced influence on the emissions than other layers, although the contribution of higher layers to emissions steadily increased from 1995 to 2021. Emission intensity effect promoted emissions declines, while the increasing consumption level restrained such decreases. This study aims to provide valuable insights into reducing the emissions of the global service industry.

Plain Language Summary

Although the service industry is often seen as a low-carbon sector, it still plays a significant role in global carbon emissions. Traditionally, these emissions have been measured based on production without considering emissions from international trade. This paper estimates the service industry’s consumption-based emissions (CBE) and examines how these emissions flow globally using a Multi-regional Input-output model. Our findings show that the CBE of the global service industry has increased by 63% and now accounts for over 30% of total global emissions, with public welfare and health services being the biggest contributors. The carbon intensity of the global service industry has decreased significantly, nearly one-quarter of the global average. Advanced countries like Japan, the UK, and the USA are the largest net importers of emissions from the service industry. Russia is the main net exporter, while China has shifted from being a net exporter to a net importer. The reduction in emission intensity has helped decrease emissions, but the rise in consumption levels has countered this effect. This study provides valuable insights into how we can reduce emissions in the global service industry.

1. 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, playing a pivotal role in driving global economic growth.
The analysis from the World Bank showed that, in 2015, the value added by services constituted 74% of GDP in high-income countries and 56.9% of GDP in low- and middle-income regions [1]. Compared to manufacturing, the service industry’s lack of physical presence, one result of its “dematerialization,” is seen as being 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 emissions of the service industry in developed countries have been explored from a production-based, territorial perspective. Local economic activities result in production-based and territorial emissions within a region, including those intended for export [4, 5]. For example, the emissions of the service sectors of 41 countries and regions are investigated from the view of consumption and an emission abatement policy for service sectors was proposed [3]. Roberts et al. (2021) examined GHG of the service industry for Australia, Germany, Italy, the UK, and the USA, using the “7see” system dynamics modeling approach [6]. Bergero et al. (2023) projected future aviation emissions by 2050 and systematically searched for pathways to net-zero aviation. Existing scholarship further reveals differences between countries with respect to the emissions of their service industries [7]. For instance, in China, the carbon emissions witnessed an 11% growth rate between 2003 and 2016 in the service industry, surpassing the economy’s growth rate over the same period [8]. It is, moreover, 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].

As such, CBE—the emissions generated in the supply chain of commodities—are critical to emissions reduction in the service industry [13,14]. CBE accounting allows for the identification of cross-border emissions, which exceed a specific territory and can increase rapidly in response to growth in international trade. 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.” Several scholars have attempted to probe into the environmental effect of trade on specific service sectors or on the service industry as a whole [3, 15]. Lenzen et al. (2018) analyzed tourism’s footprint and bilateral embodied carbon flow, concluding that the sector plays a significant role in the ascend of carbon emissions [15]. Importantly, the development level of the service industry and degree of participation in global value chains may also affect global emissions: because the service industry involves a series of cross-border activities, and supply-chain industries substantially affected its emissions, the task of clarifying transmission paths and identifying influencing factors is crucial to deepening our understanding of the cause of service industry emissions.

In addition to life-cycle assessment [16], multi-regional Input-output (MRIO) analysis is a suitable method for probing cross-border emissions within the global production network [17, 18]. The fundamental principle of MRIO is to examine the interconnectedness of diverse industries across different economies. Structural Path Decomposition (SPD) merges Structural Path Analysis (SPA) with Structural Decomposition Analysis (SDA). SPA, first introduced by Defouny and Thorbecke in 1984 [19], is a methodological approach used to assess the contribution of various production pathways to economic and environmental analysis.
indicators [20]. It has the capability to trace the correlation between different supply-chain sectors and elucidate the pathway through which different factors influence the indicators, such as carbon emissions, and can be applied to environmental impacts and economic output [21-23]. Carbon emissions of India were studied in 2007/08 via SPA, concluding that there is a similarity among sectors with less significance in household demand and sectors with higher yields for household demand have different transmission [24]. Chen et al. (2022) further applied SPA to examine the carbon emissions in the construction industry in China, India, Russia, Japan, and the USA [25]. In Tian et al. (2018), SPD is utilized to examine the primary supply chain pathways responsible for fluctuations in emissions within China's manufacturing industry from 1992 to 2012 [26]. However, one of the shortcomings of SPA is its static use; this study, in comparison, sought a comprehensive understanding of dynamic changes over the study period. As a result, the key driving factors in each transmission layer were assessed by SDA.

