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Assessing Embodied Carbon Emission and Its Intensities in the ICT Industry: The Global Case

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With the intensification of globalization, the information and communication technologies (ICT) sector, as one of the emerging industrial sectors, has played an important role in reducing carbon emissions in regional trade and improving the energy efficiency of traded products. This article uses a multi-regional input-output (MRIO) model to explore the flow of embodied carbon emissions and embodied carbon emission intensities in the ICT sector triggered by trade in 15 major economies around the world from 2000 to 2014. The article further discusses the emission-reduction strategies of each ICT sector. The results show that: (1) The overall embodied carbon emissions of ICT have demonstrated a significant downward trend, but the proportion of embodied carbon emissions caused by trade is increasing; (2) The embodied carbon emissions in the ICT sector of most developed countries in 2014 are significantly lower than in 2000, but in developing countries such as China and India they show an upward trend during this period; (3) The ICT sector's export embodied carbon emission intensity in Indonesia is much higher than that of other countries, and the embodied carbon emissions of ICT exported by Mexico have increased significantly; (4) The manufacture of computer, electronic and optical products (S1) is the main contributor to the ICT sector's embodied carbon emissions, while import embodied carbon emission intensities among publishing activities (S2) are increasing significantly in most countries. The conclusion of this paper has important implications for how to reduce ICT's embodied carbon emissions of major countries.

Keywords: embodied carbon emissions, embodied carbon emission intensity, MRIO, trade, ICT

INTRODUCTION

With global warming and frequent disasters, countries are increasingly starting to realize the severity of climate change (Sun et al., 2020; Hou et al., 2021). Studies have shown that carbon dioxide (CO_2), as the most important greenhouse gas, has always been the main influencing factor of global warming, and has caused the global temperature to rise by nearly 1°C since the pre-industrial era (Peters et al., 2019; Tiwari et al., 2021). The continuous increase in CO_2 emissions is the result of an increase in global energy demand associated with the growth in global trade (Li and Hewitt, 2008; Lu et al., 2020). Peters and Hertwich (2008) indicate that carbon emissions caused by globally traded products accounted for 21.5% of global emissions. Wu et al. (2020) also

point out that the transfer of emissions embodied in interregional trade comprises around 40% of global carbon emissions.

Many scholars are also actively exploring corresponding emission reduction strategies, including the use of clean energy or renewable energy to replace fossil fuels (Dong et al., 2017, 2018, Dong K. et al., 2020), optimizing the industrial structure (Dong et al., 2019, Dong B. et al., 2020; Zhu and Zhang, 2021), and increasing energy efficiency (He et al., 2021; Xu and Tan, 2021). Some scholars have also proposed that technological innovation can help industrial sectors achieve low-carbon development while taking into account economic improvement (Zhang et al., 2016; Wang R. et al., 2020). As a new type of industry, the information and communication technologies (ICT) industry can partially replace high-energy-consuming products, and its success in this respect and its ability to reduce carbon emissions and use energy efficiently have received widespread attention from scholars. Moyer and Hughes (2012) believe ICT can improve economic productivity, reduce energy intensity, and exert downward pressure on renewable energy costs. Global Energy Statistical Yearbook (2014) also points out that ICT have an important role to play in reducing the energy intensity and increasing energy efficiency of the economy.

However, ICT are facing issues of uneven development among regions, and even a digital divide (Anwar, 2019; Wang et al., 2021). The process of globalization and the imbalance of regional development will cause the rapid promotion of international trade. The ICT sector will flow from regions with developed industries to regions with immature ICT technology. Vogiatzoglou (2009) points out that exports of ICT products have persistently accounted for 15% of global commodity exports in the past decade. Meanwhile, trade products have also triggered the flow of carbon emissions. Since the establishment of the World Trade Organization (WTO) in 1995, policy makers have considered the impact of international trade on the economy, and have increasingly investigated its impact on the environment (Honma and Yoshida, 2020). As an important component of international trade, ICT not only promotes economic growth, but also causes a large amount of carbon emission transfer and flow (Azam et al., 2021). With the liberalization of international trade, some scholars have also highlighted an increasing transfer of CO_2 emissions from developed countries to developing countries (Schaeffer and de Sá, 1996).

Although many scholars have studied the relationship between the ICT industry and carbon emissions (Moyer and Hughes, 2012; Amri et al., 2019; Shahnazi and Dehghan Shabani, 2019; Zhou et al., 2019; Nguyen et al., 2020), few scholars have conducted in-depth research on carbon emissions caused by the flow of products in the ICT sector caused by global trade. As the ICT industry is one of the important global development sectors in the future (Li et al., 2019), it is necessary to measure its embodied carbon emissions flow and embodied carbon emission intensities, and provide corresponding cross-regional emission reduction strategies. Therefore, this paper uses a multi-regional input-output (MRIO) model to explore the flow and network relationships of embodied carbon emissions and intensities by trade in the ICT sector of the world's major economies, and proposes emission reduction strategies for each country.

Above all, three main features distinguish this study from previous studies and contribute to filling the gap in the literature. First, we explore the embodied carbon emissions of the global ICT industry and the embodied carbon emissions of imports and exports of major economies, which is necessary to understand the developing trend and emission reduction direction of the global ICT industry; Second, we measure the mutual flow and intensities of embodied carbon emissions among major economies in the world, which can better evaluate the embodied carbon emissions in export and import, and conducive to the policy formulation and negotiation of cross-regional carbon emission reduction; Third, the embodied carbon emissions and intensities of various ICT industries have also been calculated by this study, which shows heterogeneity in the ICT sector's carbon emissions and provides a good reference for government to formulate emission-reduction strategies for enterprises.

This paper is structured as follows: Section "Literature review" organizes the literature on the relationship between embodied carbon emissions, intensities and ICT sectors. Section "Methodology and data" presents the methodology and data. Section "Results and discussion" analyzes the global carbon emissions and intensities in 15 major economies. Section "Further discussion" provides further analysis of the emissions and intensities of each ICT sector. Section "Conclusions and policy implications" addresses the policy implications and concludes the paper.

LITERATURE REVIEW

Due to the rise of the ICT sector in recent years and the intensification of digital activities on a global scale, scholars have increasingly started to pay attention to research on the relationship between the ICT sectors and global embodied carbon emissions. This study intends to discuss the extant literature under two strands of research: (1) Studying the relationship between carbon emissions and ICT sectors; and (2) studying the relationship between carbon emission intensity and ICT sectors.

Carbon Emissions and ICT Sectors

Information and communication technologies contributes substantially to global greenhouse gas (GHG) pollutant emissions, but scant research has quantified the impact of ICT products on carbon emissions. From the perspective of the products themselves, the types of ICT products included are very complex, and traditional industries also include many ICT sector products, making quantification difficult (Teehan and Kandlikar, 2013). However, with the development of digital industries and the intensification of the global greenhouse effect, more and more scholars have started to pay attention to the impact of the ICT industry on carbon emissions.

Some scholars analyze the embodied carbon emissions of the ICT sector of specific countries. Zhou et al. (2019) summarize China's embodied carbon emissions of ICT and point out that the ICT sector is far from being environment friendly while considering its embodied carbon impacts, which are dozens of times greater than the direct impacts.

