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EDITED BY

Xu Zhao,
Shandong University, Weihai, China

REVIEWED BY

Chuanfu Zang,
South China Normal University, China
Xiaotian Ma,
Shandong University, China

*CORRESPONDENCE

Xiawei Liao,
xiawei.liao@bnu.edu.cn

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Global value chain participation impacts carbon emissions—Take the electro-optical equipment industry as an example

Xiaoming Ma¹, Xin Liu¹, Xiaoli Pan¹ and Xiawei Liao^{2*}

¹School of Environment and Energy, Peking University Shenzhen Graduate School, Shenzhen, China, ²Bay Area International Business School, Beijing Normal University, Zhuhai, China

This study selects the electro-optical equipment manufacturing industry as an example to explore whether participation in the global value chain increases or mitigates a country's carbon emissions and describes the impacting factors. Based on multi-regional input-output tables, a value-added decomposition model is used to decompose forward and backward value-added/final products of the world's electro-optical equipment manufacturing industries in 65 countries from 2005 to 2015. Impacts of several global value chain participation characteristics, including position, forward participation and production length, and backward participation and production length, on a country's carbon emissions, are examined. The results show that Asian countries have the highest participation rate in the global value chain, both forward and backward, of the electro-optical equipment sector with increasing proportions for forward participation, but lowest backward participation, in simple global value chains. An increase in forward global value chain participation contributes to the reducing carbon emission intensity of the electro-optical equipment manufacturing industry, particularly in terms of simple global value chain participation. On the other hand, the production length of the backward simple global value chain is positively correlated with the total imported carbon emission intensity, indicating that the longer the simple global value chain of foreign production is included in the industry's imported intermediate products and the lower the country's position in the global value chain is, the higher its imported carbon emission intensity is. Upgrade in the global value chain is able to reduce the embodied carbon emissions in the intermediate product exports and total imports.

KEYWORDS

global value chain, carbon emissions, electro-optical equipment, input-output analysis, decomposition analysis

1 Introduction

Global climate change is arguably the most pressing challenge facing humanity in the 21st century. The results of climate change, including sea-level rise, more frequent extreme weather events, and so forth, have generated wide-ranging social-economic ramifications and are expected to continue rising. In 2015, the global community adopted the Paris Agreement, a legally binding international treaty that set an ambitious goal to limit global warming to well below 2, preferably to 1.5°C, compared to pre-industrial levels. In order to achieve such a goal, countries around the world are joining hands to reduce their carbon emissions, the primary contributor to global climate change (IPCC 2013), with ‘common but shared responsibilities’. By January 2021, over 120 countries have made a commitment toward ‘carbon neutrality’ where anthropogenic carbon emissions are entirely absorbed by carbon sinks (Guterres 2020). As the world’s largest carbon emitter, China has committed to peaking its carbon emissions by 2030 and reaching carbon neutrality by 2060 (Mallapaty 2020).

When the majority of carbon emissions are generated from production activities, which are often located in developing countries, large volumes of the produced goods and services are eventually consumed by customers in developed countries through the global trade system. Studies on carbon accounting suggest that about 20–30% of total CO₂ emissions are associated with international trade (Meng et al., 2018; Zhang et al., 2020; WTO 2021). In addition to goods and services, the global trade system introduces geographical transfers of environmental externalities, which include carbon emissions. Sharing emission reduction responsibilities between global producers and consumers could facilitate international agreements on global climate policies. Accordingly, there are two approaches to carbon accounting, “production-based” and “consumption-based” (Lenzen et al., 2007; Karakaya et al., 2019). The former quantifies carbon emissions occurring in the regional territory where production takes place, while the latter quantifies emissions in a region where consumption occurs (Davis and Caldeira, 2010). In order to quantify “consumption-based” emissions, either top-down models, such as input-output tables, can be used, or trade data are coupled with production-based analyses (Tukker and Dietzenbacher 2013). The standard territorial-based emission accounting methods are adjusted by removing the emissions associated with exports and adding the emissions associated with imports (Peters and Hertwich 2008).

When existing studies on global carbon emission transfers have been primarily based on global import and export data, it is increasingly recognized that greenhouse gases are emitted along the global value chain (GVC). The value chain is defined as a product or service that follows several stages from its conception to end-use (for example, from design, through fabrication,

marketing, and distribution, to support for the final consumer). With the development of economic globalization, countries are deeply involved in the international division of labor system characterized by the division of labor in the GVC, which refers to international production sharing where production is broken (that is, fragmented) into activities and tasks carried out in different countries wherever the necessary skills and materials are available at competitive cost and quality (Gereffi and Fernandes-Stark 2011).