In conclusion, previous research on the emissions of specific service sectors has tended to be confined to a production-based, territorial 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 calculated at the country and region levels, few studies have tracked the embodied emissions flows of the entire service 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 structural path decomposition (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. The paper is composed of several parts: Section 2 outlines the indicators, methodology, and data utilized in this study. Section 3 displays the primary findings of the empirical analysis. Section 4 deliberates Discussion and policy implications, followed by the conclusions derived from the study in Section 5.

2. Methods and materials

2.1 CBE of the service industry

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

\[
\begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_n
\end{bmatrix} = \begin{bmatrix}
a_{11} & a_{12} & \ldots & a_{1n} \\
a_{21} & a_{22} & \ldots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \ldots & a_{nn}
\end{bmatrix} \begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_n
\end{bmatrix} + \begin{bmatrix}
Y_1 \\
Y_2 \\
\vdots \\
Y_n
\end{bmatrix}
\]

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

\[
\begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_n
\end{bmatrix} = \begin{bmatrix}
a_{11} & a_{12} & \ldots & a_{1n} \\
a_{21} & a_{22} & \ldots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \ldots & a_{nn}
\end{bmatrix}^{-1} \begin{bmatrix}
Y_1 \\
Y_2 \\
\vdots \\
Y_n
\end{bmatrix}
\]
\[ X = AX + Y = (I - A)^{-1}Y = BY \] (2)

The \( B \) matrix is the Leontief inverse matrix, illustrating the direct and indirect sectoral linkages; here, \( f = (f^1, f^2, \cdots, f^k, f^1, f^2, \cdots, f^k) \) 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 “\( \text{diag}(\_\_) \)” denotes the diagonalization of a matrix. Thus, the carbon emissions that are induced by final demand can be illustrated as:

\[ EC = \text{diag}(f)BY \] (3)

where \( EC = (EC^1, EC^2, \cdots, EC^k, EC^1, EC^2, \cdots, EC^k) \). Therefore, the CBE of the service industry \( (i) \) can be denoted as:

\[ EC_i = \text{diag}(f_i)B_iY \] (4)

where \( B_i \) represents the production structures of various sectors in various regions for each region’s service industry.

This paper also demonstrates carbon emissions’ incorporation into international trade flows. Hence, the embodied emissions triggered by final demand can be described by means of equation (4):

\[
\begin{pmatrix}
EC^{11} & EC^{12} & \cdots & EC^{1n} \\
EC^{21} & EC^{22} & \cdots & EC^{2n} \\
\vdots & \vdots & \ddots & \vdots \\
EC^{n1} & EC^{n2} & \cdots & EC^{nn}
\end{pmatrix}
= \begin{pmatrix}
f^1 & 0 & \cdots & 0 \\
f^2 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
f^n & 0 & \cdots & 0
\end{pmatrix}
\begin{pmatrix}
B^{11} & B^{12} & \cdots & B^{1n} \\
B^{21} & B^{22} & \cdots & B^{2n} \\
\vdots & \vdots & \ddots & \vdots \\
B^{n1} & B^{n2} & \cdots & B^{nn}
\end{pmatrix}
\begin{pmatrix}
y^{11} & y^{12} & \cdots & y^{1n} \\
y^{21} & y^{22} & \cdots & y^{2n} \\
\vdots & \vdots & \ddots & \vdots \\
y^{n1} & y^{n2} & \cdots & y^{nn}
\end{pmatrix}
\] (5)

In our model, \( EC^r \) represents the carbon emissions exports from region \( r \) to region \( s \).

Therefore, the embodied emissions of region \( r \)’s service industry to region \( s \) can be written in the matrix form:

\[ EC_i^{rs} = \text{diag}(f_i)B_iY^{rs} \] (6)

which reflects the carbon emissions resulting from the service industry required to meet a nation’s demand for goods and service.

