Innovation ecosystem in China and Latin America: Exploring the influence of global value chain participation on carbon neutrality

Ning Chengjia
School of Management, Universiti Sains Malaysia, Malaysia
Email: ningchengjia@student.com.my

Noorliza Karia *
School of Management, Universiti Sains Malaysia, Malaysia
Email: noorliza@usm.my

Lu Boling
School of Environment and Resource, Southwest University of Science and Technology, China
Email: 449586278@qq.com

** Corresponding Author*

Abstract
Purpose: This paper attempts to study the influence of GVC participation on low-carbon economic transformation in China and Latin American from the perspective of innovation ecosystems. Through a new LCIE evaluation system, to accurately estimate the role of GVC participation in the low-carbon economic transformation of developing countries such as China and Latin America. Furthermore, put the LCIE, GVC, and CEI in a single research framework, evaluating the effect of the LCIE on the process of low-carbon transformation in China and Latin America, and enriching academic results in the field of carbon emission reduction.
Design/methodology/approach: Based on literature review, this paper develops a LCIE evaluation index system, the coefficient of variation method is used to evaluate the capacity of the LCIE in China and Latin America. Furthermore, to explore the relationship between GVC participation and CEI, and the moderating effect of LCIE between GVC participation and CEI, finally, to explore the direct impact of LCIE on CEI by regression analysis, what's more, this paper conducts a robustness analysis.
Findings: this paper identify: 1) The LCIE in China and Latin America is increasing. 2) GVC participation has a "U-shaped" effect on CEI. With the improvement of GVC participation, especially the improvement of forward GVC participation, it has a positive effect on the improvement of the host country's industrial system. However, when GVC participation reaches a certain level, especially when the backward GVC participation is too high, it has a negative effect on reducing CEI. 3) The LCIE plays a moderating role in the relationship between GVC participation and CEI. The development and application of low-carbon technology are important measures to reduce CEI. LCIE can help host countries further reduce

CEI after GVC participation reaches a turning point. 4) From the perspective of the influence mechanism of the LCIE, Innovation and Industry have a significant impact, Intermediary, Infrastructure, and Environment is not significant, but the direction of their influence on CEI is consistent with expectations.
Research limitations/implications: 1) In the evaluation system of LCIE, there is no unified method. Therefore, this paper draws on other scholars' methods to calculate the index of LCIE, which possibility of missing indicators. 2) In the mechanism testing, Intermediary, Infrastructure, and Environment factors are not significant, which need to further analysis by more data samples. 3) In estimating the moderating role of the LCIE, the moderating model uses cross-term, which cannot specifically quantify the moderating effect.
Practical implications: 1) To advance the research and application of low-carbon technologies while enhancing the country's LCIE construction. 2) To actively participate in GVC, especially to improve forward GVC participation, which can achieve industrial energy structure upgrading, increasing the added value of domestic products. 3) To improve the government guidance, research investment, industry structure, infrastructure construction, and ecological environment protection.
Originality/value: 1) Novelty a new LCIE evaluation system, providing empirical reference for others similar research. 2) Novelty a new research framework that put the LCIE, GVC, and carbon emission intensity in a single research framework, evaluating the effect of the LCIE on the process of low-carbon transformation in China and Latin America, and enriching academic results in the field of carbon emission reduction.

Key words: LCIE, global value chain, carbon neutrality, carbon emission intensity

Introduction

Aiming for carbon neutrality by 2050, which the United Nations Climate Change Conference of 2021 made a proposal, countries created strategies plans for carbon neutrality (Perwez et al., 2023). Since 2021, China has successively signed the "Belt and Road" cooperation agreements with major Latin American countries, which promoted bilateral cooperation (Yu et al., 2023). However, through "Immiserizing growth" such as environmental damage, raw materials exporting, and cheap labor, it has caused problems such as environmental pollution, resource shortages, and insufficient human capital, furthermore, hindering economic development and the goals of global climate(Rashid Khan et al., 2019).

In 2021, global total carbon dioxide emissions reached 37.12 billion tons, with China's emissions reaching 11.47 billion tons (Chen et al., 2023). High carbon dioxide emissions have led to the increasingly severe global climate crisis. The emissions of Latin American countries only 1.07 billion tons, with promote low-carbon technologies (Belloc & Molina, 2023). The low-carbon transformation of the economy has become a certain choice for sustainable economic development in various countries in the future (Xin et al., 2022).

However, due to the long and complex chain of low-carbon technology innovation and industrial, making it difficult for single country or region, especially developing countries and emerging economies. To assist all of low-carbon technological innovation, creating a collaborative creativity force at the regional level through cooperation in low-carbon technology innovation is becoming a more feasible approach (Yang et al., 2021).

The innovation ecosystem concept has removed the technological development bottleneck that was previously caused by an increase in input factors traditionally. A LCIE that includes both low-carbon innovation and the ecological environment, promoting the sustainability of innovation and environmental friendliness. However, a blocked LCIE will lose its vitality. Only by expanding its boundaries continuously and achieving cooperation of regional LCIE, which through continuous communication between technology and industry, can enhance both the natural environment and the effectiveness of technological innovation (Stokke et al., 2022).
Participation in the GVC is an important way for obtaining technology spillovers (Yu et al., 2023). China and Latin America actively participate in the GVC by their respective comparative advantages, but both are downstream of the GVC participation (Shi et al., 2022). When it comes to low-carbon technologies, in the face of the dual dilemma of developed countries' technological monopoly and their own weak technological R&D foundation (Zhou, 2019). Does participate in the GVC and cooperate in LCIE can help China and Latin America achieve low-carbon transformation and leapfrog development? This requires China and Latin America to provide more empirical experience in LCIE cooperation.
In order to address the following three concerns, this paper focus on how GVC participation affects the low-carbon economic transformation of China and Latin America from the standpoint of innovation ecosystems:

1) How should the LCIE levels in Latin America and China be assessed?
2) How does GVC participation directly impact the low-carbon economies in China and Latin America?
3) What's role the LCIE played in the transformation of China and Latin America's low-carbon economy?

To answer these three questions, the main innovations and contributions of this paper are:1) Novelty a new LCIE evaluation system, providing empirical reference for others similar research. 2) To precisely calculate the contribution of GVC participation to developing nations like China and Latin America in the transition to a low-carbon economy. 3) Novelty a new research framework that put the LCIE, GVC, and carbon emission intensity in a unique research framework, evaluating the effect of the LCIE on the process of low-carbon transformation in China and Latin America, and enriching academic results in the field of carbon emission reduction.
The research study's remaining sections are arranged as follows: Section 2: Drawing from the literature review, develops the theoretical framework of this paper. Section 3 develops the econometric model and describes the variables and samples. Section 4, corresponding the three research questions to analyze the findings and discussions. Section 5, conclusions and implications.

Literature Review and Hypothesis Development

An Overview of Innovation Ecosystem

Innovation systems serve as the foundation for the theory of innovation ecosystems, which emphasize the interrelationships between innovation institutions and innovation networks

(Konietzko et al., 2020). The innovation ecosystem takes more emphasis on creating efficient innovation systems between innovation institutions and other participating institution, which with characteristics of symbiosis, spontaneity, openness, and competitiveness (Granstrand & Holgersson, 2020). It mainly consists of three parts: the basic institutions, the guiding institutions, and the supporting institutions. The basic institutions include core innovative enterprises, universities, and research institutes; The guiding institutions only refer to government policy guidance; The supporting institutions include production enterprises, financial institutions, intermediaries, social and cultural environments, etc. (Tamayo-Orbegozo et al., 2017).