Products transferred across geographical boundaries through the global trade system can be used for either final consumption or as intermediate inputs to produce other goods and services, thus entering a production value chain. The goods and services that we consume are composed of inputs from various countries around the world. According to data from UN Comtrade, trade of intermediate products made up 69.32% of global trade in 2013, increasing from 50% in 1995. Wang et al. (2017a) further classified GVC as either complex GVC or simple GVC. Simple GVC indicates GVC that includes one-time transnational trade, while complex GVC includes more than once transnational trades for intermediate products. According to Li, Meng and Wang (2019), from 2000 to 2007, GVCs, especially complex ones, expanded at a faster rate than GDP. China is playing an increasingly important role in global trades, especially simple GVC networks, while the United States and Germany remain the most important hubs in complex GVC networks. Another indicator of the complexity of GVCs is their length, which is defined by the number of production processes. The more production processes there are, the longer the GVC length is and the GVC is more complex, and vice versa (Fally 2011).

Furthermore, there are two directions for a country to participate in GVCs: forward and backward. According to WTO definitions (WTO 2019), forward GVC participation represents the “seller” perspective or supply-side in GVC participation. It captures the domestic value-added contained in exports sent to third economies for further processing and export through value chains. The value of forwarding participation corresponds to the ratio of the “domestic value-added sent to third economies” to the economy’s total gross exports, that is, how much value-added by exports is generated within the country. On the contrary, backward GVC participation represents the “buyer” perspective or sourcing side in GVCs, where an economy imports intermediates to produce its exports. The value of backward participation is indicated by the ratio of the “foreign value-added content of exports” to the economy’s total gross exports, that is, how much of the value-added created by exports happened abroad.

When studies relating to GVCs have previously primarily focused on the creation and distribution of value-added, employment, and incomes (Timmer et al., 2013), in recent years, scholars have paid increasing attention to the interaction of GVCs and environmental impacts and policies

(Hoekstra and Wiedmann, 2014). When the GVC division of labor allows countries to obtain value-added benefits, it also facilitates transfers of environmental impacts from countries with high value-added activities to low value-added activities. Many developing countries are located at the bottom of GVC bearing large proportions of environmental externalities, for example, carbon emissions, but only low value-added activities (Koopman et al., 2014). In another word, developing countries are often located at the bottom of the “smiling curve”, a curve that resembles a smiling face indicating that the market resides at the two ends of the value chain in terms of, respectively, research and development and branding and services, while the activities in the middle, for example, fabrication, manufacturing, transportation, are low value-added albeit emission-intensive. Take the production of the iPhone for example, among the US\$ 2 billion iPhone exports from China in 2009, only 4% of the value-added were in China (Xing and Detert, 2011). Therefore some countries that are abundant in natural resources often perform poorly economically, facing the so-called challenges of the resource curse (Umar et al., 2021), as demonstrated by research on Venezuela (Su et al., 2020) and Russia (Yang et al., 2021). Resource curses can also be transmitted to developed countries through the financial markets (Li et al., 2021). Because technologies vary in each country, global carbon accounting based on final import and export data and national carbon intensities may underestimate or overestimate the carbon emissions generated throughout the full value chain. It is, therefore, useful to examine carbon emission distributions of countries through the lens of GVC and how a certain country upgrading its location at the GVC could affect its carbon emissions.

Existing studies on GVC and carbon emissions have focused on the national level and quantified the relationship between position along the GVC and national embodied carbon emissions (Wang et al., 2019; Fei et al., 2020). However, few studies have shed light on the impacts of other indexes of GVC, that is, participation length and complexity, on carbon emissions, especially at a sector level. This study, therefore, fills this gap. Selection of the electro-optical equipment manufacturing sector is due to two reasons: 1) as this industry has a long GVC across the globe with a high degree of production fragmentation, i.e., intermediate inputs sourced from different countries; 2) there are significant carbon emissions generated at different production processes of the electro-optical equipment industry. This study 1) first quantifies the country-level carbon emissions through the GVC of the electro-optical equipment (EOE) manufacturing sector at a global scale and 2) examines the impacts of several GVC characteristics, including GVC position, forward participation and length, backward participation and length, on carbon emissions.

2 Methods and data

There are primarily three types of methods examining sector-level GVC and its carbon emissions: 1) global trade statistics of intermediate production inputs; 2) global trade statistics based on customs data; 3) trade decomposition based on value-additions. The first two methods have relatively low data requirements. While the first method has low accuracy, the second method only covers a few main sectors (Amador and Cabral 2016). This study adopts the value-added decomposition model based on the OECD Multi-Regional Input-Output Model (OECD 2018) to decompose the forward and backward value-additions along the GVC of the world’s electronic optical equipment manufacturing industry and calculate the carbon emissions for global electronic optical equipment in 65 countries from 2005 to 2015. According to the Wang-Wei-Zhu (WWZ) decomposition method (Wang et al., 2013), exports can be decomposed into 16 components, including domestic value-added, foreign value-added, returning value-added, double counting, and so forth. The methodological framework of this study is summarized in Figure 1.

2.1 Multi-regional input–output model

An Input-Output Model is a representation of the interdependencies between different sectors of a flow system, like an economy (Leontief, 1936). The multi-regional input-output (MRIO) model is developed based on the traditional IO model, taking into account the impacts of inter-regional trades. MRIO has become one of the most widely used approaches to analyze the interdependencies of different economies and their associated environmental impacts and externalities (Mi et al., 2018). Each column in the IO table represents the required inputs from other industries to produce the given amount of the product represented by that column. When the output flows associated with a particular level of final demand (exogenous in a standard IO model) are known, the total emissions throughout the (global) economy can be estimated by multiplying these output flows with the emission intensity coefficient (emission per unit of gross output) in each country/industry.