Moreover, the consumption-based carbon intensity (CCI) 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:

\[ VA = \text{diag}(\nu)BY = HY \] (7)

where \( VA = (VA^1, VA^2, \cdots, VA^k, VA^1, VA^2, \cdots, VA^k) \) is the sectoral value added in various regions. \( \nu = (\nu^1, \nu^2, \cdots, \nu^k, \nu^1, \nu^2, \cdots, \nu^k) \) 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 \( H_i^{rs} \), 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 CCI of the service industry can be formulated as:
\[
CCl_i = \frac{EC_i}{VA_i} = \frac{\text{diag}(e_i)H_i}{\text{tr}(H_iY)} \quad (8)
\]

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. 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 obtained using these two approaches differ. The former is applied to obtain the total carbon emissions as it is measured as the environmental performance of total output, while the latter is closely related to the environmental efficiency of consumption level, that is, CBE per unit of value added. Therefore, we adopted the second definition to calculate the CCI in a manner that would ensure conformity at the sectoral level. In equation (6), \( l \) denotes a unit vector.

2.2 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:

\[
(I - A)^{-1} = I + A^2 + A^3 + \cdots = I + A + A^2 + A^3 + A^{(>3)} \quad (9)
\]

Therefore, the path decomposition of the EESI can be formulated as equation (10):

\[
EC = f'(I - A)^{-1}Y = \underbrace{f'1Y}_{1st\ layer} + \underbrace{f'A Y}_{2nd\ layer} + \underbrace{f'A^2 Y}_{3rd\ layer} + \underbrace{f'A^3 Y}_{4th\ layer} + \underbrace{f'A^{(>3)} Y}_{other} \quad (10)
\]

In modern industrial structures, sectoral linkages proceed infinitely in upstream and downstream directions, which can be extracted by means of SPA [31]. Equation (10) helped us probe a higher sequence of environmental contributions via upstream production structures. The measure “total environmental impact” includes direct impact from the manufacturing process (1st layer) and indirect impacts from the upstream production process (e.g., 2nd layer).

In relation to this study, the 1st layer (\( f'1Y \)) 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 (\( f'A Y \)). The greater the number of sectors that are regarded as inputs, the greater the increases to \( A^2 Y \), leading to indirect emissions in the 3rd layer (\( f'A^2 Y \)). Likewise, \( f'A^{(>3)} Y \) 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.”

2.3 Structural path decomposition of the EESI
By incorporating SPA and SDA, 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 (4), the change of EESI can be divided into several influencing factors:

\[ \Delta E_C = E_C^1 - E_C^0 = \text{diag}(f^1)^B Y^1 - \text{diag}(f^0)^B Y^0 \]

\[ = \Delta f B Y + f \Delta B Y + f B \Delta Y \] (11)

From Equation (11), \( \Delta E_C \) is total change in the EESI. \( \Delta f \), \( \Delta B \), and \( \Delta Y \) show changes in EESI that are affected by changes in emission intensity, the input-output structure, and final demand, respectively. Furthermore, final demand can be disentangled into demand structure (\( \Delta Y_{str} \)) and demand level (\( \Delta Y_{lev} \)). 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. (2019) and Li et al. (2021) [33, 34], by utilizing the SPA in Equation (11), various factors can be further disintegrated into different transmission layers, and Equation (10) can be expanded the following:

\[ \Delta E_C = \Delta(f'Y) + \Delta(f'AY) + \Delta(f'A^2Y) + \Delta(f'A^3Y) + \Delta(f'A^3Y) = \]

\[ = \frac{1}{2} \Delta f'(Y_0 + Y_1) + \frac{1}{2} (f^{1'} + f^{0'}) \Delta Y \] first layer

\[ + \frac{1}{6} \Delta f'[A_0(2Y_0 + Y_1) + A_1(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [f^{0'} \Delta A(2Y_0 + Y_1) + f^{1'} \Delta A(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [(2f^{0'} + f^{1'}) A_0 A_0 \Delta Y + (2f^{1'} + f^{0'}) A_1 A_1 \Delta Y] \] second layer

\[ + \frac{1}{6} \Delta f'[A_0 A_0(2Y_0 + Y_1) + A_1 A_1(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [f^{0'} \Delta A A_1(2Y_0 + Y_1) + f^{1'} \Delta A A_1(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [f^{0'} A_0 \Delta A(2Y_0 + Y_1) + f^{1'} A_0 A_1 \Delta A(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [(2f^{0'} + f^{1'}) A_0 A_0 \Delta Y + (2f^{1'} + f^{0'}) A_1 A_1 \Delta Y] \] third layer