With the application of innovation ecosystem theory, scholars have proposed various evaluation methods for innovation ecosystems at different aspects, see Table 1:

Table 1 Empirical Statistics of the Innovation Ecosystem Evaluation System

Reference	Evaluation System	Innovation	Industry	Government	Inter-mediary	Environment	Infrastructure	Calculate Method
Paasi et al. (2023)	Ecosystem actors，Ecosystem properties，Environment and outcomes	√	√			√		system dynamics method
Cao et al. (2023)	innovation communities, innovation resources, innovation environment, and innovation capabilities	√	√	√	√		√	niche-fitness model
Cobben et al. (2023)	Ecosystem success，Ecosystem health，Structural antecedents，Relational antecedents	√	√	√	√			Delphi
Huang et al. (2023)	Investment，information and communication technology，Government efficiency，	√	√	√			√	Necessary condition analysis and qualitative comparative analysis

Rong et al. (2020)	Tertiary education expenditure，R&D construct, cooperation, configuration and capability	√	√	√			√	Case study

From Table 1, it can be seen that in the evaluation of the innovation ecosystem, mainly conducted from five aspects: innovation chains, industrial chains, financial services, government support, and intermediary support. However, there is little literature to research when considering the ecological environment (Gomes et al., 2023). Shi et al. (2023) developed the evolutionary game model to estimate that various institutions in the LCIE, and confirmed that those institutions promote low-carbon technology innovation and application through dynamic games. Stokke et al. (2022) analyzed the challenges faced by enterprises from the perspective of low-carbon development, and fund that enterprises are the main force in reducing carbon emissions and are also a core component of the LCIE. Brink (2022) claimed that ecological value is the main value embodiment of innovative ecosystems.

However, current research mainly focuses on exploring how the LCIE operates internally (Shi et al., 2023; Xie & Wang, 2020), structure (Ganco et al., 2020; Shi et al., 2023), dynamic evolution (Rong et al., 2020), and there are few literature on evaluating the capacity of LCIE. This paper draws on the method of Cao et al. (2023), and constructs a LCIE evaluation system, which introduces ecological environmental indicators, furthermore, comparative analysis of the LCIE capabilities between China and Latin America.

Global Value Chain and Carbon Emissions

International collaboration and the division of labor have emerged as the dominant trends in industrial development. By leveraging the comparative advantages of different regions, the goal of reducing production costs and globalizing sales is achieved, ultimately forming a GVC. high value-added production links that are mostly carried out by upstream countries of GVC, for example: product research and development, standard formulation, product dealing, and after-sales service, whereas the downstream countries of GVC mostly handles low-value manufacturing links, for example: the supply of raw materials, processing, and assembly of intermediate products (Yu et al., 2023). Scholars have conducted extensive empirical research on the relationship between GVC participation and carbon emissions but received inconsistent conclusions.

Fei et al. (2020) through research China's GVC participation, pointed out that China has achieved rapid economic development through active participation in the GVC, but has also led to higher carbon emissions. Shi et al. (2022) through comparative analysis, claimed that developed countries are located upstream of the GVC, mainly responsible for research and development, sales, and other aspects. Their high GVC participation generates less carbon emissions. However, in developing countries' GVC participating, the opposite phenomenon occurs: with the GVC participation degree increases, the country’s carbon emissions will increase too. According to Wang et al. (2019), there is an "inverted U-shaped" link between GVC participation and carbon emissions, meaning that there is a pattern of initially growing and then lowering carbon emissions in tandem with GVC participation.

Another group of scholars claimed that GVC participating reduced carbon emissions. Espinosa-Gracia et al. (2023). As demonstrated by Espinosa-Gracia et al. (2023), the association between GVC and carbon emissions in the short term might easily result in estimation bias. In the long term, there will be less carbon emissions the more GVC participation there is, especially the increase in investment in intermediate product production, which will effectively reduce carbon emissions. Ali and Gniniguè (2022) pointed out that GVC participating can improve regional industrial structure and infrastructure levels, which has a moderating effect on regional carbon emissions.

This is in line with the findings of studies by Liu and Zhao (2021) and Assamoi et al. (2020), who both verified a one-way causal relationship between GVC participation and carbon emissions.

Different evaluation perspectives lead to heterogeneity in the relationship between GVC participation and carbon emissions, hence, more research is required. In light of this, the first hypothesis put out in this paper is:

Hypothesis 1: There is a U-shaped relationship between GVC participation and carbon emission intensity.

Global Value Chain and Low Carbon Technology Innovation Ecosystem

One of the reasons explaining the variation in the global value chain's influence on carbon emissions is the advancement of research and technology. Scalera et al. (2018) claimed that the improvement of industrial innovation capabilities enhances the international competitiveness while achieving a GVC climbing. Furthermore, Ambos et al. (2021) analyzed the increase in GVC participation from the perspective of national innovation, confirmed that open collaborative innovation by countries can not only improve their own technological, but also contribute to the improve of GVC participation. The improvement of the host country's technological can improve production efficiency, thereby encouraging the modernization of the industrial structure, lowering the amount of energy consumption, and accomplishing the reduction of carbon emissions aim (Liu et al., 2020). According to the findings of Ho et al. (2018) and Qiaoling et al. (2022). Who both confirmed that the promoting role of technology learning and technology introduction in GVC participation, which technology spillover effects enhance the ecological dividend of the host country.

Some studies have focused on the foreign direct investment (FDI) during the process of GVC participation, claimed that capital is also an important factor in industrial carbon emissions reduction (Banerjee, 2022; Essandoh et al., 2020; Sinha et al., 2022). However, in the empirical analysis, scholars generally claimed that the reason why FDI can drive the increase in host country GVC participation is due to the technology spillover effect brought by FDI (Hoa et al., 2023). For developing countries, actively participating in GVC can reduce the cost of technology purchase, furthermore, relying on technology absorption capacity to gradually absorb advanced technologies and improve their technological level (Ma et al., 2023). In recent years, some scholars have found that FDI not only has technology spillover effects, but also has pollution transfer effects (Duan & Jiang, 2021), which negative to the local ecological environment and the quality of economic development (Demena & Afesorgbor, 2020).

In those studies, it can be seen that the improvement of GVC participation cannot be without technological innovation, whether through technological cooperation or FDI. When it comes to innovative low-carbon technology, new technologies need market testing, research institutions for technological research and development carries high risks (Bi et al., 2015), while relying on enterprises to carry out technological innovation in low-carbon also faces the dilemma of high costs (Foss & Saebi, 2018). The emergence of an innovation ecosystem has changed the old research and development model, which through the cycle of "guidance-innovation-application-re-innovation", various institutions within the system reduce research and development risk, accelerate research and development transformation (Granstrand & Holgersson, 2020), then achieve GVC growth.

However, there are few literatures that developed innovation ecosystems and GVCs within a single research framework. According to the theory of innovation ecosystem, this paper estimates the influence of LCIE on the relationship between GVC and CEI. Therefore, this paper proposes the second hypothesis:

Hypothesis 2: The LCIE has a moderating effect on the relationship between GVC participation and CEI.

Low carbon technology innovation ecosystem and carbon emission intensity

The primary definition of CEI is carbon emissions per GDP unit (Song et al., 2022). The lower the CEI, the better the economic development in low-carbon. Relying on the use of low-carbon technology in different fields for reducing CEI, furthermore, achieving low-carbon transformation will bring a competitive advantage in future competition (Liu & Zhao, 2021). However, at present, low-carbon technology is an emerging field of science, and immature development of low-carbon technology, low-carbon transformation for enterprises needs higher additional costs, which increase economic burden, and reduce their willingness in low-carbon transformation (Weko & Goldthau, 2022).

To achieve the goal of low-carbon economic transformation and lower the cost of low-carbon transformation, the government needs to strengthen guidance (Wang et al., 2022), promote the development of low-carbon technology research and innovation, continuously reduce the application cost of low-carbon technologies, and provide appropriate subsidies to enterprises with high low-carbon industries to reduce their production costs (Shi et al., 2023); On the other hand, government should strengthen environmental protection and use environmental indicators to constrain pollution behavior (Granstrand & Holgersson, 2020).