2.2 Global value chain participation

According to Koopman et al. (2014), GVC participation can be used to indicate a country’s participation in the GVC of a certain industry and can be expressed by the upcoming equation:

$$GVC_Participation_{ir} = \ln\left(1 + \frac{IV_{ir}}{E_{ir}}\right) + \ln\left(1 + \frac{FV_{ir}}{E_{ir}}\right), \quad (1)$$

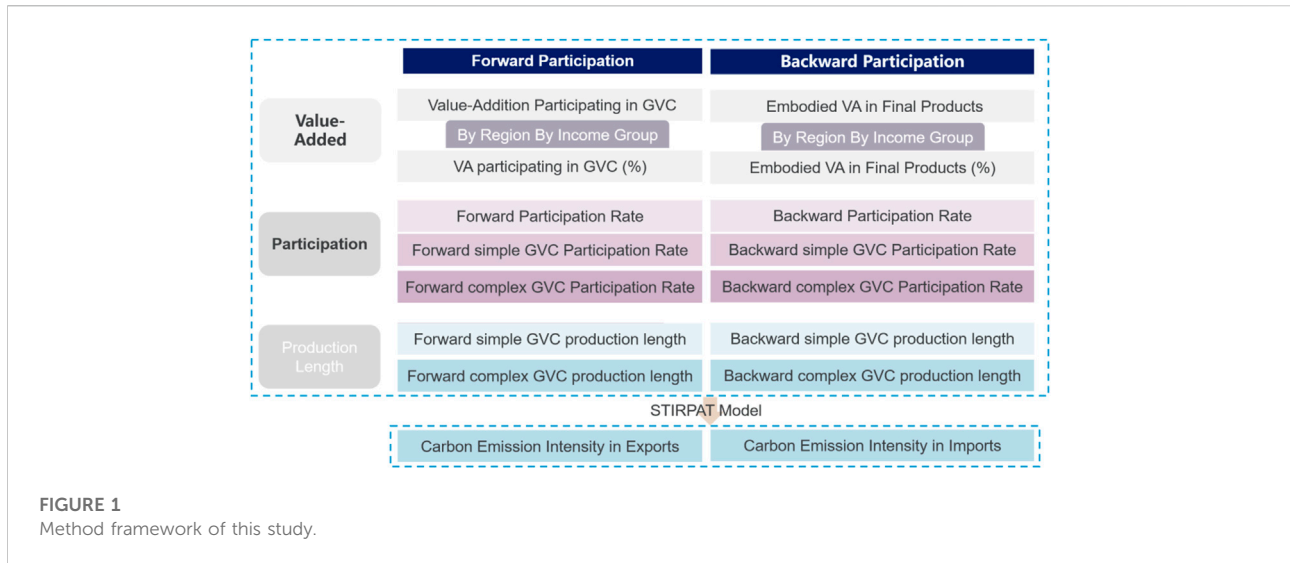


FIGURE 1 Method framework of this study.

where IV_{ir} indicates the indirect value-addition export of sector i of country r , equalling the sum of domestic value-additions created for the total export of intermediate products of sector i . FV_{ir} represents foreign value-additions embodied in the total exports of sector i of country r and E_{ir} denotes country r 's sector i 's total exports. Forward and backward participation indicators can be calculated by dividing forward participation and backward participation, respectively, by the total export, indicating how much of the exported goods are for the global value chain and how much of the exported goods are from the global value chain, respectively. Other characteristics of participation, including the length and complexity, can be calculated according to Wang et al. (2017b) and are detailed in Supporting Information.

2.3 Stochastic impacts by regression on the population, affluence, and technology model

Based on the impact, population, affluence, and technology (IPAT) model, Dietz and Rosa (1994) proposed the stochastic impacts by regression on population, affluence, and technology (STIRPAT) model that allows a hypothesis test on different weights of the impacting factors of environmental externalities, that is, population, affluence, and technology. Based on the basic equation of a STIRPAT model, we developed the following equation

$$\begin{aligned} \ln C_{it} = & \alpha_0 + \beta_1 \ln GVC_{it} + \beta_2 \ln Laborit y_{it} + \beta_3 \ln Valu_{it} \\ & + \beta_4 \ln Hsemp_{it} + \epsilon_{it}, \end{aligned} \quad (2)$$

where i denotes the country, t denotes the year, $\ln C_{it}$ measures the carbon intensity, which represents the environmental impacts of the EOE industry, $\beta_2 \ln Laborit y_{it}$ and $\beta_3 \ln Valu_{it}$ are the number of employers in the industry and labor value-added, respectively, representing the Population and Affluence factors. $\ln GVC_{it}$ represents a series of GVC characteristics (Figure 2) of the EOE sector, proximity to technology advancement. The higher the positions are in GVCs, the more advanced technologies are used. Finally, we have introduced another factor, labor salary- $\beta_4 \ln Hsemp_{it}$, to indicate the sophistication of labor skills. Figure 2 illustrates the methodological framework for analyzing GVC participation's impacts on carbon emissions. Forward participation in GVC is expressed as GVC_pat_f , which includes participation in simple GVC, that is, $GVC_pat_f_s$, and participation in complex GVC, that is, $GVC_pat_f_c$. Similarly, backward participation, GVC_pat_b can be categorized by participation in simple GVC, $GVC_pat_b_s$, and participation in complex GVC, $GVC_pat_b_c$. The symbols are summarized in the upcoming Table 1.