\[ + \frac{1}{6} \Delta f'[A_0 A_0 A_0(2Y_0 + Y_1) + A_1 A_1 A_1(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [f^{0'} \Delta A A_1 A_1(2Y_0 + Y_1) + f^{1'} \Delta A A_1 A_1(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [f^{0'} A_0 \Delta A A_1(2Y_0 + Y_1) + f^{1'} A_1 \Delta A A_0(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [f^{0'} A_0 A_0 \Delta A(2Y_0 + Y_1) + f^{1'} A_1 A_1 \Delta A(2Y_1 + Y_0)] + \]

\[ + \frac{1}{6} [(2f^{0'} + f^{1'}) A_0 A_0 A_0 \Delta Y + (2f^{1'} + f^{0'}) A_1 A_1 A_1 \Delta Y] \] fourth layer
We can disintegrate the impact of the factors driving EESI at supply-chain level with SPD, which suits for analysis of EESI at micro-level. The decomposition of the first layer impacts represents service industry emissions that are directly ascribed to final consumption, which is influenced by emission intensity and final demand (structure and level). In other words, this is a direct transfer from production to consumption, including emissions from financial and business services to direct consumption. In the second layer, the first-order technical coefficient structure A is added, illustrating the products and corresponding emission flow between two sectors. The third and fourth layers are supplemented with the second-order and third-order technical coefficient structure to represent the changes in the complex inputs structure effected on the EESI. This study displays the results of SPD of the first, second, third, and fourth layers.

2.4 Data

The data in this analysis was obtained from EXIOBASE3, one of the most comprehensive EE-MRIO databases. EXIOBASE3 covers 44 countries, 5 regions, and 163 sectors from 1995 to 2021. EXIOBASE3 has several advantages over other MRIO tables [35]. Due to its high compatibility with the System of Environmental Economic Accounting (SEEA), EXIOBASE3 has a high-resolution sector classification. Eora and WIOD, in comparison, only cover 26 and 56 sectors; the 26 years data span is, further, suitable for analyzing the evolution of CBE of the service industry. Regarding the issue of price comparability over the study period, this paper applies a GDP deflator, originated from the World Bank, to treat the original data as the 2015 constant price. The reason why we chose the 2015 base year is that the current GDP price and constant GDP price are calculated based on 2015 according to the World Bank. Moreover, following Huo et al. (2021) [36], 28 different service sectors in EXIOBASE3 were selected to analyze CBE of the service industry; these were aggregated into 10 categories for comparability and consistency according to their nature. The full name of the country abbreviations and the classification of the regions can be found in Table S1.

3. Results

3.1 CBE and CCI of the service industry

Using Equation 3, 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
manner 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. 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 CCI of the global service industry presented an apparent tendency towards improvement, decreasing from 17.4 to 10.4 ton/thousand euro during the study period (-67.3%), which was far below the global level (Figure 1B). Notably, the CCI of the global service industry firstly declined gradually during 1995-2001, then doubled during 2001-2008, and then fell by 43.3% between 2008 and 2021. This trend was similar to the change witnessed at the global level. In contrast to the structure of emissions, transport—including air transport, water transport, and inland transport—played a prominent role in determining the CCI. In 2021, water and air transport drove 24.4% and 23.7% of the CCI of the service industry, respectively, followed by financial and business services (14.2%) (Table S3). Reducing the CCI of the transport sectors will help reduce the CCI of the global service industry. Public and welfare services, educational services, and health services contributed the least to the CCI of the global service industry, with a share of less than 6%.

In terms of national economies, significant spatial disparities exist in terms of CBE and CCI—this can be seen clearly in Figure 2 and Figure S1. In Figure S1, EESI accounted for a significant part in the national CBE, especially in European countries. Overall, the advanced economies, including the United States, Canada, and Australia, had a lower intensity than developing countries such as China and India. In 2021, the service industries of Estonia, South Africa, Russia, Greece, and China had the highest CCI, reaching 1087.8, 175.4, 150.4, 132.1, and 121.6 tons/thousand euro. Nevertheless, the top five countries with the highest intensity of the service industry were Bulgaria, China, Russia, Estonia, and Romania, amounting to 611.7, 580.4, 517.6, 461.8, and 429.8 ton/thousand euro in 1995. Except for Estonia and Japan, most countries have significantly lowered their CCI through energy efficiency improvement approaches (Figure 2). Additionally, this trend was similar in 2004 and 2013 (Figure S2).