Research institutions, such as universities, study institutes, and enterprise owned research institutions, should actively carry out development of core low-carbon technologies and continue to develop low-carbon technologies with market application value. Enterprises adopt a technology introduction approach by introducing low-carbon technologies for production activities. By paying for technology introduction costs, it can lower the cost of low-carbon applications while also providing financial support for additional low-carbon technology research and development (Cui et al., 2022).

Finally, a low-carbon technology cycle development mechanism of "government guidance-technological innovation-enterprise application" will be formed. Based on this, taking consideration of the effects of this cycle on the natural environment, and a low-carbon technology innovation ecosystem will be formed to achieve the goal of reducing CEI (see Figure 1).

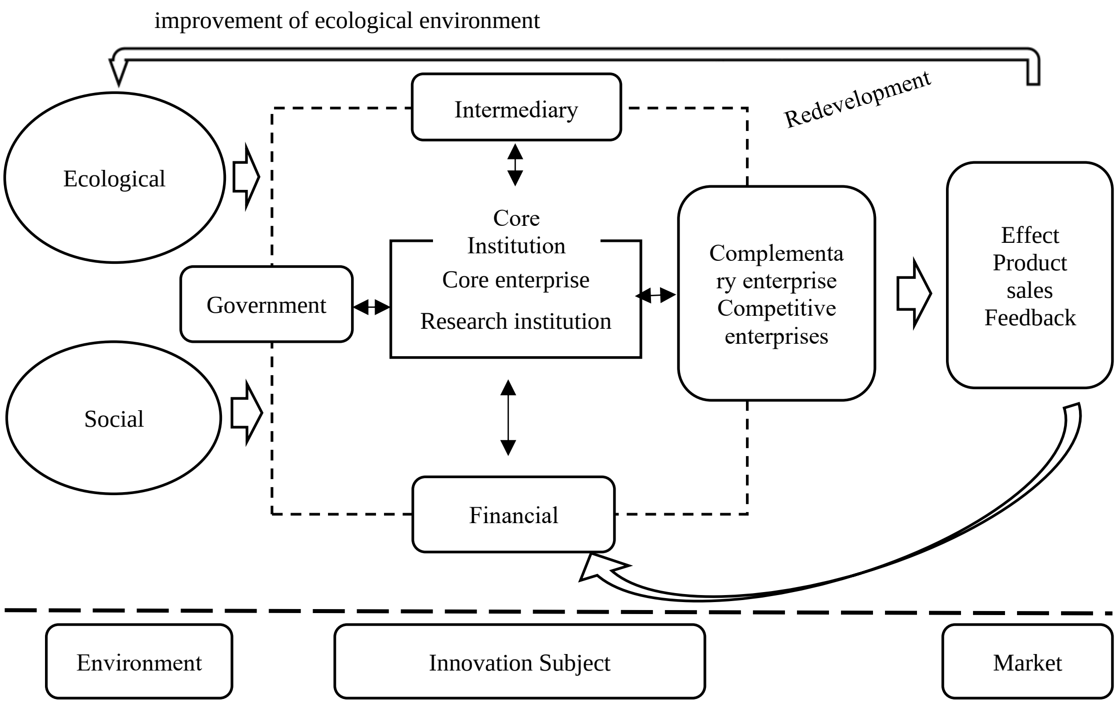

Figure 1 Low carbon technology innovation ecosystem

The LCIE develops environmental factors into the system, which can promote the improvement of the ecological environment in a virtuous cycle. Thus, the third hypothesis is investigated out:

Hypothesis 3: The LCIE has a negative effect on CEI.

Theoretical Framework

In conclusion, researchers have produced excellent findings in their analyses of the problems relating to the innovation ecosystem and the relationship between GVC participation and CEI. There are, as far as we are known, less studies on the relationship between LCIE, CEI, and GVC participation. What's more, the evolution of LCIE still needs further research.

Based on this, a novelty evolution method of LCIE is proposed, what's more, this paper put LCIE, GVC and CEI in a single framework, with a novelty view to explore those relationship in China and Latin America.

Corresponding the research questions and the gaps of studies, the theoretical framework, as illustrated in Figure 2, of this paper is proposed:

1) This paper draws the indicator selection principle of Cobben et al. (2023) and develops a LCIE evaluation index system based on the current status of low-carbon development in

China and Latin America from five perspectives: innovation, infrastructure, industry, intermediary, environment. The coefficient of variation method is used to evaluate the capacity of the LCIE in China and Latin America.

2) This paper examines the relationship between GVC participation and CEI using the research methodology of Assamoi et al. (2020), and claims that there is a U-shaped association between the two. (Wang et al., 2019).

3) To explore the moderating effect of LCIE between CEI and GVC participation, and explore the direct impact of LCIE on CEI, furthermore, this paper conducts a robustness analysis.

4) Based on the five components of the LCIE, the impact coefficients of each component are estimated separately. Through the heterogeneity impact analysis of the five components, this paper develops implications.

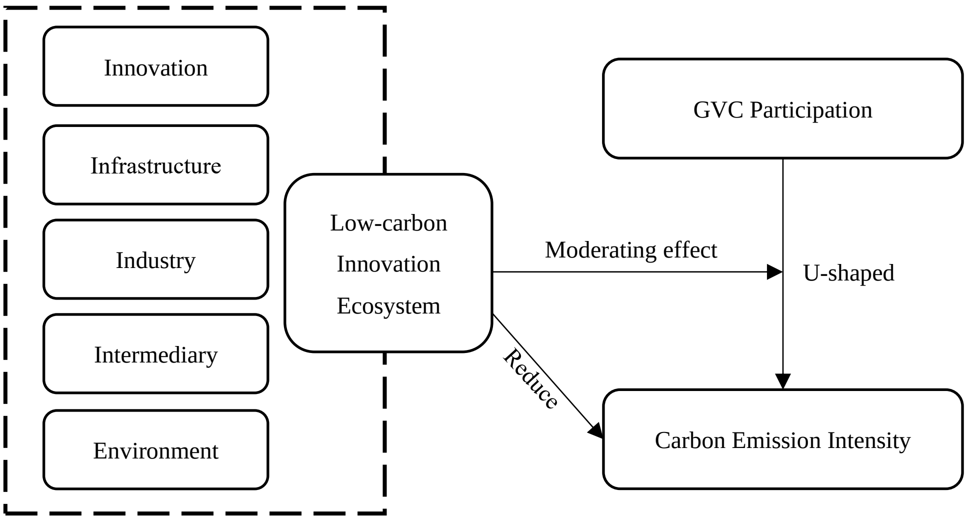

Figure 2 Theoretical framework

Methods

The first thing covered in this section is the calculation of LCIE. Second, developed the econometric model. Finally, the data sources and samples will be explained.

Evolution of LCIE

Scholars have developed more research on the innovation ecosystem. There is a general perception that an innovation ecosystem composed of an innovation chain, an industry chain, and a service chain that work together (Ganco et al., 2020). The innovation chain is responsible for technological innovation and upgrading, the industry chain is responsible for technological transformation and providing direction for technological improvement, and the service chain is responsible for providing policy and financial support, The three chains form a stable innovation ecosystem through symbiosis (Shi et al., 2023). Within the system, various chains usage their comparative advantages to complement each other, creating a technological innovation "spontaneity" and boosting the innovation ecosystem's sustainable competitiveness (Thomas et al., 2022).

An innovation ecosystem's worth lies in value co-creation, and openness and competitiveness are the characteristics of the innovation ecosystem. Each participant innovates systematically with other participants by leveraging their own heterogeneity and forming a network relationship, furthermore, achieving a transformation from guided innovation to independent innovation (Ganco et al., 2020).