Shahnazi and Dehghan Shabani (2019) analyze the correlation between the development of the ICT industry and carbon emissions in Iran's provinces, and their results show that an increase in ICT in a province first leads to an increase and then a decrease in CO_2 emissions in other provinces. Due to the prominence of the ICT sectors of some developed countries and the associated advantages of ICT for economic development, these countries have become a good target for many scholars to study ICT and embodied carbon emissions growth (Malmodin et al., 2014; Malmodin and Lundén, 2016). For example, Malmodin and Lundén (2016) conduct a detailed study of embodied carbon emissions of the ICT sector in Sweden from 1990 to 2015. They point out that although the embodied carbon emissions of the ICT sectors in that country have decreased since their peak in 2010, embodied carbon emissions from their manufacturing processes abroad are the largest source of ICT-related carbon emissions in Sweden.

Some scholars have expanded their research to the global region and analyze the relationship between the development of the global ICT industry and the impact of carbon emissions, and quantified the potential reduction of emissions in ICT (Moyer and Hughes, 2012; Bastida et al., 2019). Malmodin and Bergmark (2015) explore possible reductions globally within a 2030 timeframe, and predict a potential reduction of total GHG emissions by 2030 of about 8 Gtonnes CO_2 or 12% of global GHG emissions due to ICT solutions. Asongu (2018) investigates how ICT counteracts the negative influence of globalization on CO_2 emissions in his study of 44 Sub-Saharan African countries over the period 2000–2012. The author finds that ICT can be employed to dampen the potentially negative effect of globalization on environmental degradation through CO_2 emissions. Malmodin and Lundén (2018) analyze carbon emissions of the global ICT sectors for 2010-2015, and point out that the ICT sectors have turned their previously growing carbon footprints into shrinking ones.

However, related research on the embodied carbon emissions of the ICT sector caused by global trade is relatively insufficient. With the rapid development of globalization and the systematic construction of global industrial chains and value chains, this will be a very important component.

Carbon Emission Intensities and ICT Sectors

Energy intensity and carbon emission intensity are two important indicators for studying the environmental impact of industries. Some scholars are concerned about the interaction between the ICT industry and energy intensity. And the Global Energy Statistical Yearbook (2014) points out that the ICT industry plays an important role in reducing energy intensity and improving industrial efficiency, but few scholars pay attention to the energy intensity of the ICT industry itself. Wang and Han (2016) study the impact of ICT on energy intensity in China, and point out that the impact of ICT investment in energy intensity is significantly negative in western and central regions in China.

However, relatively speaking, the intensity of carbon emissions caused by energy is more representative and has been widely

studied by scholars (Pan et al., 2019; Liu et al., 2021a). However, research on carbon emission intensity and ICT-related research is relatively rare, and we can only find some relevant evidence in some research on the industrial framework or emerging technology industry. For example, Liu et al. (2021b) have shed light on the effect of Artificial Intelligence (AI) on carbon emission intensity. Their results show that AI tends to have a greater effect in reducing carbon emission intensity in the labor-intensive and tech-intensive industries. Chen et al. (2019) investigate the impact of ICT on CO_2 emission intensity by using Internet penetration and mobile phone penetration as proxies in China, and point out that the reduction effect of Internet penetration on CO_2 emission intensity in China's eastern and central provinces is more obvious. In contrast with the reduction effect of Internet penetration on CO_2 emission intensity in China's eastern provinces, it is greater in China's central provinces.

Few scholars have demonstrated concern about the intensive impact of global embodied carbon emissions. Although Jiang and Liu (2015) quantify the flow of embodied carbon emissions from the global ICT industry and trade, they do not highlight the impact of trade intensity under the global value chain system, and the research period is relatively lagging. This article will build a research framework on embodied carbon emissions and carbon emission intensities of global ICT trade in the context of global value chains. The paper will also analyze the volume and technical advantages and disadvantages of major economies' embodied carbon emissions, and recommend cross-regional emission-reduction strategies.

Furthermore, we will absorb the research experience of the above-mentioned scholars, based on previous studies on carbon emissions and carbon emission intensities in the ICT industry, and expand the analysis of embodied carbon emissions and the measurement of embodied carbon emission intensities from the perspective of global value chains in major economies around the world. Furthermore, this study will explore in detail the dynamic changes of the embodied carbon emissions and intensities of each ICT sector.

METHODOLOGY AND DATA

Multiregional Input–Output Model

The basic methodology used in this study is the multi-regional input-output (MRIO) model from the perspective of both the environment and the global value chain. This model put forward by Moses (1955), can depict economic links among regions. The row equivalent of the MRIO can be expressed as:

$$x_i^r = \sum_{s=1}^{R} \sum_{j=1}^{N} a_{ij}^{rs} x_j^s + \sum_{s=1}^{R} y_i^{rs} \qquad (1)$$

Where x_i^r is denoted as the total output of sector i in region r. a_{ij}^{rs} is the direct requirement coefficient of sector i in region r for sector j in region s, which can be calculated by $a_{ij}^{rs} = t_{ij}^{rs}/x_j^s$, and t_{ij}^{rs} is the intermediate use of sector i in region r for sector j in

region s; y_i^{rs} is the final demand of region s by sector i in region r. And the basic model of MRIO can be expressed in matrix form:

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

where $X = \left[x_i^r\right]_{RN \times 1}$, $A = \left[a_{ij}^{rs}\right]_{RN \times RN}$, $Y = \left[\sum_s y_j^{rs}\right]_{RN \times 1}$.

And we define $F = \left[f_i^r\right]_{1 \times RN}$ as the carbon emission intensity generated by the unitary output of sector i in region r. Embodied carbon emissions of an economy can be expressed as:

$$EC = F (I - A)^{-1} Y \qquad (3)$$

where $B = (I - A)^{-1} = \left[b_{ij}^{rs}\right]_{RN \times RN}$, the embodied carbon emissions from sector i in region r to sector j in region s can be calculated as:

$$EC_{ij}^{rs} = \sum_{k=1}^{R} f_i^r b_{ij}^{rk} y_j^{ks} \qquad (4)$$

Therefore, the element of domestic embodied carbon emissions diagonal matrix $DEC = \left[DEC_i^r\right]_{RN \times RN}$ can be calculated as:

$$DEC_i^r = \sum_{k=1}^{R} f_i^r b_{ii}^{rk} y_i^{kr} \qquad (5)$$

The element of export embodied carbon emissions from sector i in region r to sector j to region s can make up the export embodied carbon emissions matrix $EEC = \left[EEC_{ij}^{rs}\right]_{RN \times RN}$, which can be represented as:

$$EEC_{ij}^{rs} = \sum_{k=1}^{R} f_i^r b_{ij}^{rk} y_j^{ks} \left(r \neq s, i \neq j\right) \qquad (6)$$

The element of import embodied carbon emissions from sector i in region r to sector j to region s can make up the import embodied carbon emissions matrix $IEC = \left[IEC_{ij}^{rs}\right]_{RN \times RN}$, which can be represented as:

$$IEC_{ij}^{rs} = \sum_{k=1}^{R} f_j^s b_{ji}^{sk} y_i^{kr} \left(r \neq s, i \neq j\right) \qquad (7)$$