In 2021, China, the United States, and Japan were the top three in terms of CBE of service industry, which reached, in absolute terms, 2,466.4, 1,583.9, and 314.2 million tons respectively (Figure 2, Table S4). What is striking in this map is the rapid growth of China, quadrupling from 561.5 million tons to 2,466.4 million throughout the research period. Moreover, the contribution of different service categories to the service industry’s overall CBE varied considerably across countries and regions. For instance, in the United States, aligned with the sectoral composition of the global service industry, the contributions from public and welfare services, financial and business services, and health services were found to be more significant than those of other sectors, sectoral contributions to the service industry’s CBE showed no substantial changes over time (Figure 2). This stands in stark contrast to China, which showed considerable variation in sectoral contributions across the period. While public and welfare services represented a significant share (19.5%) of the China’s EESI in 1995, financial and business services accounted for 17.5% and tourism for 12.9% (Figure 2, Table S4). By 2021, health services reached 37.4% of service industry
emissions in China, public and welfare services accounted for 18.1%, and financial and business services 13.3% (Figure 2, Table S5). Likewise, in Indonesia, nearly 20% of emissions originated from water transport in 1995, while in 2021, approximately one-third of emissions were derived from public and welfare services, owing to the rising awareness of the importance of public health in developing societies.

3.2 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 (Figure 3, Figure 4). In 2021, the EESI in the United States, the UK and Japan imported 141.8, 53.6 and 51.1 million ton, respectively. Figure 3 also shows the embodied emissions transfer structure of 10 sectors in the main countries in 1995 and 2021. Clearly, air and water transport accounted for a significant proportion of the EESI, up to 40% in most net importing countries. 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 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). Moreover, tourism played a key role accounting for an increasing share of emissions embodied in trade, especially in advanced economies. For instance, the ratio of tourism increased from 0.3% to 21.6% in emission embodied in exports in India.

It should be noted that 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 depicts the emissions inflow of the top three net importers (the UK, the USA and China) of EESI in 1995, 2004, 2013 and 2021. Clearly, 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. Besides, 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. It should be noted that the USA has become one of the most significant importing destinations for EESI in
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.

3.3 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 findings, depicted in Figure 5 and Figure S4, reveal that the global EESI primarily stem from transmission structures comprising three layers or fewer.

The EESI of the first three layers occupied more than 70% of the CBE (Figure 5A). The results indicates that 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 satisfies household service demands, thereby leading to carbon emissions directly triggered by households and making a single-layer transmission pattern (i.e., transport → final consumption). Notably, 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.

According to Figure 5B, the emissions impact of the global service industry is predominantly influenced by the top 10 countries, collectively contributing over 70% of the total emissions in 2021. The countries with the 10 highest contribution shares were China, the United States, WWM (RoW Middle East), WWA (RoW Asia and Pacific), Japan, the Republic of Korea, India, Germany, WWL (RoW America), and the United Kingdom, together accounting for a total contribution rate of 74.5%. The impact of China, WWM, WWL, India, and the Republic of Korea on the emissions of the global service industry is steadily increasing, while the impact of the United States, Russia, Japan, United Kingdom, France, and Germany is gradually weakening (Figure S2). Emerging economies have made
significant advancements in bolstering their domestic service sectors, thus assuming an increasingly pivotal role in the escalation of emissions. Consequently, heightened focus is warranted on these nations and their escalating influence on the emissions of the global service sector.

Second, 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, Figure 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 background of the “Belt and Road” strategy and boost of bilateral trade mechanism, China vigorously deepens financial opening-up and strengthen financial services for real economy. The effect of China on the global EESI is therefore examined further below, as shown in Tables S5.

China mainly affected the global EESI through the 2nd and higher layers. 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. It’s worth mentioning that S113 (Construction) exhibited a growing significance within the first layer, while its impact on other layers declined.

Clearly, most of China’s EESI were imported from the United States’ sectors via the heavy chemical industries and machinery manufacturing industries of these two countries, such as 1-Petroleum, chemicals & non-metallic mineral products, 3-Electrical & machinery and 6-Transport equipment (Figure S5). For instance, in 2021, more than half of the emissions embodied in China’s financial and business services were imported from the United States’ Electrical & machinery via the same industry of China. Approximately one-third of emissions embodied in China’s financial and business services were originated from the United States’ Petroleum, chemicals & non-metallic mineral products via the same sector of China. Heavy chemical industries and machinery manufacturing industries became the most important transmission industries of interregional emissions linkages between China and the United States.