This paper claims that the participants in the LCIE mainly consist of five parts: Innovation (Brink, 2022; Paasi et al., 2023), Infrastructure (Cobben et al., 2023; Granstrand & Holgersson, 2020), Industry (Cobben et al., 2023), Intermediary (Cobben et al., 2023), and Environment (Cobben et al., 2023), where Innovation includes two indicators: the total amount of low-carbon patents and researchers. Infrastructure includes two indicators: transportation facilities and Internet penetration rate. Industry includes two indicators: enterprise technology expenditure and technology export. Intermediate refers to government guidance, and Environment refers to air pollution index. The indicator explanation and justification are shown in Table 2:

Table 2 LCIE evaluation indicator system

Name	Indicator	Explanation	Justification
Innovation	The number of low-carbon patents	Number of utility and authorized low-carbon technology patents	The primary indicator of low-carbon development is low carbon technology patents. The more researchers, the more conducive to low-carbon technology innovation.
	The number of researchers	Number of researchers per million population	
Infrastructure	Transportation facilities	The sum of highway and railway mileage	Improving infrastructure can enhance the flow of innovative elements and improve innovation efficiency.
	Internet penetration rate	Internet users / total number of people	
Industry	Enterprise technology expenditure	Expenses incurred by enterprises for purchasing intellectual property rights	The export and import costs of technology reflect the importance that enterprises attach to technological innovation.
	Technology export	Income generated from technology exports	
Intermediary	Government guidance	research and development investment / GDP	Develop policies, encourage and guide innovation activities, and maintain the order of the innovation ecosystem
Environment	Air pollution index	Annual PM2.5 Pollution Index	Reducing the pollution index, on the one hand, provides a good ecological environment for innovative activities, while also being one of the primary goals of a low-carbon innovation ecosystem.

Note: Appendix A provides the statistical foundation for the quantity of low-carbon patents.

To avoid interference from subjective factors in determining the weight of each factor, this paper uses the coefficient of variation method (Han et al., 2023) to estimate the comprehensive score of the LCIE: through data standardization, the ratio of standard deviation to average of the indicator data is calculated to represent the weight of the indicator. See Equations (1), (2), and (3):

$$\mathrm{B}_i = \frac{\sigma_i}{\widehat{X_i}} \quad (1)$$

$$\mathrm{Q}_i = \frac{B_i}{\sum_{i=1}^{n} B_i} \quad (2)$$

$$\sum_{i=1}^{n} W_i = 1 \quad (3)$$

Where, B_i represents the coefficient of variation of i (i=1, 2..., n), σ_i represents the standard deviation of i, $\widehat{X_i}$ represents the average of i, Q_i represents the weight of i. The total weight is 1.

Development of Econometric model

Based on other scholars' method, this paper chooses regression method to analysis the relationship between the three factors.

Drawing on the method of Fei et al. (2020), the GVC participation of the sample countries is first calculated based on their export data, as shown in Equation (4):

$$\mathrm{GVC}_p = \frac{DVA}{E_s} + \frac{MVA+OVA}{E_s} \quad (4)$$

Where, GVC_p represents GVC participation, OVA stand for foreign value-added from other nations, MVA for foreign value added via direct import, and DVA for domestic value added, E_s represents total exports.

Following the theoretical framework, this paper developed the econometric model, as illustrate Equation (5), to investigate the relationship between GVC participation and CEI.

$$CEI_{it} = \alpha_0 + \alpha_1 GVC_{pit} + \delta_i + \mu_t + \varepsilon_{it} \quad (5)$$

Where, CEI_{it} represents the carbon emission intensity of country i in year t, GVC_{pit} represents the GVC participation index of country i in year t. δ_i and μ_t represents the fixed effects of country and time, ε_{it} represents random error term. α represents the coefficient of influence of each variable.

This paper confirms that GVC participation has a dual effect on CEI, namely a "U-shaped" effect. Therefore, according to the method of Assamoi et al. (2020), by introducing the concept of GVC_{pit}^2 to observe the impact curve of GVC participation on CEI (see Equation 6), if the coefficient of GVC_{pit}^2 and GVC_{pit} are contrary, It suggests a "U-shaped" link between CEI and GVC participation. Therefore, Additional research is required to determine the elements that influence the inflection point. If the coefficients are in the same direction, it indicates that there is no moderating variable between GVC participation and CEI.

$$CEI_{it} = \alpha_0 + \alpha_1 GVC_{pit} + \alpha_2 GVC_{pit}^2 + \delta_i + \mu_t + \varepsilon_{it}$$

(6)

The economic meaning of each code in Equation (6) is the same as that in Equation (5). To avoid estimation deviation, this paper introduces control variables, see Equation (7):

$$CEI_{it} = \alpha_0 + \alpha_1 GVC_{pit} + \alpha_2 GVC_{pit}^2 + \alpha_i C_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (7)$$

Where, C_{it} is the set of control variables. Based on the results of other scholars, this paper selects energy efficiency, industrial structure, openness, and per capita GDP as the control variables. The explanations are as follows:

Energy efficiency (ene) describes the amount of primary energy used per GDP unit. When energy efficiency increases, less energy is needed to grow the GDP unit by unit (Cao et al., 2023). Enhancing energy efficiency can help cut carbon emissions and lessen the impact of environmental restrictions on economic growth. Conversely, it will result in a rise in carbon emissions (Pan et al., 2019).

Industrial structure (is) refers to industrial (including construction) value added as a proportion of GDP. The secondary industry generates the highest carbon emissions in economic development (Cao et al., 2023), and The likelihood of a rise in carbon emissions increases with the percentage of secondary industry (Zhao et al., 2022).

Openness (ope) refers to proportion of total imports and exports to GDP. The level of economic openness is a good indicator of a nation's level of economic activity since it increases acceptance of the flow of low-carbon innovation elements. This is good for low-carbon technology innovation and exchange (Muhammad, 2019).

Per capita GDP (pgdp) refers to the ratio of total population to total GDP. Economic income is an important influencing factor for residents to pay attention to air quality (Li & Zhang, 2023). A lower per capita GDP means less disposable income, which may pay a greater focus on resource acquisition. There is a lower level of concern for environmental protection. When per capita GDP is higher, environmental awareness is relatively higher (Assamoi et al., 2020; Sarkodie & Strezov, 2019).

Furthermore, to demonstrate the influence of LCIE between GVC participation and CEI, this paper draws on the method of (Li & Zhang, 2023; Zhao et al., 2022) and introduces the LCIE index into the econometric model, as shown in Equations (8) and (9):

$$CEI_{it} = \beta_0 + \beta_1 GVC_{pit} + \alpha_2 GVC_{pit}^2 + \beta_2 eco_{it} + \beta_i C_{it} + \delta_i + \mu_t + \varepsilon_{it}$$

(8)

$$CEI_{it} = \beta_0 + \beta_1 GVC_{pit} + +GVC_{pit}^2 \beta_2 eco_{it} + \beta_3 GVC_{pit} * eco_{it} + \beta_i C_{it} + \delta_i + \mu_t + \varepsilon_{it}$$

(9)

Where, β is the influence coefficient of each variable, eco_{it} represents the LCIE index, and other indicators are the same as Equation (7), β_3 is $GVC_{pit} * eco_{it}'s$ moderating effect coefficient.

Data Source

This paper examines how the LCIE affects the relationship between CEI and GVC participation in China and Latin America. Given that the countries of Latin America have significantly differing levels of economic and technological development, this paper selects these sample countries, which per capita GDP range of 5000 to 20000 US dollars, population over 10 million, and land area over 500000 square kilometers (large countries) in 2020. Based on the availability of data, the countries of Argentina, Brazil, Chile, Colombia, Mexico, and Peru are included in the research samples of Latin America.

The time sample is from 2011 to 2021, with 2011 as the starting time because China became the world's largest carbon emitter during this year; 2021 is the end date because some countries have not yet released their economic performance data for 2022.

Where, the UIBC (University of International Business and Economic) GVC database is the source of the GVC participation index. According to Appendix A, the number of low-carbon patent patents in various countries is retrieved and calculated in the IncoPat database. All other variable data are from the World Bank database.