Next, we define $V = \left[v_i^r\right]_{1 \times RN}$ as the value-added coefficients generated by the unitary output of sector i in region r, which can be calculated by $v_i^r = va_i^r / x_i^r$, where va_i^r denotes the value added of sector i in region r. According to the global value flow analysis method (Fan et al., 2021), the element of embodied value-added cross countries matrix $EVA = \left[EVA_{ij}^{rs}\right]_{RN \times RN}$ can be calculated as:

$$EVA_{ij}^{rs} = \sum_{k=1}^{R} v_i^r b_{ij}^{rk} y_j^{ks} \qquad (8)$$

And the element of embodied carbon emission intensity of sector i in region r flowing into sector j in region s can make up the matrix $ECI = \left[ECI_{ij}^{rs}\right]_{RN \times RN}$, which can be calculated as:

$$ECI_{ij}^{rs} = EC_{ij}^{rs} / EVA_{ij}^{rs} \qquad (9)$$

Similarly, the domestic embodied carbon emission intensity of sector i in region r can make up the diagonal matrix $DECI = \left[DECI_i^r\right]_{RN \times RN}$, which can be calculated as:

$$DECI_i^r = DEC_i^r / \sum_{k=1}^{R} v_i^r b_{ii}^{rk} y_i^{kr} \qquad (10)$$

The export embodied carbon emission intensity of sector i in region r can make up the diagonal matrix $EECI = \left[EECI_i^r\right]_{RN \times RN}$, which can be calculated as:

$$EECI_i^r = \sum_{s=1}^{R} \sum_{j=1}^{N} EEC_{ij}^{rs} / \sum_{k=1}^{R} v_i^r b_{ij}^{rk} y_j^{ks}, (r \neq s, i \neq j) \qquad (11)$$

And the export carbon emission intensity from region r to region s can be calculated as:

$$EECI^{rs} = \sum_{i=1}^{N} \sum_{j=1}^{N} EEC_{ij}^{rs} / \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{R} v_i^r b_{ij}^{rk} y_j^{ks}, (r \neq s, i \neq j) \qquad (12)$$

The import embodied carbon emission intensity of sector i in region r can make up the diagonal matrix $IECI = \left[IECI_i^r\right]_{RN \times RN}$, which can be calculated as:

$$IECI_i^r = \sum_{s=1}^{R} \sum_{j=1}^{N} IECI_{ij}^{rs} / \sum_{k=1}^{R} v_j^s b_{ji}^{sk} y_i^{kr}, (r \neq s, i \neq j) \qquad (13)$$

And the import carbon emission intensity from region r to region s can be calculated as:

$$IECI^{rs} = \sum_{i=1}^{N} \sum_{j=1}^{N} IEC_{ij}^{rs} / \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{R} v_j^s b_{ji}^{sk} y_i^{kr}, (r \neq s, i \neq j) \qquad (14)$$

Data

Here we will use the MRIO model to measure the embodied carbon emissions of global ICT sectors. The World Input–output tables coming from the World Input–output database (WIOD) are released in 2016. The 2016 version covers 43 countries for the period 2000–2014 (Timmer et al., 2015). We have selected 15 major countries as the research objects of this study, and other countries are classified as other countries (ROW)[1], the country names and abbreviations are shown in **Table 1**. In order to make comparative prices, the multiregional input–output tables are processed at constant 2010 prices, and use a double-shrink method to select the price indexes for each sector's products (Miller and Peter, 2009). The price indexes are selected as the consumer price index of countries from the World Bank (2020). And the data of the 56 sectors are classified according to the International Standard Industrial Classification Revision 4 (ISIC Rev.4). We select five sectors as ICT departments, including one ICT manufacturing sector and four ICT service sectors, which are shown in **Table 2**.

The direct carbon emissions come from Corsatea et al. (2019), and the data fit perfectly with WIOD and are applied to this study.

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[1]The ROW is different from ROW of WIOD, it includes 28 countries and ROW countries in WIOD.

TABLE 1 | Major countries and their abbreviations.

Abbreviation	Countries
AUS	Australia
BRA	Brazil
CAN	Canada
CHN	China
DEU	Germany
ESP	Spain
FRA	France
GBR	United Kingdom
IDN	Indonesia
IND	India
JPN	Japan
KOR	Korea
MEX	Mexico
RUS	Russia
USA	United States

TABLE 2 | Information and communication technologies sectors in WIOD.

Codes	Sector names	ISIC Rev.4
S1	Manufacture of computer, electronic and optical products	C26
S2	Publishing activities	J58
S3	Motion picture, video and television program production, sound recording and music publishing activities; programming	J59–J60
S4	Telecommunications	J61
S5	Computer programming, consultancy and related activities; information service activities	J62–J63

RESULTS AND DISCUSSION

Global ICT Embodied Carbon Emissions

Calculated based on Eq. (3), the embodied carbon emissions of global ICT sectors and their proportion of global embodied carbon emissions have been shown in **Table 3**. In 2001, the embodied carbon emissions of the ICT sectors reach their highest point – 118.16 Mt. Since then, carbon emissions have been reduced year by year. In 2009, affected by the financial crisis, the embodied carbon emissions of ICT reach a historical low of 89.86 Mt. After 2009, there is a slight increase in ICT's carbon emissions. From the perspective of the percentage of ICT's embodied carbon emissions, there is a decreasing trend year by year after 2001, from 0.53% in 2001 to 0.30% in 2014.

From the perspective of the composition of embodied carbon emissions, domestic embodied carbon emissions accounted for the main part of ICT's embodied carbon emissions, reaching 58.89 Mt in 2014, and accounting for 61.63%. Although trade-embodied carbon emissions are not a major component, their share has been slowly increasing, from 34.99% in 2000 to 38.37% in 2014. With the gradual expansion of the ICT sectors, the carbon emissions caused by their trade will gradually occupy the main part.
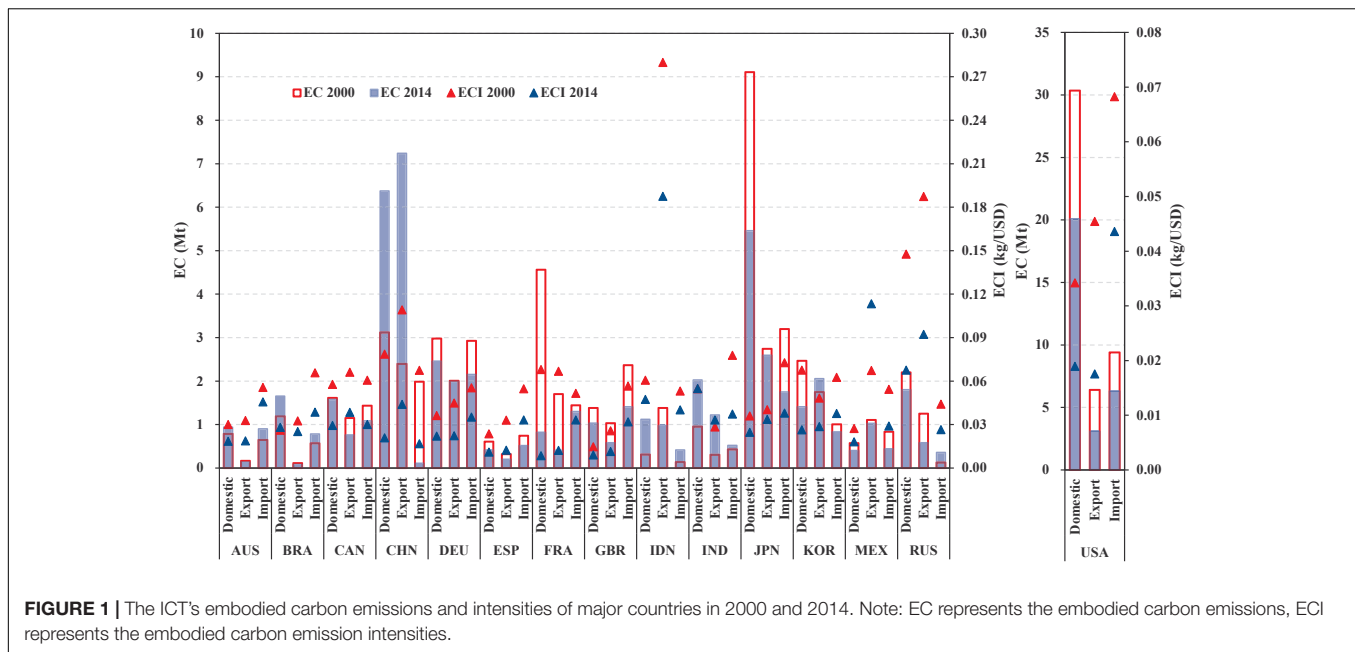
Domestic, Export, and Import Embodied Carbon Emissions and Intensities of Major Countries
Embodied Carbon Emissions