2.4 Data sources

We selected the 10-year period from 2005 to 2015 due to data availability in the OECD input-output table database and examined all 65 countries that are covered by the database (OECD 2018). Sector carbon emission data are obtained also from the OECD database (OECD 2018). According to the Chinese National Economy Sector Classification (GB/T 4754-2017), the "Communication, Computer and other Electronic Equipment" sector corresponds to the EOE sector

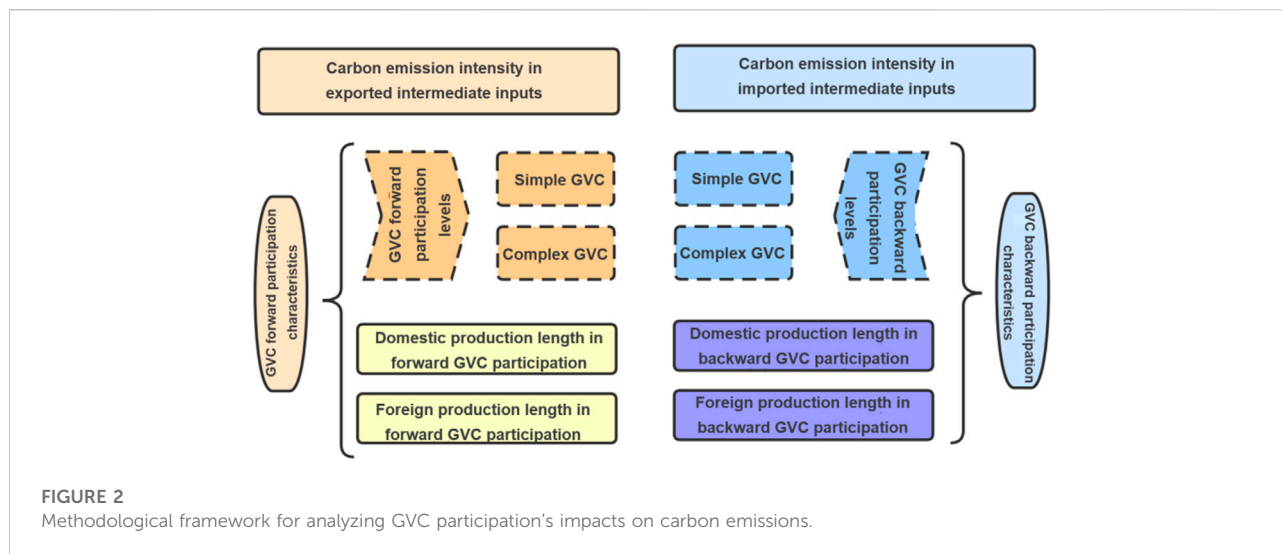


FIGURE 2
Methodological framework for analyzing GVC participation's impacts on carbon emissions.

TABLE 1 Symbol representation.

Symbol	Representation
C	Carbon intensity
Labority	Number of employers
Value	Labor value-added
Hsemp	Labor salary
GVC_pat_f_s	Forward participation in simple GVC
GVC_pat_f_c	Forward participation in complex GVC
GVC_pat_b_s	Backward participation in complex GVC
GVC_pat_b_c	Backward participation in complex GVC

in the OECD IO tables. Prices are also adjusted to compare prices accordingly.