Results and Discussion

Corresponding the research questions，this section first measured the LCIE index of the sample countries. Secondly, to analyze the influence of GVC participation on CEI. Thirdly, to analyze the influence of LCIE in the relationship between GVC participation and CEI. Fourthly, based on empirical results, to develop the discussion.

LCIE evaluation index

This paper calculates the LCIE index of sample countries based on the constructed LCIE evaluation system, and the results are shown in Table 3.

Table 3 LCIE Index

Country	Innovation		Infrastructure		Industry		Intermediary	Environment	Total
	Low-carbon patent	Researcher	Transport	Internet	Technology expenditure	Technology exportation	Government	Air pollution	
Coefficient of Variation	2.6720	0.7828	1.5788	0.5849	1.6815	2.2151	1.0082	0.8006	11.3238
Weight	0.2360	0.0691	0.1394	0.0517	0.1485	0.1956	0.0890	0.0707	1.0000
Argentina	0.0000	0.0542	0.0068	0.0488	0.0038	0.0001	0.0151	0.0000	0.1287
Brazil	0.0001	0.0537	0.0425	0.0443	0.0159	0.0013	0.0435	0.0057	0.2070
Chile	0.0000	0.0244	0.0028	0.0517	0.0047	0.0002	0.0111	0.0147	0.1096
China	0.2131	0.0679	0.1394	0.0353	0.1485	0.1956	0.0890	0.0236	0.9124
Colombia	0.0000	0.0041	0.0012	0.0353	0.0036	0.0001	0.0102	0.0082	0.0628
Mexico	0.0000	0.0134	0.0109	0.0378	0.0138	0.0155	0.0077	0.0119	0.1110
Peru	0.0000	0.0072	0.0000	0.0335	0.0009	0.0000	0.0044	0.0161	0.0621

Note: Only the LCIE index of sample countries in 2021 is listed here, and other annual indices show in Appendix B

Based on the statistical analysis of the LCIE index of the sample countries from 2011-2021, except Peru, the rest of the countries show a trend of annual growth (see Figure 3), which is consistent with the low intensity of scientific research investment in Peru, what’s more, cause of rich in mineral resources, Peru has low willingness in low-carbon technology development.

The LCIE index of China, Brazil, and Chile has grown rapidly, which is closely related to the increasing technology investment and talent cultivation year by year.

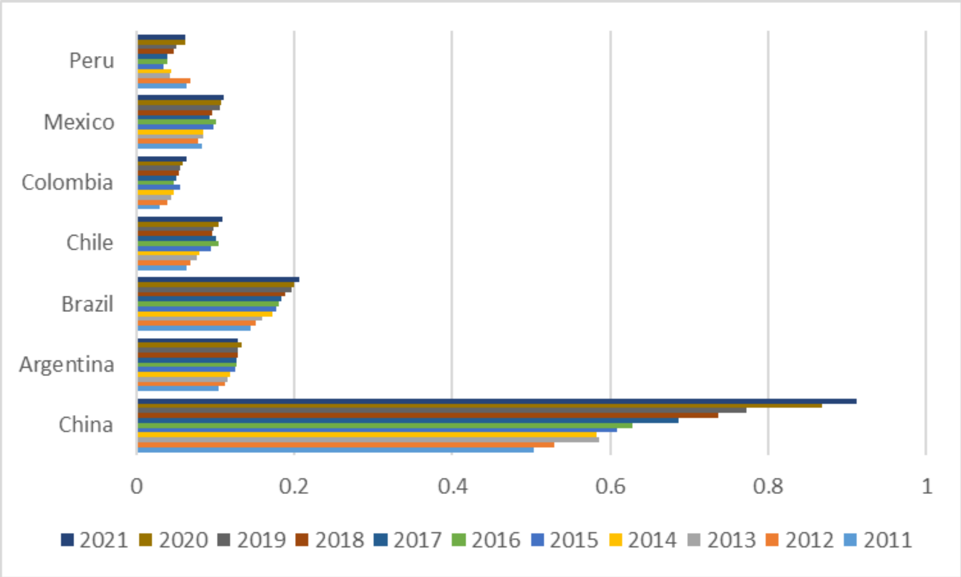

Figure 3 Statistics of LCIE Index in Sample Countries

Considering China's high carbon emissions and large population, the impact of the LCIE on lowering carbon emissions cannot be seen by merely comparing the LCIE index. This paper presents an in-depth analysis based on the GVC participation to further elucidate the influence path of the LCIE on the reduction of carbon emissions in the background of economic globalization.

Results of Model Test

This paper first makes descriptive statistics on each variable, as shown in Table 4. The average carbon emission intensity of the sample countries is 0.2178. Although China's carbon emission intensity has significantly decreased in 2011-2021, it is still the highest among the sample countries. The average GVC participation is 0.1912, indicating that the sample countries are all downstream of GVC. The average LCIE index is 0.1799, but the sample countries have significant differences in the LCIE index. From the standard deviation analysis of each variable, the data dispersion is relatively small.

Table 4 Descriptive statistics for average variables

Variables	Interpretation	Unit	Mean	SD	Min	Max
CEI	Total carbon emissions/GDP	t	0.2178	0.1469	0.1079	0.7129
GVC participation	The proportion of domestic and foreign added value of intermediate goods to total exports	-	0.1912	0.071	0.1141	0.4114
eco	LCIE index	-	0.1799	0.2131	0.029	0.9124
ene	Primary energy consumption per unit of GDP	%	3.7551	1.5105	2.15	8.75

is	Industry (including construction) value added/GDP	%	29.4605	6.7347	18.188	46.529
ope	Total import and export volume/GDP	%	0.3973	0.1649	0.1808	0.7991
pgdp	GDP/total population	$	3.9714	0.1359	3.7246	4.2107

The VIF validation shows that the correlation between each variable is less than 10, which means that there was no multicollinearity, then these variables can be used for data analysis (Tamura et al., 2018). Therefore, based on the econometric model, the correlation between GVC participation and CEI is displayed in Table 5. Model (1) illustrates the "U-shaped" relationship between GVC membership and carbon emission intensity, meanwhile, as control factors are added, models (2) - (5) demonstrate how the influence of GVC participation on CEI varies.

Table 5 The relationship between CEI and GVC participation

	(1)	(2)	(3)	(4)	(5)
GVC	-0.6527*** (-3.94)	-0.4099*** (-2.68)	-0.3925** (-2.60)	-0.3569** (-2.41)	-0.3598** (-2.42)
GVC^2	0.0083*** (4.18)	0.0050*** (2.67)	0.0045** (2.42)	0.0043** (2.35)	0.0043** (2.38)
ene		0.5979*** (4.78)	0.5711*** (4.59)	0.5375*** (4.39)	0.4990*** (3.68)
is			0.1205* (1.73)	0.1905** (2.51)	0.2316** (2.37)
ope				-0.2218** (-2.06)	-0.2835** (-2.00)
pgdp					-0.0522 (-0.67)
Constant	47.9364*** (15.85)	27.3170*** (5.40)	23.6437*** (4.37)	29.6449*** (4.91)	33.5768*** (3.98)
Fixed effect	YES	YES	YES	YES	YES
R-squared	0.20	0.41	0.43	0.46	0.47
F test	167.95	102.48	61.24	50.83	32.62

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

As shown in Table 5, models (1) - (5) show the changes in GVC and GVC2 coefficients after the addition of control variables. The coefficients of both remain contrary and pass the significance test. The difference is that models (1) - (2) show a strong correlation between the two on CEI, while models (3) - (5) show a significant decrease.

Where, the contrary effect of GVC and GVC2 indicates that GVC partitioning has a "U-shaped" curve effect, which first suppresses and then enhances CEI, this result also supports hypothesis 1.