Figure 1 shows the ICT's embodied carbon emissions [calculated by Eqs. (5–7)] and embodied carbon emission [calculated by Eqs. (10–11) and Eq. (13)] intensities of 15 major countries in 2000 and 2014. From the perspective of ICT's embodied carbon emissions, the amount of ICT emissions in most developed countries reduces significantly in 2014. For example, domestic, export, and import embodied carbon emissions of ICT in France decreased from 4.56, 1.70, and 1.44 Mt in 2000 to 0.82, 0.41, and 1.30 Mt in 2014, respectively. The ICT's domestic, export and import embodied carbon emissions of the United States decreased from 30.34, 6.40, and 9.41 Mt in 2000 to 20.09, 3.08, and 6.31 Mt in 2014. Even so, the United States has the highest embodied carbon emissions of ICT in the world, which reflects its leading role and considerable investment in internal communications technology on a global scale (Adedoyin et al., 2020). However, some developing countries, such as China, India, Brazil, etc., have shown an increase trend in embodied carbon emissions. For example, China's domestic and export embodied carbon emissions of ICT increase from 3.12 and 2.39 Mt in 2000 to 6.37 and 7.24 Mt in 2014. India's export and import embodied carbon emissions of ICT increase from 0.31 and 0.43 Mt in 2000 to 1.22 and 0.52 Mt in 2014, respectively. Brazil's domestic and import embodied carbon emissions of ICT also increase from 1.19 and 0.57 Mt in 2000 to 1.65 and 0.78 Mt in 2014, respectively. This reflects that these countries are at an important stage of economic development, and are in the process of rapid expansion, although their new technologies and digital industry technologies are not fully mature (Wang H. et al., 2020; Sahoo et al., 2021). Nevertheless, the growth of these countries' ICT industries is reflected in their domestic and export products, which have increased embodied carbon emissions. The China Academy of Information and Communications Technology

TABLE 3 | Information and communication technologies domestic and trade carbon emissions and its proportion.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Domestic EC (Mt)	73.37	78.69	74.05	73.46	71.96	68.33	66.43	63.92	57.83	56.55	57.69	57.18	57.45	57.98	58.89
Trade EC (Mt)	39.49	39.47	37.22	37.22	39.58	40.24	42.48	40.56	38.15	33.31	36.97	37.79	36.87	36.79	36.67
ICT proportion (%)	0.51	0.53	0.49	0.46	0.44	0.41	0.40	0.37	0.34	0.32	0.32	0.31	0.30	0.30	0.30
Proportion of domestic emissions (%)	34.99	33.40	33.45	33.63	35.49	37.07	39.00	38.82	39.75	37.07	39.05	39.79	39.09	38.82	38.37
Proportion of trade emissions (%)	65.01	66.60	66.55	66.37	64.51	62.93	61.00	61.18	60.25	62.93	60.95	60.21	60.91	61.18	61.63

FIGURE 1 | The ICT's embodied carbon emissions and intensities of major countries in 2000 and 2014. Note: EC represents the embodied carbon emissions, ECI represents the embodied carbon emission intensities.

(CAICT) reports that China's digital economy accounted for 34.8% of GDP in 2018, and 36.2% in 2019 (CAICT, 2020). And according to a report by McKinsey in 2017, China has been one of the world's largest investors and adopters of digital technologies. For example, there are 731 million Internet users in 2016 in China, which is 1.7 times as many users as there are in India and the European Union, and 2.5 times as many users as there are in the United States that year (McKinsey, 2017). China's export embodied carbon emissions of ICT in 2014 surpass the domestic embodied carbon emissions, and become the main growth force of its ICT embodied carbon emissions. In the future, as China's technology continues to improve, export embodied carbon emissions will become China's main source of carbon emissions growth.

Embodied Carbon Emission Intensities

The carbon emission intensities of trade reflect to a certain extent the technological differences in a country's trade products and can provide intuitive emission reduction strategies. From the perspective of embodied carbon emission intensities (**Figure 1**), the amount of such emission intensities in most countries in 2014 show a downward trend compared with that in 2000. For example, the ICT's export embodied carbon emission intensities of France decrease from 0.07 kg/USD in 2000 to 0.01 kg/USD in 2014. Export and import embodied carbon emission intensities of ICT in China decrease from 0.11 kg/USD and 0.07 kg/USD in 2000 to 0.04 kg/USD and 0.02 kg/USD in 2014. The United States decreases its export and import embodied carbon emission intensities from 0.05 kg/USD and 0.07 kg/USD in 2000 to 0.02 kg/USD and 0/04 kg/USD in 2014. This reflects to a certain extent that the progress of production technology has promoted the process of carbon emission reduction in the ICT sector. However, it must be noted that India's domestic embodied carbon emission intensity and export embodied carbon emission

intensity of ICT have both increased slightly, which requires the attention of local government departments. From the selected countries, Indonesia's export embodied carbon emission intensity of ICT is much higher than that of other countries. Even though there is a significant decrease in 2014 compared to 2000, the export embodied carbon emission intensities of 0.19 kg/USD should still receive the attention of the authorities. For example, key considerations for Indonesia will be to find ways of optimizing the energy structure of products in the export sector and the industrial energy consumption intensity of its ICT sector. The country will also need to improve its energy poverty environment (Setyowati, 2021). In 2000, Russia's domestic and export embodied carbon emission intensities of ICT are relatively high, reaching 0.15 kg/USD and 0.19 kg/USD respectively, but in 2014 the export embodied carbon emission intensities decrease to 0.07 kg/USD and 0.09 kg/USD, respectively.

Embodied Carbon Emission and Intensity Flows Among Major Countries
Embodied Carbon Emission Flows