3 Results

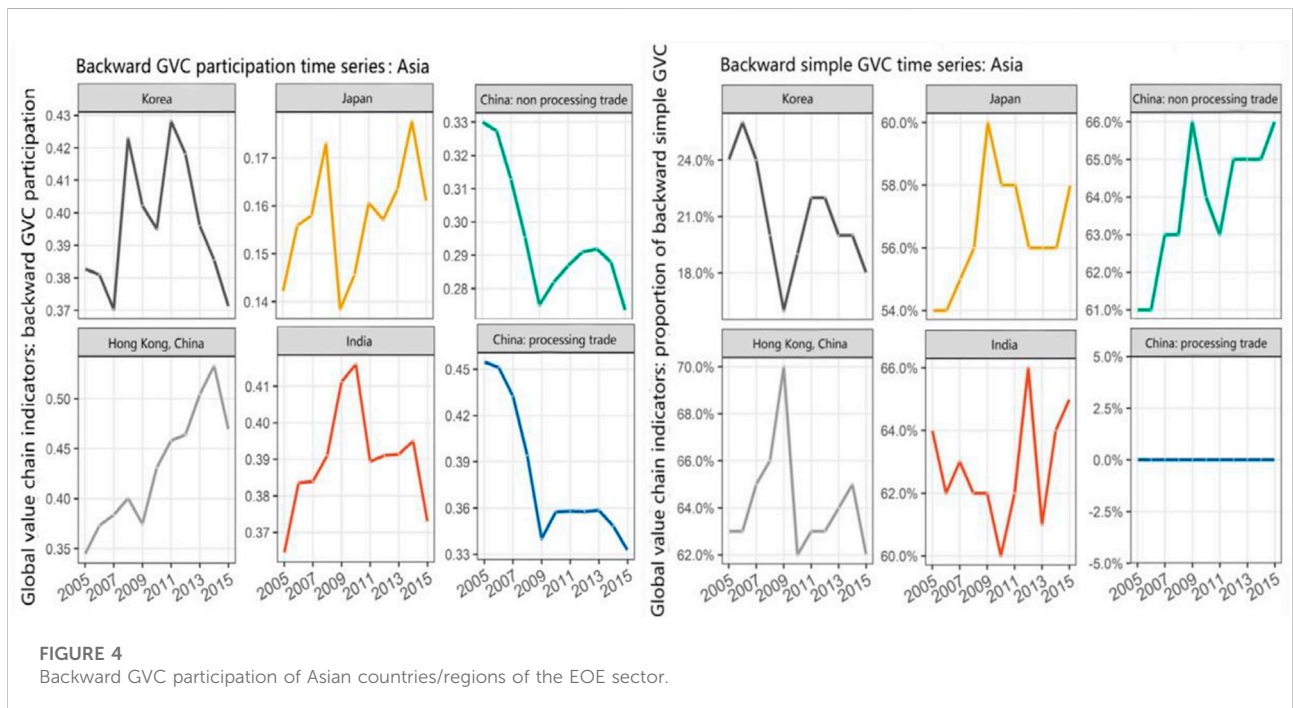
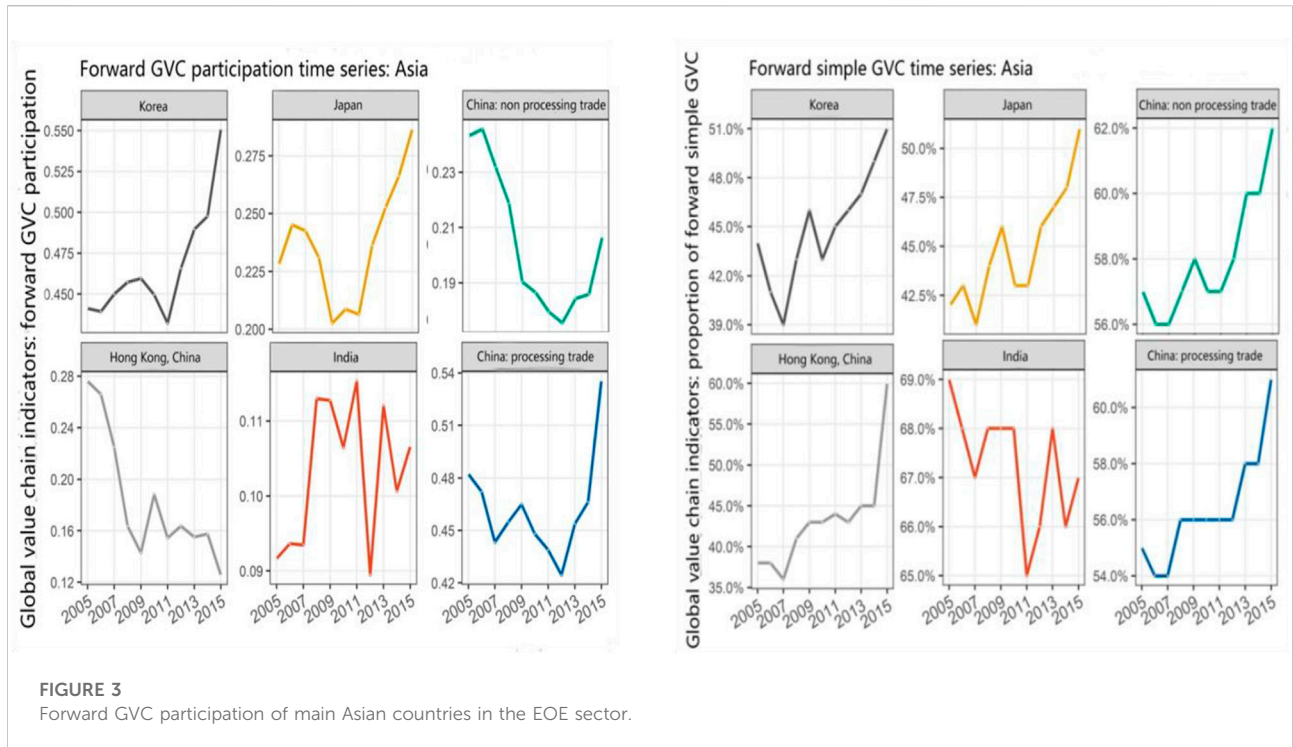
3.1 Forward global value chain participation in the electro-optical equipment manufacturing industry