3.4 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 in terms of a number of distinct factors, namely: emission intensity, technical coefficient structure, demand structure, and demand level (Figure 6). 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 [39]. The global economy began to recover in 2014. 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 results demonstrate that the global EESI increased by 63% in 1995–2021, which increased by 13.6% from 1995 to 2000, increased by13.5% from 2000 to 2008,
increased by 12.6% from 2008 to 2014 and increased by 12.3% from 2014 to 2021. The results are shown in Figure 6.

From 1995 to 2021, sectoral emission intensity effect is identified as the primary depressor capable of decreasing emissions in the first and second layers, accounting for 90.1% and 330.2% decreases, respectively (Figure 6). However, emission intensity effect contributed to the most of the increase of emissions in the third and higher layers. This suggests that there is a need for further improvement in the sectoral efficiency of energy utilization to meet the increasing final demand within transmission structures involving more layers. Clearly, sectoral emission intensity effect curbed significantly the emissions of the global service industry in the transmission structure with no more than two layers. In other words, the enhancement of emission reduction techniques played an intermediary role in the process whereby the service sector directly fulfills final consumption, which is also supported by Su et al. (2019) [33]. Increasing consumption level effect was the prominent factor driving the growth of emissions in all the layers. The input-output structure exerts its most significant inhibitory effect on the reduction of global EESI within the third and subsequent layers.

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 partly 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.

4. Discussion

Our analysis investigated inter-temporal changes in EESI at the global and country levels. We found that the CBE of the global service industry increased substantially from 1995 to 2021 while the CCI of the global service industry experienced a downward trend. The service industries of China, the United States, and Japan were the highest emitters. We also examined the influences shaping emissions within the service industry, delineating them down to the supply-chain level using the SPD. Our findings revealed that developed countries were foremost as net importers of EESI, while developing countries primarily served as net exporters. The emissions originating from industrial pathways in the first and second layers represented approximately half of the CBE. Notably, the emission intensity effect emerged as the primary driver behind the decline in the global EESI, whereas the final demand level effect exerted the greatest influence on the escalating the global EESI. These findings underscore two significant implications for emissions reduction within the service industry from a consumption-side view: one concerning the environmental performance of the service sector and the other regarding the factors driving service industry emissions. These key findings motivate the exploration of alternative strategies for achieving sustainable growth in
The service industry plays a pivotal role in the contemporary industrial framework. With the continuous advancement of industrialization, the demand for services has steadily increased. The share that service sector activities play in the national economy has been on the rise, particularly in developed countries, where it often reaches up to 75%. As the economic focus gradually shifts from manufacturing to the service industry, the latter is expected to generate more carbon emissions and pollution. It is widely accepted that the service industry is environmentally benign, generating less pollution than manufacturing [40].

Our data depict that the EESI represent a relatively low share of global emissions, and that CCI declined steadily, which is consistent with previous studies [41, 42]. However, this study accords with earlier observations that the EESI have increased substantially [43, 44]. The results of this paper indicate that the EESI continue to show a significant upward trend, which differs from the common understanding that the service industry is environmentally benign. Thus, balancing the dual goals of achieving economic growth in the service industry and environmental protection has become one of the challenges many countries must confront in the ongoing process of achieving sustainable development in their service industry.

The trends in service industry emissions vary among different countries. Few prior studies have compared differences in the service industry at the country level. 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 (https://unctadstat.unctad.org/datacentre/dataviewer/US.GDPComponent), 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 can be expected to shoulder more emission reduction responsibilities in relation to the service industry. During the stage, China experienced an ascend in the EESI but a substantial decrease in the CCI of the service industry, which can be attributed to significant progress in environmental protection and ecological remediation, including the optimization of the agglomeration of producer services [45].

The emissions of the service industry reveal a high variation among different categories, which is seldom mentioned in previous studies. Transportation, especially air and water transport, dominated most CBE, a finding supported by Van et al. (2018) [46]. This can be attributed to the fact that air transport and water transport require a large amount of energy consumption, resulting in substantial emissions [47]. In other words, as the fastest-growing major contributor to global climate change, the transport sector occupies nearly 25% of emissions, a figure that is projected to double by 2050—as such, the transportation system is a crucial area for emission reductions [48]. More importantly, there have been pronounced structural shifts in the emissions sources in developing countries over the research period, while the emissions of the service industry in developed countries mainly stem from activities within the public and welfare services, financial and business services, and health services sectors. On the one hand, the service industry represents over 70% of the GDP in developed countries, which possess a well-developed healthcare system, financial institutions, and education system. Thus, the industrial sources of emissions are relatively stable. On the other
hand, it seems possible that the service industry induces remarkable growth in developing
countries but is underutilized.