Calculated based on Eq. (6–7), the embodied carbon emission flows of the ICT industry in 2000 and 2014 within the world's 15 major countries and other countries (ROW) are shown in **Figure 2**. On the whole, ICT's embodied carbon emissions have shown a downward trend, especially in European countries and the United States. For example, the ICT's embodied carbon emissions of France's exports to Germany decrease from 0.208 Mt in 2000 to 0.034 Mt in 2014, and the ICT's embodied carbon emissions of United States exports to Germany decrease from 0.472 Mt in 2000 to 0.173 Mt in 2014. Relatively speaking, embodied carbon emissions in the Asia-Pacific region have shown an increasing trend. The embodied carbon emissions of China's exports to other countries are more obvious. For example,
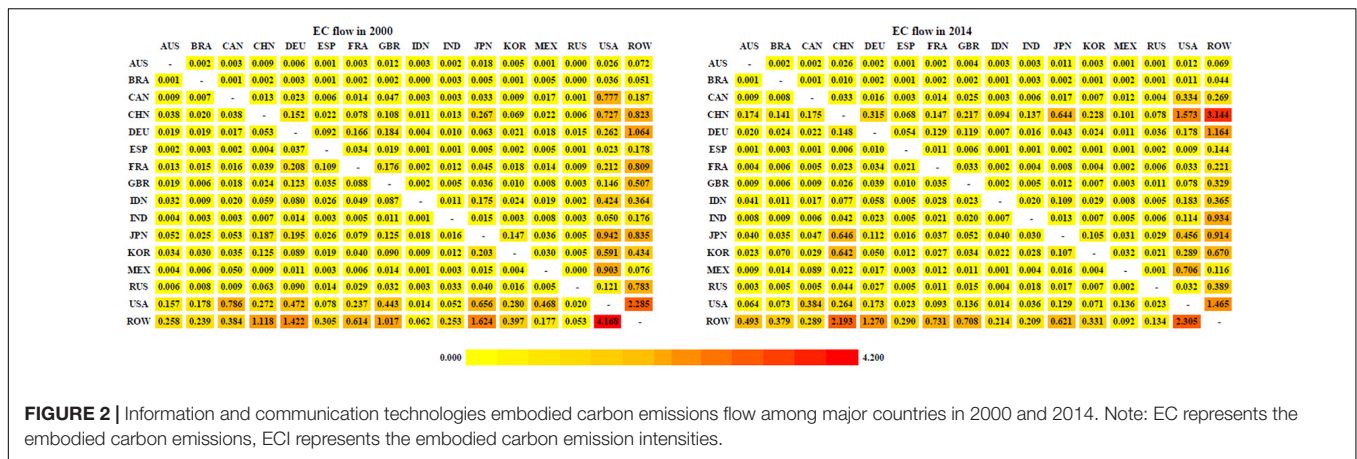
EC flow in 2000

	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IDN	IND	JPN	KOR	MEX	RUS	USA	ROW
AUS	-	0.002	0.003	0.009	0.006	0.001	0.003	0.012	0.003	0.002	0.018	0.005	0.001	0.000	0.026	0.072
BRA	0.001	-	0.001	0.002	0.003	0.001	0.002	0.002	0.000	0.003	0.005	0.001	0.005	0.000	0.036	0.051
CAN	0.009	0.007	-	0.013	0.023	0.006	0.014	0.047	0.003	0.033	0.009	0.017	0.000		0.777	0.187
CHN	0.038	0.020	0.038	-	0.152	0.022	0.078	0.108	0.011	0.013	0.267	0.069	0.022	0.006	0.727	0.823
DEU	0.019	0.019	0.017	0.053	-	0.092	0.166	0.184	0.004	0.010	0.063	0.021	0.018	0.015	0.262	1.064
ESP	0.002	0.003	0.002	0.004	0.037	-	0.034	0.019	0.001	0.001	0.005	0.002	0.005	0.001	0.023	0.178
FRA	0.013	0.015	0.016	0.039	0.208	0.109	-	0.176	0.002	0.012	0.045	0.018	0.014	0.009	0.212	0.809
GBR	0.019	0.006	0.018	0.024	0.123	0.035	0.088	-	0.002	0.005	0.036	0.010	0.008	0.003	0.146	0.507
IDN	0.032	0.009	0.020	0.059	0.080	0.026	0.049	0.087	-	0.011	0.175	0.024	0.019	0.002	0.424	0.364
IND	0.004	0.003	0.003	0.007	0.014	0.003	0.005	0.011	0.001	-	0.015	0.003	0.008	0.003	0.050	0.176
JPN	0.052	0.025	0.053	0.187	0.195	0.026	0.079	0.125	0.018	0.016	-	0.147	0.036	0.005	0.942	0.835
KOR	0.034	0.030	0.035	0.125	0.089	0.019	0.040	0.090	0.009	0.012	0.203	-	0.030	0.005	0.591	0.434
MEX	0.004	0.006	0.050	0.009	0.011	0.003	0.006	0.014	0.001	0.003	0.015	0.004	-		0.903	0.076
RUS	0.006	0.008	0.009	0.063	0.090	0.014	0.029	0.032	0.003	0.033	0.040	0.016	0.005	-	0.121	0.783
USA	0.157	0.178	0.786	0.272	0.472	0.078	0.237	0.443	0.014	0.052	0.656	0.280	0.468	0.020	-	2.285
ROW	0.258	0.239	0.384	1.118	1.422	0.305	0.614	1.017	0.062	0.253	1.624	0.397	0.177	0.053	4.168	-

EC flow in 2014

	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IDN	IND	JPN	KOR	MEX	RUS	USA	ROW
AUS	-	0.002	0.002	0.026	0.002	0.001	0.002	0.004	0.003	0.003	0.011	0.003	0.001	0.001	0.012	0.069
BRA	0.001	-	0.001	0.010	0.002	0.001	0.002	0.002	0.001	0.003	0.002	0.001	0.002	0.001	0.011	0.044
CAN	0.009	0.008	-	0.033	0.016	0.003	0.014	0.025	0.003	0.006	0.017	0.007	0.012	0.004	0.334	0.269
CHN	0.174	0.141	0.175	-	0.315	0.068	0.147	0.217	0.094	0.137	0.644	0.228	0.101	0.078	1.573	3.144
DEU	0.020	0.024	0.022	0.148	-	0.054	0.129	0.119	0.007	0.016	0.043	0.024	0.011	0.036	0.178	1.164
ESP	0.001	0.003	0.001	0.006	0.010	-	0.011	0.006	0.001	0.001	0.002	0.001	0.002	0.001	0.009	0.144
FRA	0.004	0.006	0.005	0.023	0.034	0.021	-	0.033	0.002	0.004	0.008	0.004	0.002	0.006	0.033	0.221
GBR	0.009	0.006	0.009	0.026	0.039	0.010	0.035	-	0.002	0.005	0.012	0.007	0.003	0.011	0.078	0.329
IDN	0.041	0.011	0.017	0.077	0.058	0.005	0.028	0.023	-	0.020	0.109	0.029	0.008	0.005	0.183	0.365
IND	0.008	0.009	0.006	0.042	0.023	0.005	0.021	0.020	0.007	-	0.013	0.007	0.005	0.006	0.114	0.934
JPN	0.040	0.035	0.047	0.646	0.112	0.016	0.037	0.052	0.040	0.030	-	0.105	0.031	0.029	0.456	0.914
KOR	0.023	0.070	0.029	0.642	0.050	0.012	0.027	0.034	0.022	0.028	0.107	-	0.032	0.021	0.289	0.670
MEX	0.009	0.014	0.089	0.022	0.017	0.003	0.012	0.011	0.004	0.004	0.016	0.004	-	0.001	0.706	0.116
RUS	0.003	0.005	0.005	0.044	0.027	0.005	0.011	0.015	0.004	0.018	0.017	0.007	0.002	-	0.032	0.389
USA	0.064	0.073	0.384	0.264	0.173	0.023	0.093	0.136	0.014	0.036	0.129	0.071	0.136	0.023	-	1.465
ROW	0.493	0.379	0.289	2.193	1.270	0.290	0.731	0.708	0.214	0.209	0.621	0.331	0.092	0.134	2.305	-

0.000   4.200

FIGURE 2 | Information and communication technologies embodied carbon emissions flow among major countries in 2000 and 2014. Note: EC represents the embodied carbon emissions, ECI represents the embodied carbon emission intensities.

the ICT's embodied carbon emissions of China's exports to the United States increases from 0.727 Mt in 2000 to 1.573 Mt in 2014, and exports to Japan increases from 0.267 Mt in 2000 to 0.644 Mt in 2014. The ICT's embodied carbon emissions of Japan and South Korea's exports to China also show significant growth, from 0.187 and 0.125 Mt in 2000 to 0.646 and 0.642 Mt in 2014, respectively.