Same as OECD data categorization, we have analyzed regional characteristics of several regions, including the Asian region (AR), transition countries (TCs), European Union (EU), NAFTA, Latin-American countries (LAC), ASEAN, and other countries. AR includes South Korea, Japan, India, China, Hong Kong (China), and Chinese Taipei. Regarding the EOE industry, except India and Hong Kong having relatively low GVC participation, indicated by value-added from participating in GVC, from 2005 to 2015, the other countries have had relatively high and

stable participation. In particular, China has enjoyed the highest growth rate with Japan demonstrating a slightly declining trend. Transition Countries, including Poland, Russia, Croatia, and Turkey, had much lower participation levels, which are comparable to or even lower than that of India and Hong Kong. LAC countries have similar levels of participation as TC countries. On the contrary, EU countries had much higher participation levels, ranging from one to ten times that of TC countries. Except for Germany and the United Kingdom which have demonstrated fluctuating but overall growing trends, other countries have all witnessed declining value addition gains from participating in EOE GVCs. It should be noticed that ASEAN countries, including the Philippines, Malaysia, Singapore, Vietnam, Cambodia, Thailand, and Indonesia, have had high participation levels in EOE GVCs, with fast increasing trends, particularly the Philippines.

According to our analysis, Asian countries and regions have the highest participation rate in the GVC of the EOE industry. Chinese Taipei, South Korea, Mexico, China, and Singapore are the top five countries/regions with the highest value additions in the sector. LAC countries have the lowest while also decreasing forward GVC participation. South Korea, Japan, Chinese Taipei, and the processing sectors of China have experienced increasing forward participation, while the non-processing trade of China and Hong Kong has experienced significant decreasing trends.

However, it should be noted that the proportion of Asian/ASEAN countries' forward participation in complex GVC demonstrates decreasing trend but an increasing trend for simple GVC, indicating that the EOE manufacturing industry in Asian countries is increasingly exporting to the GVC whose exported goods are only traded across national boundaries once. It can be seen from Figure 3, that except for India, forward



participation in simple GVC of main Asian economies has all demonstrated significant upward trends. Most exports from Asian countries are provided for final customers, while only

small proportions are as intermediate products. Such results demonstrate that Asian countries are important global suppliers, while their position in GVC is gradually moving

from simple and low value-added assembly processes toward closer to the final consumers, such as high value-added after-sale services.

In terms of production length, forward participation length is longer in Asian countries, i.e., China, South Korea, Chinese Taipei, and India, while shorter in EU countries, indicating that Asian countries are still located more upstream than EU countries. Furthermore, forward participation length has demonstrated increasing trends in most countries, indicating the GVC of the EOE industry is getting increasingly complex.

3.2 Backward global value chain participation in the electro-optical equipment manufacturing industry

In terms of their backward participation in the GVC, final EOE products in Asia also have the highest embodied foreign value-additions whereas the proportions are the lowest in TC countries. Specifically, EOE products in China, South Korea, Chinese Taipei, Japan, and Mexico have the highest value-additions from foreign countries. In terms of the proportion, foreign value-addition makes up the highest proportions in the value of final EOE products in ASEAN countries. As shown in [Figure 4](#), backward participation proportions of South Korea, Japan, and Chinese Taipei have all declined significantly after 2013, indicating their upward position changes along the GVC. In terms of export value-added, embodied foreign value-added also make up higher proportions in ASEAN countries while lower proportions in LAC countries. In terms of specific countries, the United States and Japan have relatively low proportions of embodied foreign value additions in their total value additions of exports, meaning most of the value additions created by their exports are left within their borders, while on the contrary, most of the VAs created by exports of Vietnam, Malaysia, and Mexico are generated abroad.

Comparing participation in simple and complex GVC, the US has the highest proportion of backward participation in simple GVC, indicating that value-addition embodied in the imports of the US mostly comes directly from the exporting country instead of a third country or region. In contrast to forward participation, ASEAN countries have the lowest proportion of backward participation in simple GVC, indicating that value-additions embodied in ASEAN countries' imports are mostly sourced from another third-party country or region instead of from the exporting country directly. Meanwhile, Asian countries also have the highest backward participation length, mainly China and India, while EU and NAFTA countries have relatively shorter backward participation lengths.

In general, Asian countries, mostly India and ASEAN countries, have longer backward participation lengths than forward participation lengths, with different changing trends

and rates, meaning that Asian countries are engaged at relative downstream positions of the GVC for EOE. Take India for example, its forward participation length is decreasing, while backward participation length has been increasing, indicating its "locked-in" position at the lower end of GVCs moving gradually toward the final consumers. On the contrary, forward participation lengths of China, Japan, and Chinese Taipei have all demonstrated a faster increasing rate than their respective backward participation lengths, indicating their potential to move towards upstream positions along the GVC.