Specifically, with the improvement of GVC participation, it means that the trade activity of participating countries in both China and Latin America has increased. By integrating into the global industrial and value chains, participating in global division of labor, eliminating outdated production capacity, implementing low-carbon industry, and continuously adjusting their own industrial structure, then achieve the goals of economic growth and carbon emissions reduction. However, with the continued increase of GVC participation, only relying on industrial adjustment cannot achieve the goal of further reducing CEI. Instead, as production capacity gradually increases, there will be an increase in CEI.

Considering the influence of control variables, it can be seen that energy efficiency and industrial structure have a positive effect on CEI. An increase in energy consumption per unit of GDP means an increase in primary energy use, which leads to more carbon emissions. In terms of industrial structure, the high proportion of added value in the secondary industry means that the industrial and construction industries have developed rapidly, and the secondary industry is the main carbon emitting industry. Consequently, there is a strong positive relationship between carbon emissions and industrial structure.

There is a notable negative link between the degree of openness and CEI, meaning that a higher degree of openness results in a lower CEI. The degree of openness not only represents the import and export of goods, but also includes the flow of production factors such as technology and talent, as well as the transfer and acceptance of the industrial chain. A higher degree of openness can attract more high-quality resources.

The per capita GDP rejected the significance test despite having a negative connection with CEI. The sample countries' per capita GDP varied significantly from one another, which explains the cause. The previous analysis claimed that a higher per capita GDP can improve residents' environmental awareness, thereby reducing CEI, while a lower per capita GDP has no effect or negative effect on CEI. Therefore, the per capita GDP of the sample countries has resulted in a non-significant correlation.

From the perspective of coefficient, GVC participation has a strong negative correlation with CEI. Although the square term has a significant positive correlation, the coefficient is only 0.0043. This also indicates that GVC participation has more advantages than disadvantages on the carbon emissions of host countries. Engaging in active GVC participation is a useful strategy to lower CEI. In order to examine the impact of GVC involvement on CEI in more detail, this paper considers the moderating effect of LCIE. Table 6 reports the influence of LCIE on CEI, Model (6) reports direct effects, Model (7) reports the relationship between LCIE, GVC participation and CEI, and Model (8) reports moderating effects of LCIE.

Table 6 Moderating effect by LCIE

	（6）	（7）	（8）
eco	-0.5265*** （-4.25）	-0.3109** （-2.44）	-0.5311*** （-3.17）
GVC		-0.3307** （-2.30）	-0.6040*** （-3.06）
GVC^2		0.0034* （1.88）	0.0048** （2.53）
eco* GVC			0.0053* （1.97）
ene		0.4514*** （3.41）	0.3963*** （2.99）

is		0.1751* （1.80）	0.2106** （2.18）
ope		-0.2371* （-1.72）	-0.2863** （-2.08）
pgdp		-0.0656 （-0.87）	-0.0796 （-1.08）
Constant	59.2480*** （12.32）	48.5567*** （4.76）	60.4652*** （5.19）
Fixed effect	YES	YES	YES
R-squared	0.21	0.51	0.55
F test	120.26	31.22	27.58

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

In Table 6, Model (6) shows a significant negative correlation between the LCIE and CEI, indicating that as the capacity of the LCIE increases, CEI can be significantly reduced. This result also supports Hypothesis 3.

To observe the moderating role of the LCIE between GVC participation and CEI, models (7) and (8) report the relationship between the three variables. In model (7), the influence direction of the LCIE and GVC on CEI is consistent with the previous model results. However, after introducing the cross-term of the LCIE and GVC participation in model (8), the cross-term effect is significant, Moreover, there have been significant changes in the LCIE and GVC participation coefficient, indicating that the moderating effect of the LCIE is significant.

This means that the sample countries should actively participate in the GVC and enhance their own LCIE, which can more efficiently reduce CEI. Therefore, hypothesis 2 has been verified. The influence of control variables is consistent with the previous text and will not be repeated.

Robustness tests

This paper draws on the methods of Jiménez et al. (2023) and Li and Zhang (2023), which to group sample countries. Due to the significant differences in indicators between China and Latin American countries, after excluding China, this paper uses Latin American country data as a sample for regression analysis. The influence direction of each variable is consistent with the basic regression, indicating that the econometric model in this paper has stability.

Table 7 Results of robustness test

	Latin America
eco	-0.5991*** （-2.79）
GVC	-0.7840*** （-2.76）
GVC^2	0.0067** （2.24）
eco* GVC	0.0077* （1.91）
ene	0.3798*** （2.68）

is	0.2064** (2.07)
ope	-0.3147** (-2.00)
pgdp	-0.1133 (-0.98)
Constant	60.4304*** (4.60)
Fixed effect	YES
R-squared	0.55
F test	21.33

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Further Analysis

Decomposition of GVC participation and CEI

It has been established that GVC participation has an impact on CEI, nevertheless, GVC participation can be split in two ways: forward or backward. (Liu et al., 2020). When a country exports technology, services, and completed goods, it is said to be engaged in forward GVC participation. Conversely, when a country engages in backward GVC participation, it means that it is primarily engaged in imports of final goods and intermediate products and exports of raw materials. The total value of participating in GVC is equal to the sum of the two. In order to replace GVC participation for regression, this paper further breaks down GVC participation into forward and backward GVC participation. The regression results are shown in Table 8.

Table 8 Decomposition of GVC participation

	GVC_f	GVC_b
eco	-0.5852*** （-3.11）	-0.4743*** （-2.70）
GVC_f GVC_b	-0.2906** （-2.18）	-0.1180 （-0.92）
eco* GVC_f eco* GVC_b	0.0047* （1.66）	0.0057* （1.95）
ene	0.5096*** （3.98）	0.4818*** （3.64）
is	0.2692** （2.58）	0.2061** （2.00）
ope	-0.2732* （-1.85）	-0.3445** （-2.36）
pgdp	-0.0515 （-0.67）	-0.0995 （-1.28）
Constant	54.1816*** （4.62）	48.4434*** （4.25）
Fixed effect	YES	YES
R-squared	0.51	0.51
F test	27.24	33.03

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1.

Table 8 shows that the basic regression is in line with the influence of the LCIE index, forward GVC participation, and control variables on CEI. This suggests that enhancing LCIE and forward GVC participation can effectively lower CEI.

The regression analysis reveals that the effect of backward GVC participation is not significant. This suggests that factors like low added value, outdated industrial structure, and raw material extraction will prevent even improved backward GVC participation from reaching the target of reducing carbon emissions. However, the effect is not significant, which does not mean that backward GVC participation is meaningless.

Backward GVC participation can help host countries improve their industrial system and production chain. If low-carbon technology can be used for production and energy consumption structure transformation, it can also achieve the goals of reduction in carbon emissions.

Mechanism test

The research and application of low-carbon technology, as well as the transformation of industrial energy consumption structure, can be achieved in the LCIE. To further study the influence of LCIE on CEI and provide support for future implications, this paper divides the LCIE into five indices: innovation, industry, infrastructure, intermediary, and environment. The results of five components on CEI and GVC participation are shown in Table 9:

Table 9 results of mechanism test

	Innovation *GVC	Industry *GVC	Infrastructure *GVC	Intermediary *GVC	Environment *GVC
CEI	-0.0024* （-1.77）	-0.0063*** （-3.82）	-0.0013 （-1.28）	-0.0009 （-0.78）	0.0030 (1.60)
GVC^2	0.0017** （2.04）	0.0023*** （3.12）	0.0012 （1.58）	0.0012 （1.49）	-0.0009 （-0.70）
Constant	39．1179*** （21.69）	42.6031*** （21.79）	38.6956*** （20.92）	37.9627*** (21.95)	36.0731*** （21.43）
Fixed effect	YES	YES	YES	YES	YES

Notes: *** p < 0.01, ** p < 0.05, * p < 0.1.