Embodied Carbon Intensity Flows

Calculated based on Eq. (12) and Eq. (14), the embodied carbon intensities of global ICT industry trade in 2000 and 2014 are shown in **Figure 3**. In 2000, the embodied emission intensities of Indonesia and Russia's exports to other countries are significantly higher than those of other countries. For example, the embodied emission intensities of Indonesia's exports to Germany, France, the United Kingdom, and the United States all reach 0.30 kg/USD, and the embodied carbon intensity of ICT products export from Russia to India reaches 0.28 kg/USD. In 2014, embodied carbon intensity showed a significant downward trend, but relatively speaking, the ICT's embodied carbon intensities of Indonesia's exports to other countries are still higher than those of other countries in 2014, 0.29 kg/USD from Indonesia to Germany, and 0.25 kg/USD from Indonesia to Canada, which should have aroused the attention of the relevant government departments. The embodied carbon intensities of Mexico's exports of ICT products have shown an increasing trend. For example, the embodied carbon intensity of Mexico's exports to the United States increases from 0.07 kg/USD in 2000 to 0.12 kg/USD in 2014, and exports to China also increase from 0.06 kg/USD in 2000 to 0.10 kg/USD in 2014. This shows that the export of ICT products may not reduce the carbon intensity to achieve emission reduction due to technical restrictions, which has caused the significant spillover effect[2] of export carbon emissions (Liu and Liu, 2019; Wang and Li, 2019). Relatively speaking, the embodied carbon intensities of European countries, such as Spain, France, and the United Kingdom, are at the low level. The ICT's embodied carbon intensities of their exports to other countries are all about 0.01 kg/USD, reflecting the

[2] The flow of embodied carbon emissions in one region affects the level of carbon emissions in other regions.

technological advantages and emission reduction driving forces of ICT products in these European countries.

FURTHER DISCUSSION

After investigating the embodied carbon emissions and embodied carbon emission intensities of the ICT sector in various countries, we find that there is relatively little understanding of the internal ICT sector, and the internal ICT manufacturing products or services that have caused the increase in embodied carbon emissions are worthy of attention. Therefore, we continue to explore the impact of each ICT sector.

Embodied Carbon Emissions of ICT Sectors

Figure 4 shows the global embodied carbon emissions of each ICT sector from 2000 to 2014 and their proportions in 2000 and 2014. The sector that manufacture of computer, electronic and optical products (S1) produces the most embodied carbon emissions from 2000 to 2014, and the changing trend almost reveals a 'W' shape. In 2006, the sector of manufacture of computer, electronic and optical products (S1) is the top producer of embodied carbon emissions (30.39 Mt). However, the proportion of embodied carbon emissions produced by the sector decrease from 68.6% in 2000 to 62.2% in 2014. Other ICT sectors, all of which belong to ICT services, have relatively low embodied carbon emissions. For example, the embodied carbon emissions of computer programming, consultancy and related activities and information service activities (S5) are 8.00 Mt in 2014, accounting for 21.8% of global ICT embodied carbon emissions that year. By 2000, although these emissions have increased, they represented 18.2% of global ICT embodied carbon emissions. The embodied carbon emissions of publishing activities (S2) are 2.96 Mt in 2014. This represents 8.1% of global ICT embodied carbon emissions, up from 2.7% in 2000. The sector representing motion picture, video and television program production, sound recording and music publishing activities, programming (S3) and telecommunications (S4) show a decreasing proportions of
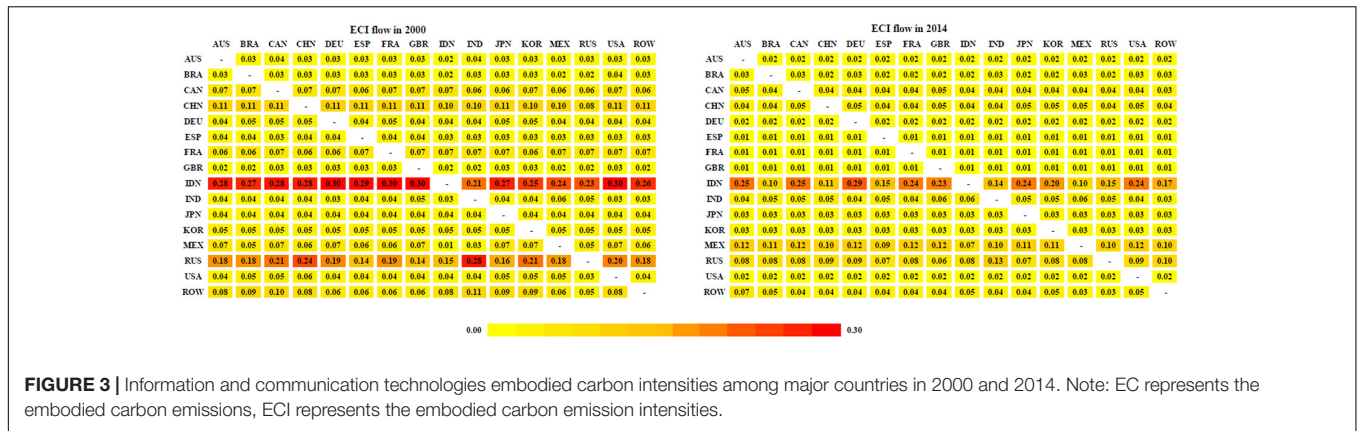
ECI flow in 2000

	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IDN	IND	JPN	KOR	MEX	RUS	USA	ROW
AUS	-	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.04	0.03	0.03	0.03	0.03	0.03
BRA	0.03	-	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.02	0.02	0.04	0.03	
CAN	0.07	0.07	-	0.07	0.07	0.06	0.07	0.07	0.07	0.06	0.06	0.07	0.06	0.06	0.07	0.06
CHN	0.11	0.11	0.11	-	0.11	0.11	0.11	0.11	0.10	0.10	0.11	0.10	0.10	0.08	0.11	0.11
DEU	0.04	0.05	0.05	0.05	-	0.04	0.05	0.04	0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.04
ESP	0.04	0.04	0.03	0.04	0.04	-	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
FRA	0.06	0.06	0.07	0.06	0.06	0.07	-	0.07	0.07	0.06	0.07	0.06	0.07	0.07	0.07	0.07
GBR	0.02	0.02	0.03	0.03	0.03	0.03	0.03	-	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.02
IDN	0.28	0.27	0.28	0.28	0.30	0.29	0.30	0.30	-	0.21	0.27	0.25	0.24	0.23	0.30	0.26
IND	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.05	0.03	-	0.04	0.04	0.06	0.05	0.03	0.03
JPN	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	-	0.05	0.04	0.04	0.04	0.04
KOR	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	-	0.05	0.05	0.05	0.05
MEX	0.07	0.05	0.07	0.06	0.07	0.06	0.06	0.07	0.01	0.03	0.07	0.07	-	0.05	0.07	0.06
RUS	0.18	0.18	0.21	0.24	0.19	0.14	0.19	0.14	0.15	0.26	0.16	0.21	0.18	-	0.20	0.18
USA	0.04	0.05	0.05	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.03	-	0.04
ROW	0.08	0.09	0.10	0.08	0.06	0.06	0.06	0.06	0.08	0.11	0.09	0.09	0.06	0.05	0.08	-