3.3 Global value chain participation's impacts on carbon emissions

All variables passed the stationary tests, as shown in [Supplementary Table S1](#), indicating that all variables are stationary. The impacts of various GVC characters, including forward participation, forward production length, backward participation, and backward production length on carbon emissions are examined and presented. It is found by this study that an increase in forward participation can reduce the carbon emission intensity of the EOE manufacturing industry after the level of participation reaches a certain threshold. In other words, forward participation in GVC may negatively affect carbon reduction at the beginning but will contribute to carbon reduction after the participation level reaches a certain turning point, showing an invert-U shape, which is consistent with findings from [Wang et al. \(2019\)](#) at the aggregated economy-level. Participating in GVC often initially promotes emission-intensive production activities in a country and therefore contributes to emission increases. However, with the participation growing at a later stage, technological advancement and industrial structural change contribute to reducing a country or a sector's emission intensities.

Specifically, participating in GVC is able to reduce carbon emission intensities for countries in Asia, North America, and Transitioning countries, primarily in East Europe. On the contrary, participating in GVC increases carbon emission intensity for the EOE manufacturing industry for countries in Latin America and ASEAN. However, as shown in [Table 2](#), purely increasing forward GVC participation does not reduce carbon emissions. An increase in forward participation in complex GVC contributes to carbon emission reductions, likely due to the more specialized workforce.

In addition, increasing job skills, indicated by their salary levels, also corresponds to decreasing carbon intensities, whereas increasing the number of jobs, that is, labor-intensive, is correlated with increases in carbon intensities. Labor-intensive processes are often emission-intensive but low in value addition at the same time, involving manufacturing and so forth. On the contrary, high labor

TABLE 2 Regression results of forward participation in GVC (top), simple GVC (middle), and complex GVC (lower) and the carbon intensity of exports of intermediate products.

	Coefficient	Residual	T
Variables	Inexgr C	Inexgr C	Inexgr C
Inlabority	1.22**	0.53	2.32
InVa	-121.14***	16.67	-7.27
GVC_pat_f	-182.65*	131.24	-1.59
InHsemp	-6.54***	2.48	-2.64
Constant	1770.96***	198.29	8.93
R-squared	0.4994		
*** <i>p</i> < 0.01, ** <i>p</i> < 0.05, * <i>p</i> < 0.1			
	Coefficient	Residual	T
Variables	Inexgr C	Inexgr C	Inexgr C
Inlabority	0.004***	0.001	3.05
InVa	-0.32***	0.04	-7.65
GVC_pat_f_s	-1.12**	0.54	-2.08
InHsemp	-0.02***	0.01	-23.05
Constant	9.51***	0.50	18.93
R-squared	0.5583		
*** <i>p</i> < 0.01, ** <i>p</i> < 0.05, and * <i>p</i> < 0.1			
	Coefficient	Residual	T
Variables	Inexgr C	Inexgr C	Inexgr C
Inlabority	0.90*	0.51	1.77
InVa	-119.68***	16.78	-7.13
GVC_pat_f_c	49.41	239.23	0.21
InHsemp	-7.21***	2.48	-2.91
Constant	1726.41***	199.79	8.64
R-squared	0.4633		
*** <i>p</i> < 0.01, ** <i>p</i> < 0.05, and * <i>p</i> < 0.1			

Labority indicates the domestic share of employment, ranging from 0.53 to 168.63%; VA denotes the value-added (current price) per employer, ranging from US\$4264.8 to US\$502,809. GVC_pat_f represents the forward participation in GVC, ranging from 0.005 to 0.7; GVC_pat_f_s and GVC_pat_f_c denote, respectively, forward participation in simple GVC and complex GVC; Hsemp represents the proportion that domestic salary makes in the exports of intermediate products, ranging from 2.67 to 37.23%.

skill requirements are often correlated with product design, high technology, services, etc. which are often low in emissions and high in value addition. Overall, production process upgrades, that is, the transition from labor-intensive to skill-intensive, are correlated with a reduction in carbon intensities.

Similarly, looking at the backward participation reveals that for countries that are currently located at the lower segments of the GVC, increasing backward participation in simple GVC leads to increased embodied carbon imports (Table 3).

Moving up in terms of backward participation in GVC contributes to reducing carbon intensity. Regionally, backward production length for countries in Asia,

TABLE 3 Regression results of the backward production length in simple GVC (upper) and complex GVC and the imported carbon intensity.

	Coefficient	Residual	T
Variables	Inexgr C	Inexgr C	Inexgr C
Inlabority	0.001*	0.001	1.62
InVa	-0.14***	0.03	-4.15
Plyi_GVC_s	0.40***	0.11	3.53
InHsemp	-0.01**	0.00	-2.02
Constant	7.24***	0.43	16.88
R-squared	0.0494		
*** <i>p</i> < 0.01, ** <i>p</i> < 0.05, and * <i>p</i> < 0.1			
	Coefficient	Residual	T
Variables	Inexgr C	Inexgr C	Inexgr C
Plyd_GVC_c	0.28**	0.12	2.39
InVa	-0.14***	0.034	-4.19
Inlabority	0.0015*	0.0009	1.79
InHsemp	-0.009***	0.0048	-1.76
Constant	7.39***	0.43	16.99
R-squared	0.0288		
*** <i>p</i> < 0.01, ** <i>p</i> < 0.05, and * <i>p</i> < 0.1			

especially ASEAN, is negatively correlated with its imported carbon intensities.