In Table 9, by studying the influence of the cross-terms between the five parts and GVC participation on CEI. Innovation and Industry have a significant promoting effect on the reduction of CEI. These results are consistent with the previous discussion, indicating that technological factors have a significant influence on reducing CEI.

Infrastructure and Intermediary have shown a promoting effect on the reduction of CEI, but the regression results are not significant. This conclusion does not negate the influence of these two parts and needs further research.

The regression results of environmental factors show a positive correlation with CEI. An increase in CEI will lead to ecological environment deterioration, and there is a high positive correlation between the two. However, the regression results show that they are not significant, indicating that environmental factors need to work together with other components in the LCIE to have an influence on the CEI.

In summary, based on the results of the basic regression model, the influence of GVC participation on CEI has a U-shaped relationship. With the improvement of GVC participation, domestic industries produce products with higher added value through competition and development, improving technological level and production efficiency. With the application of low-carbon technology and the transformation of energy consumption structure, CEI is significantly reduced. However, when GVC participation reaches a certain level, The carbon emission reduction of domestic industries has reached a bottleneck, the continued improvement of GVC participation will lead to an increase in carbon emissions, which is consistent with the conclusion of Li and Zhang (2023).

Liu and Zhao (2021) claimed that countries with low GVC participation can significantly reduce CEI by increasing the export of final products and increasing the technological content of intermediate products. However, it is necessary to improve energy efficiency and industrial structure transformation, which relies on the development of technology. This paper confirms that the LCIE plays a moderating role. Xie and Wang (2020) confirmed that enterprise technology introduction and cooperation can form an innovation ecosystem, which is conducive to own development, enhancing competitiveness, and obtaining sustainable competitive advantages in an open competitive environment.

With the integration and development of enterprises, an innovation ecosystem has gradually formed, further promoting the upgrading of production technology. However, with the increasing carbon emissions, reducing CEI has become an important part of enterprise structure transformation (Zhao et al., 2022). Reducing CEI requires the joint participation of all sectors of society. In order to avoid simply examining the influence of technological factors on carbon emissions, the LCIE develops environmental factors, low-carbon technology development, and government guidance in the evaluation system to comprehensively estimate the influence of LCIE on GVC participation and CEI.

Through further analysis, forward GVC participation has a significant negative influence on CEI, while backward GVC participation has a positive effect on CEI. Furthermore, mechanism analysis shows that Innovation and Industry factors have a significant negative influence on CEI, while Infrastructure, Intermediary, and Environmental factors have no significant effect on reducing CEI. However, it cannot negate the role of these three factors in carbon emission reduction, The improvement of infrastructure can improve the production efficiency, promote the flow of technological factors, and with the support of government policies, a low-carbon consensus can be formed more quickly. The changes in environmental factors reflect the residents' demand for a high-quality environment, and on the other hand, it is a direct reflection of the decrease in CEI. This conclusion has also been demonstrated by Cao et al. (2023).

Conclusions

Based on the influence of LCIE on CEI and GVC participation, this paper takes China and six Latin American countries as research samples, and develops empirical analysis on their economic data in 2011-2021, the conclusions are as follow:

The LCIE in China and Latin America is increasing. This indicates that countries pay more attention to the construction of LCIE. Although some countries have experienced fluctuations in the LCIE index due to the impact of COVID-19 between 2019 and 2021, the overall trend is on the rise.

GVC participation has a "U-shaped" effect on CEI. With the improvement of GVC participation, especially the improvement of forward GVC participation, it has a positive effect on the improvement of the host country's industrial system. By improving industrial production efficiency and process, it has a positive effect on reducing CEI. However, when GVC participation reaches a certain level, especially when the backward GVC participation is too high, it has a negative effect on reducing CEI.

The LCIE plays a moderating role in the relationship between GVC participation and CEI. The development and application of low-carbon technology are important measures to reduce CEI. LCIE can help host countries further reduce CEI after GVC participation reaches a turning point. From the perspective of the influence mechanism of the LCIE, Innovation and Industry have a significant impact, indicating that countries and enterprises can achieve a rapid reduction in CEI through research and development investment in the short term. The impact of Intermediary, Infrastructure, and Environment is not significant, but the direction of their influence on CEI is consistent with expectations, indicating that the three variables work together to reduce CEI by improving the capacity of LCIE.

Theoretical Implications

Based on the conclusions, this paper provides the following theoretical implications for China and Latin America to reduce CEI: Firstly, improving the evaluation method of LCIE. Based on this paper, considering more affecting factors of LCIE to form a more scientific evaluation method. Secondly, exploring more cooperation paths for LCIE in different regions, which will be positive to the common progress of low-carbon science and technology in all countries. Thirdly, conducting a more in-depth study of GVC in the development of low-carbon technologies, it will more comprehensively promote the development of LCIE.

Practical and Social Implications

Based on the conclusions, this paper provides the following practical implications for China and Latin America to reduce CEI: Firstly, to improve the construction of country's LCIE and promote the research and application of low-carbon technologies. Secondly, to actively participate in GVC, especially to improve forward GVC participation, which can achieve industrial energy structure upgrading, increasing the added value of domestic products. Thirdly, to improve the government guidance, research investment, industry structure, infrastructure construction, and ecological environment protection.

Limitations and Suggestions for Future Research

This paper develops empirical research on the influence of LCIE between GVC participation and CEI, moreover, proposes policy implications for reducing CEI in China and Latin America. However, there are still many limitations in this paper: Firstly, in the evaluation system of LCIE, there is no unified method. Therefore, this paper draws on other scholars' methods to calculate the index of LCIE, which possibility of missing indicators. It is necessary to further improve the evaluation system. Secondly, in the mechanism testing, Intermediary, Infrastructure, and Environment factors are not significant, which need to further analysis by more data samples. Thirdly, in estimating the moderating role of the LCIE, the moderating model uses cross-term, which cannot specifically quantify the moderating effect. It is necessary to further study and quantitatively analyze the moderating role of the LCIE.

Acknowledgement

This study was funded by the Southwest University of Science and Technology Education and Teaching Reform and Research (No. 19xn0059).

We also want to thank the reviewers and editors of AAMC for their helpful insights in improving this paper.

References

Ali, E., & Gninigué, M. (2022). Global value chains participation and structural transformation in Africa: Are we advocating environmental protection? *Journal of Cleaner Production, 366,* 132914.

Ambos, B., Brandl, K., Perri, A., Scalera, V. G., & Van Assche, A. (2021). The nature of innovation in global value chains. *Journal of World Business*, *56*(4), 101221.

Assamoi, G. R., Wang, S., Liu, Y., Gnangoin, T. B. Y., Kassi, D. F., & Edjoukou, A. J. (2020). Dynamics between participation in global value chains and carbon dioxide emissions: empirical evidence for selected Asian countries. *Environ Sci Pollut Res Int*, *27*(14), 16496-16506.

Banerjee, K. (2022). FDI flow in Energy Sector among BCIM, BIMSTEC+1 and ASEAN+4 sub-regional alignments. *Journal of Environmental Science and Economics*, *1*(3), 33-50.

Belloc, I., & Molina, J. A. (2023). Are greenhouse gas emissions converging in Latin America? Implications for environmental policies. *Economic Analysis and Policy*, *77*, 337-356.

Bi, K., Huang, P., & Ye, H. (2015). Risk identification, evaluation and response of low-carbon technological innovation under the global value chain: A case of the Chinese manufacturing industry. *Technological Forecasting and Social Change*, *100*, 238-248.

Brink, T. (2022). Organising direction of innovation ecosystems for extended clean energy production. *Journal of Cleaner Production*, *376,*134150.

Cao, H., Peng, L., Yan, Z., & Xu, J. (2023). Does perfect regional innovation ecosystem curb carbon emissions? A measure based on the niche fitness. *Environmental Impact Assessment Review*, *102*, 107219.