ECI flow in 2014

	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IDN	IND	JPN	KOR	MEX	RUS	USA	ROW
AUS	-	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
BRA	0.03	-	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.03	0.04
CAN	0.05	0.04	-	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03
CHN	0.04	0.04	0.05	-	0.05	0.04	0.04	0.05	0.04	0.04	0.05	0.05	0.05	0.04	0.05	0.04
DEU	0.02	0.02	0.02	0.02	-	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
ESP	0.01	0.01	0.01	0.01	0.01	-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
FRA	0.01	0.01	0.01	0.01	0.01	0.01	-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
GBR	0.01	0.01	0.01	0.01	0.01	0.01	0.01	-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
IDN	0.25	0.10	0.25	0.11	0.29	0.15	0.24	0.23	-	0.14	0.24	0.20	0.10	0.15	0.24	0.17
IND	0.04	0.05	0.05	0.05	0.04	0.05	0.04	0.06	0.06	-	0.05	0.05	0.06	0.05	0.04	0.04
JPN	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	-	0.03	0.03	0.03	0.03	0.03
KOR	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	-	0.03	0.03	0.03	0.03
MEX	0.12	0.11	0.12	0.10	0.12	0.09	0.12	0.12	0.07	0.10	0.11	0.11	-	0.10	0.12	0.10
RUS	0.08	0.08	0.08	0.09	0.09	0.07	0.08	0.08	0.06	0.08	0.13	0.07	0.08	-	0.09	0.10
USA	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	-	0.02
ROW	0.07	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.05	0.03	0.03	0.05	-

0.00 — 0.30

FIGURE 3 | Information and communication technologies embodied carbon intensities among major countries in 2000 and 2014. Note: EC represents the embodied carbon emissions, ECI represents the embodied carbon emission intensities.
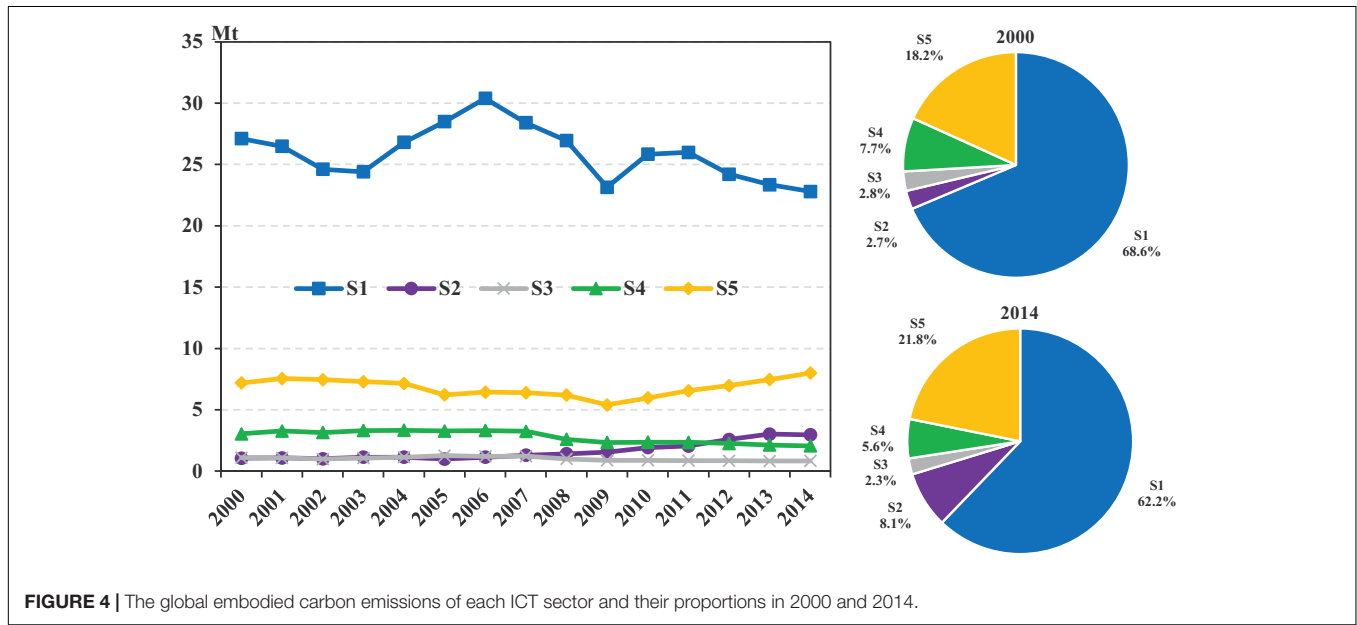

FIGURE 4 | The global embodied carbon emissions of each ICT sector and their proportions in 2000 and 2014.

embodied carbon emissions, from 7.7 and 2.8% in 2000 to 5.6 and 2.3%, respectively.

Embodied Carbon Emissions and Intensities of Each ICT Sector in Various Countries

Figure 5 shows the embodied carbon emissions and intensities of ICT sectors in each country in 2000 and 2014. From a quantitative point of view, the embodied carbon emissions of the sector of manufacture of computer, electronic and optical products (S1) in most countries are much higher than those of other sectors, and the amount in 2014 is less than that in 2000. The import and export embodied carbon emissions of manufacture of computer, electronic and optical products (S1) in China have both risen significantly, and Brazil's import embodied carbon emissions have increased. The embodied carbon emissions of manufacture of computer, electronic and optical products (S1) in other countries show a downward trend from 2000 to 2014. What is more anomalous is that in 2000, the embodied carbon emission

of the telecommunications (S4) sector is the highest in India at 0.141 Mt. In 2014, the computer programming, consultancy and related activities; information service activities (S5) sector has the highest embodied carbon emissions at 0.806 Mt.