4.2 Driving factors of EESI

From the results of the SPA conducted in this study, 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 indicates that the global
EESI are mainly directly serving final demands without complex intermediate inputs
transmission, which can be declined by improvement of fuel efficiency and production
technology [37, 38]. Meanwhile, China played an increasingly role in the global EESI, which
is attributed to the fast pace of China’s opening-up in the service sectors since the entry of
WTO. At the sectoral level, China’s construction, manufacture of machinery and equipment
played prominent role in the global EESI. China's flourishing trade and investment landscape
has fostered closer ties with other nations, making it a key exporter of goods that are then
distributed further by its trading partners. These countries become the transmission partners
of China’s effect on the global EESI. These sectors are typical ones with their nature.

The SPD analysis reveal that is the decline of the global EESI was primarily ascribed
to the emission intensity enhancement. In particular, the inhibitory effect of sectoral emission
intensity is much stronger in the process of service sector directly providing demands for
households. In contrast, increasing final consumption substantially drives increases in such
emissions. Also, the final consumption pattern has a promotive effect on increasing emissions,
highlighting the need for further improvement in consumption patterns.

In comparison to existing literature, certain scholars have focused on exploring the
emissions transmission layers of specific service sectors within particular regions or within a
global analytical framework [24, 38]. However, such approaches may not effectively
contribute to enhancing the emissions reduction performance of the global service sector.
Moreover, the service industry holds significant importance in international economic and
trade cooperation. Therefore, this study endeavors to establish a comprehensive global
analytical framework for the service sector, encompassing sectors like transportation,
healthcare, and financial services, among others, while identifying the critical transmission
layers of emissions. The findings of this study provide valuable insights for policymakers to
formulate effective emission reduction regulations tailored to the variations in key
transmission layers of EESI.

5. Conclusions

This study used a multi-regional SPD approach to examine temporal changes in the
EESI, map the EESI transfer, and reveal the driving factors of emissions from a supply chain
perspective.

First, during the study period, the global EESI experienced steady growth at 63%,
while the CCI declined slightly. The proportion of the EESI to global emissions stabilized at a
level of 30%. Public and welfare services, health services, and financial and business services
contributed most to the growth of the global EESI, while transport, especially air transport
and water transport, played an increasingly important role in shaping the CCI of the global service industry.

Second, China, the United States, and Japan have the highest EESI. Moreover, in developing countries, there have been significant changes in the industrial composition of EESI. According to the results of our analysis of the EESI flows at the country level, developed countries are net importers, while developing countries are net exporters. Transportation, especially air transport, plays a crucial role in embodied emissions in imports and exports.

Third, based on the results of SPA, the second layer was identified as the significant path for the global EESI, while the role of higher layers to the global EESI was shown to be gradually increasing. More importantly, higher layers experienced a more considerable degree of increase. Final demand level effect was the prominent element driving the growth of EESI in all the layers. The curbing effect of input-output structure on the decline of the global EESI is the strongest on the third and higher layers.

The findings of this study carry significant practical implications. Firstly, they underscore the importance of prioritizing public and welfare services, health services, financial services, and transportation by promoting the adoption of green technology practices and enhancing efficiency in transportation systems. Secondly, they emphasize the crucial role of trade relationships between nations, particularly highlighting the significance of trade interactions involving China and other countries. Thirdly, our findings underscore the role of international trade on global EESI within the second layer. The decline of global EESI can benefit from adjusting the trade structure at the national level. Lastly, our analysis reflects the necessity of adjusting the consumption pattern of the service industry in alignment with upstream supply industries. Measures including improving the technological efficiency of upstream industries and reducing the utilization of high-emission products can be accomplished.

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Open Research

Appendix A. Supplementary data

Supplementary data to this article can be found online at website.

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Figure 1. The CBE, CCI 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 CCI of the service industry during 1995-2021. The percentage indicates the share of CCI by different service categories. The grey line and black line represent the CCI of the global economy and the
Figure 2. The CBE and CCI 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.
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 15 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.

Figure 5. Contribution of each layer to the CBE of the service industry at the global and country levels.
Figure 6. Changes the emissions of the global service industry from 1995 to 2021.