4 Conclusion and discussion

4.1 Conclusion

This study finds that Asian, especially ASEAN, countries have the highest forward participation rate in the EOE industry while Latin American countries have a relatively low participation rate. In terms of production length, forward production length is relatively long for Asian countries while short for European countries, indicating that Asian countries are located at relatively lower segments of the GVC. Furthermore, the forward production length of Asian countries in the GVC of EOE demonstrates an increasing trend. Similarly, Asian countries also have the highest backward participation in the GVC of EOE. The highest proportions of value addition of final EOE products in ASEAN countries are actually incurred elsewhere, whereas most value additions of final EOE products in Latin American countries are generated within their own country. Revealingly, Asian countries normally have longer backward production length than forward production length, reflecting their relatively low position at the GVC.

Overall, increasing forward participation rate contributes to reducing the carbon intensity embodied in the exports while the impact changes from reducing carbon emissions to increasing

carbon emissions with the participation rate decreases, indicating certain thresholds for realizing the carbon mitigation impacts. From the perspective of backward participation, increasing importing from simple GVC reduces the carbon reduction effects. Furthermore, regression analysis shows that the increase in proportions of high-skilled employees, indicating technology improvement, also has positive effects on reducing the total carbon emission intensity of intermediate product imports and exports.

4.2 Discussion

4.2.1 Reducing emissions by participating in the global value chain

Modern productions are often broken into more than one country, and therefore, all countries along the value chain have shared value-added benefits. Participating in the global value chain first may incur two effects on a country/sector's environmental impacts by promoting production efficiency through specializing comparative advantages while also increasing production activities. At a later stage, participating in GVC introduces technological advancement with economic development. Consistent with other studies at national scales (Liu et al., 2020), our analysis of the EOE sector confirms that GVC participation and carbon emissions demonstrate an inverse-U shape with carbon emissions increasing first but decreasing after certain points. Different countries at different places of the curve may anticipate different impacts brought by furthering participation in GVC. Countries in North America and Europe may expect carbon emission reduction effects, while Latin American and ASEAN countries may experience carbon emission increase first; therefore, we need to focus on upgrading their GVC positions and nurturing industries that are skill and technology-intensive.

4.2.2 Upgrading global value chain positions to reduce carbon emissions

A regional study on the Belt and Road countries has found that GVCs' position upgrading could reduce carbon emissions (Shi et al., 2022), which is further confirmed by in-depth sector-specific analyses conducted by this study. It is not difficult to comprehend such results on the national scale, given that low GVC positions are often resource, and therefore emission, intensive while having low-value additions. Our results have shown that Asian countries would most benefit from such a transition by increasing their forward participation in complex GVCs. From 2000 to 2018, Asia's share in the world's total domestic value-added *via* forwarding linkages has increased from 23.0 to 30.2 percentage by a margin of almost one-third, while China has overtaken Japan as the largest generator of Asia's domestic value-added *via* forward linkages making up about 44.2 percent of the region's total (Xing et al., 2022). Therefore

there is considerable potential for China to upgrade its GVC position in order to reduce its carbon emissions without compromising its economic conditions. Last but not least, the COVID-19 pandemic and the associated travel constraints have reshaped the global trade patterns and the global value chain. However, its impacts are yet to be studied.

4.2.3 Policy implications

According to our results, Asian countries are of prominent importance in the GVCs, however, often located at the bottom of the "Smiling Curve". Although Asian countries not only have longer backward production length, their backward production length is demonstrating an increasing trend, which indicates a possibility of low-locked effects. Therefore, it is advisable for Asian countries, especially those in ASEAN, not only to participate in GVC but also to improve their GVC position by cultivating high-value-added processes, including smart manufacturing, financing, and final consumption. Second, enterprises should be encouraged to promote research and development, marketing, design, and other high-value-added but low-emission processes. Technological improvement has particular positive impacts on both reducing carbon emissions and increasing value-additions. In addition, improving working efficiency, by measures such as standardization and improving labor skills, can also contribute to reducing carbon emissions. Last but not least, in order to facilitate global carbon emission reduction responsibility sharing, countries specializing in material manufacturing, operation, and other resource and emission-intensive processes should internalize the environmental costs into production costs.

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found at: http://stats.oecd.org/Index.aspx?DataSetCode=IOTS_2021.

Author contributions

XM: methodology, resources, validation, and writing—review and editing. XL: writing—draft, investigation, and formal analysis. XP: data curation, calculation, visualization. XL: conceptualization, validation, supervision, and writing—review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.943801/full#supplementary-material>

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