From the perspective of carbon emission intensities, the export carbon emission intensity of the publishing activities (S2) sector in many countries has increased significantly by 2014. For example, Australia increases its export carbon emission intensity of the S2 sector from 0.02 kg/USD in 2000 to 0.15 kg/USD in 2014. Germany increases from 0.03 kg/USD in 2002 to 0.08 kg/USD in 2014. The import carbon emission intensities of the other four sectors have shown varying degrees of downward trends. The export carbon emission intensities of ICT sectors in most countries have shown a significant downward trend, reflecting the rapid progress of ICT products exported by these countries. For example, the export carbon emission intensity of China's manufacture of computer, electronic and optical products (S1) sector decrease from 0.12 kg/USD to 0.05 kg/USD in 2000, and the export carbon emission intensities of the S1 sector in the United States decrease from 0.06 kg/USD to 0.02 kg/USD. India
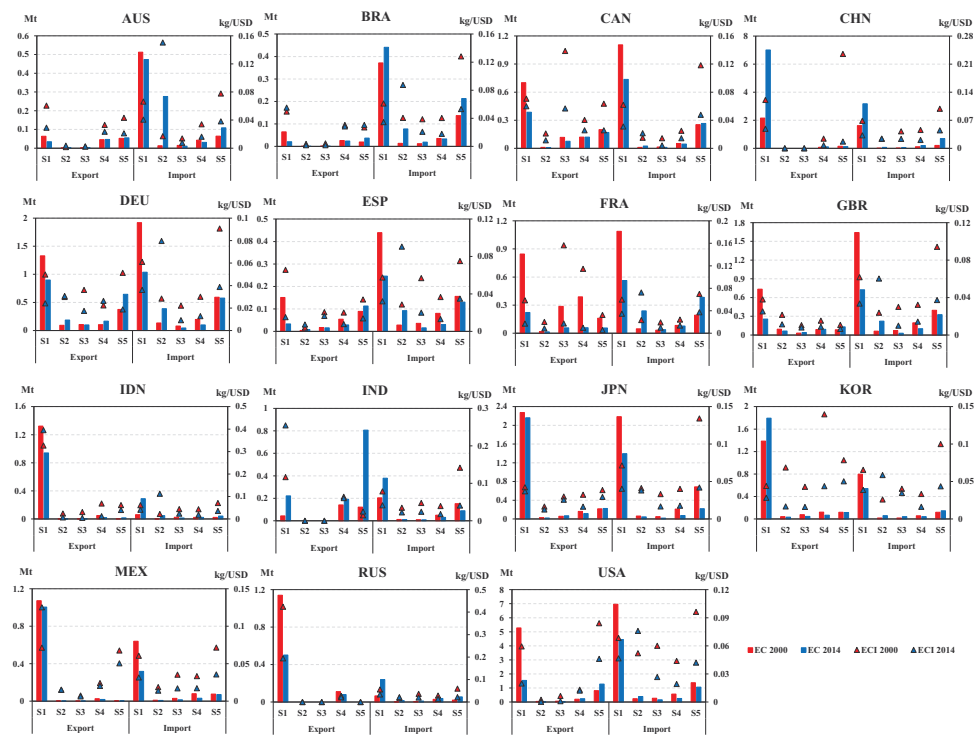
FIGURE 5 | The embodied carbon emissions and intensities of the ICT sectors in each country in 2000 and 2014. Note: EC represents the embodied carbon emissions, ECI represents the embodied carbon emission intensities.

and Indonesia are relatively special; their sector of manufacture of computer, electronic and optical products (S1) has shown an upward trend in export carbon emission intensity, indicating that the export technology of its ICT manufacturing sector has not yet shown much carbon emission reduction potential.

CONCLUSION AND POLICY IMPLICATIONS

Conclusion

This article explores the embodied carbon emissions and carbon emission intensities of 15 major countries around the world, and further discusses the changes in various industrial sectors in each country. Accordingly, the main conclusions are as follows:

(1) In 2001, global ICT carbon emissions reach the highest value in our study. Since then, in terms of quantity, the share of ICT embodied carbon in the world has slowly declined. The proportion of ICT embodied carbon emissions decrease from 0.53% in 2001 to 0.30% in 2014. The proportion of domestic carbon emissions caused by own consumption is relatively high. In 2014, this part of carbon emissions accounts for 61.63% of global ICT embodied carbon emissions. However, the ICT's embodied carbon emissions caused by trade gradually increase, from 34.99% in 2000 to 38.27% in 2014.

(2) From the perspective of the ICT's embodied carbon emissions and embodied carbon emission intensities of various countries, the embodied carbon emissions of ICT in the United States have been much higher than those of other countries. In 2000, the embodied carbon emissions of exports and imports are 6.40 and 9.41 Mt, respectively. But by 2014, there are a significant downward trend in the embodied carbon emissions of exports and imports, which reach 3.08 and 6.31 Mt, respectively. Similarly, the embodied carbon emissions of most countries in 2014 are significantly lower than in 2000. However, in some developing countries, such as India, China, and Brazil, embodied carbon emissions have shown an upward trend. China's export embodied carbon emissions in 2014 exceed domestic embodied carbon emissions, becoming the main growth force of carbon emissions in its ICT sector. From the perspective of carbon emission intensities, the embodied carbon emission intensities of most countries have decreased slightly. However, India's domestic embodied carbon emissions and export embodied carbon emissions have shown a slight increase. The embodied carbon emission intensity of Indonesia's exports is much higher than that of other countries, and should receive attention from the government.

(3) From the perspective of regional trade, the embodied carbon emissions of ICT products in the Asia-Pacific

region are increasing. The embodied carbon emissions of ICT products exported from China to other countries have increased, as have those of Japan and South Korea's ICT products exported to China. In 2000, the embodied carbon emission intensities of ICT products exported from Indonesia and Russia to other countries show a trend higher than that of other countries. However, by 2014, the embodied carbon emission intensity of the ICT sector in most countries has declined. The embodied carbon emission intensity of ICT products exported by Mexico has shown an increasing trend in contrast to the embodied carbon emission intensities of ICT product exports from European countries, which have been at a low level.

(4) From the perspective of the embodied carbon emissions and intensities of various ICT industry sectors, the sector of manufacture of computer, electronic and optical products (S1) is the main embodied carbon component of the ICT sectors, both globally and locally for each country. However, with the passage of time, the percentage of embodied carbon emissions in the ICT manufacturing industry (S1) has been decreasing year by year. In comparison, the embodied carbon emissions of the ICT service industries (S2–S5) have been increasing year by year. As far as countries are concerned, the embodied carbon emissions of India's ICT service industry are higher than those of the manufacturing industry, which is reflected in the sectors of telecommunications (S4) and computer programming, consultancy and related activities; information service activities (S5). In addition, the import embodied carbon emission intensities of the publishing activities (S2) sector in most countries have increased significantly, reflecting the technical disadvantages of imported products in this sector. The embodied carbon emission intensities of exports of various countries and ICT sectors have shown a significant downward trend.

Policy Implications

(1) Although the embodied carbon emissions of the global ICT sector are not high, the sector has already demonstrated its technological advantages and has shown a special advantage in reducing carbon emissions. However, the promotion of trade carbon emissions needs to attract the attention of local governments. It should be noted that the control of the embodied carbon emission intensities of exports can reduce the growth of embodied carbon emissions, and that the ICT sector can further reduce its carbon emissions.

(2) Developing countries such as China, India, and Brazil need to pay special attention to the significant increase in embodied carbon emissions from the ICT sector. China needs to pay attention to the embodied carbon emissions of the export sector, while India needs to pay attention to the embodied carbon emission intensity changes of exports, and realize that maintaining a downward trend is conducive to achieving emission reductions. This requires above countries to enhance the competitiveness

of their enterprises in carbon reduction technologies. The Indonesian government needs to focus on the high embodied carbon emission intensity of exports, which is much higher than other countries and is the main driving force behind the embodied carbon emissions of the country's ICT sector.

(3) From the perspective of regional coordinated emission reduction, the embodied carbon emissions of the ICT sector in the Asia-Pacific region remain high, mainly in China, Japan, and South Korea. A coordinated development policy in the Asia-Pacific region could help accelerate the process of regional carbon emission reduction. The growth of embodied carbon intensity in Mexico's exports and the high level of embodied carbon intensity in Indonesia have both reminded local governments to strengthen the regulation of ICT exports, improve the energy efficiency of these products, and learn more from the experience of European countries in achieving low-carbon intensity development.

(4) Regarding the ICT sector, carbon emissions caused by trade in the manufacturing industry account for a relatively high proportion, while carbon emissions caused by trade in the service industry are on the rise. This requires countries to optimize the export carbon intensities of ICT-manufactured products and strengthen supervision of the export of ICT service industries. The Indian government should pay particular attention to the export of ICT services, mainly the embodied carbon emissions of telecommunications (S4) and computer programming, consultancy and related activities; information service activities (S5).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

XD: conceptualization, validation, investigation, resources, data curation, and funding acquisition. QJ: conceptualization, writing – review and editing. JW: methodology, software, visualization, writing – original draft, writing – review and editing. All authors contributed to the article and approved the submitted version.

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