Chen, X. H., Tee, K., Elnahass, M., & Ahmed, R. (2023). Assessing the environmental impacts of renewable energy sources: A case study on air pollution and carbon emissions in China. *J Environ Manage*, *345*, 118525.

Cobben, D., Ooms, W., & Roijakkers, N. (2023). Indicators for innovation ecosystem health: A Delphi study. *Journal of Business Research*, *162*,113860.

Cui, F., Lim, H., & Song, J. (2022). The Influence of Leadership Style in China SMEs on Enterprise Innovation Performance: The Mediating Roles of Organizational Learning. *Sustainability*, *14*(6), 3249.

Demena, B. A., & Afesorgbor, S. K. (2020). The effect of FDI on environmental emissions: Evidence from a meta-analysis. *Energy Policy*, *138*.

Duan, Y., & Jiang, X. (2021). Pollution haven or pollution halo? A Re-evaluation on the role of multinational enterprises in global CO2 emissions. *Energy Economics*, *97*.

Espinosa-Gracia, A., Almazán-Gómez, M. Á., & Jiménez, S. (2023). CO2 emissions and global value chains indicators:new evidence for 1995–2018. *Journal of Environmental Management*, *343*, 111192.

Essandoh, O. K., Islam, M., & Kakinaka, M. (2020). Linking international trade and foreign direct investment to CO(2) emissions: Any differences between developed and developing countries? *Sci Total Environ*, *712*, 136437.

Fei, R., Pan, A., Wu, X., & Xie, Q. (2020). How GVC division affects embodied carbon emissions in China's exports? *Environmental Science and Pollution Research*, *27*(29), 36605-36620.

Foss, N. J., & Saebi, T. (2018). Business models and business model innovation: Between wicked and paradigmatic problems. *Long Range Planning*, *51*(1), 9-21.

Ganco, M., Kapoor, R., & Lee, G. (2020). From Rugged Landscapes to Rugged Ecosystems_ Structure of Interdependencies and Firms' Innovative Search. *Academy of Management Review*, *45*(3), 1-57.

Gomes, L. A. d. V., Castillo-Ospina, D. A., Facin, A. L. F., Ferreira, C. d. S., & Ometto, A. R. (2023). Circular ecosystem innovation portfolio management. *Technovation*, *124*, 102745.

Granstrand, O., & Holgersson, M. (2020). Innovation ecosystems: A conceptual review and a new definition. *Technovation*, *90-91*.

Han, Y., Liu, J., Li, J., Jiang, Z., Ma, B., Chu, C., & Geng, Z. (2023). Novel risk assessment model of food quality and safety considering physical-chemical and pollutant indexes based on coefficient of variance integrating entropy weight. *Sci Total Environ*, *877*, 162730.

Ho, C.-Y., Wang, W., & Yu, J. (2018). International knowledge spillover through trade: A time-varying spatial panel data approach. *Economics Letters*, *162*, 30-33.

Hoa, P. X., Xuan, V. N., & Phuong Thu, N. T. (2023). Nexus of innovation, renewable consumption, FDI, growth and CO2 emissions: The case of Vietnam. *Journal of Open Innovation: Technology, Market, and Complexity*, *9*(3), 100100.

Huang, Y., Li, K., & Li, P. (2023). Innovation ecosystems and national talent competitiveness: A country-based comparison using fsQCA. *Technological Forecasting and Social Change*, *194*, 122733.

Jiménez, J. L., Valido, J., & Pellicer, A. A. (2023). Evaluating the effect of air transport resident subsidies on non-residents tourists' expenditure. *Journal of Air Transport Management*, *106*, 102319.

Konietzko, J., Bocken, N., & Hultink, E. J. (2020). Circular ecosystem innovation: An initial set of principles. *Journal of Cleaner Production*, *253*, 119942.

Li, G., & Zhang, X. (2023). Does GVC embedding reduce carbon emissions? Empirical evidence from 218 Chinese cities. *Structural Change and Economic Dynamics*, *66*, 253-263.

Liu, C., & Zhao, G. (2021). Can global value chain participation affect embodied carbon emission intensity? *Journal of Cleaner Production*, *287*, 125069.

Liu, H., Zong, Z., Hynes, K., & De Bruyne, K. (2020). Can China reduce the carbon emissions of its manufacturing exports by moving up the global value chain? *Research in International Business and Finance*, *51*, 101101.

Ma, N., Sun, W., Wang, Z., Li, H., Ma, X., & Sun, H. (2023). The effects of different forms of FDI on the carbon emissions of multinational enterprises: A complex network approach. *Energy Policy*, *181*, 113731.

Muhammad, B. (2019). Energy consumption, CO2 emissions and economic growth in developed, emerging and Middle East and North Africa countries. *Energy*, *179*, 232-245.

Paasi, J., Wiman, H., Apilo, T., & Valkokari, K. (2023). Modeling the dynamics of innovation ecosystems. *International Journal of Innovation Studies*, *7*(2), 142-158.

Pan, X., Ai, B., Li, C., Pan, X., & Yan, Y. (2019). Dynamic relationship among environmental regulation, technological innovation and energy efficiency based on large scale provincial panel data in China. *Technological Forecasting and Social Change*, *144*, 428-435.

Perwez, U., Shono, K., Yamaguchi, Y., & Shimoda, Y. (2023). Multi-scale UBEM-BIPV coupled approach for the assessment of carbon neutrality of commercial building stock. *Energy and Buildings*, *291*, 113086.

Qiaoling, S., Yuli, S., Chao, Z., Ye, C., & Xue, R. (2022). How would GVCs participation affect carbon intensity in the "Belt and Road Initiative" countries? *Energy Economics*, *111*, 106075.

Rashid Khan, H. U., Nassani, A. A., Aldakhil, A. M., Qazi Abro, M. M., Islam, T., & Zaman, K. (2019). Pro-poor growth and sustainable development framework: Evidence from two step GMM estimator. *Journal of Cleaner Production*, *206*, 767-784.

Rong, K., Lin, Y., Yu, J., Zhang, Y., & Radziwon, A. (2020). Exploring regional innovation ecosystems: an empirical study in China. *Industry and Innovation*, *28*(5), 545-569.

Sarkodie, S. A., & Strezov, V. (2019). Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. *Sci Total Environ*, *646*, 862-871.

Scalera, V. G., Perri, A., & Hannigan, T. J. (2018). Knowledge connectedness within and across home country borders: Spatial heterogeneity and the technological scope of firm innovations. *Journal of International Business Studies*, *49*(8), 990-1009.

Shi, Q., Zhao, Y., Qian, Z., Zheng, L., & Wang, S. (2022). Global value chains participation and carbon emissions: Evidence from Belt and Road countries. *Applied Energy*, *310*, 118505.

Shi, T., Han, F., Chen, L., Shi, J., & Xiao, H. (2023). Study on value Co-creation and evolution game of low-carbon technological innovation ecosystem. *Journal of Cleaner Production*, *414*, 137720.

Sinha, A., Balsalobre-Lorente, D., Zafar, M. W., & Saleem, M. M. (2022). Analyzing global inequality in access to energy: Developing policy framework by inequality decomposition. *J Environ Manage*, *304*, 114299.

Song, Y., Chen, X., Li, Z., Zeng, Z., & Zhang, M. (2022). Exploring the effect of a low-carbon city pilot policies on carbon dioxide emission intensity: Based on the PSM-DID method. *Chinese Journal of Population, Resources and Environment*, *20*(3), 209-216.

Stokke, R., Kristoffersen, F. S., Stamland, M., Holmen, E., Hamdan, H., & De Boer, L. (2022). The role of green public procurement in enabling low-carbon cement with CCS: An innovation ecosystem perspective. *Journal of Cleaner Production*, *363*, 132451.

Tamayo-Orbegozo, U., Vicente-Molina, M.-A., & Villarreal-Larrinaga, O. (2017). Eco-innovation strategic model. A multiple-case study from a highly eco-innovative European region. *Journal of Cleaner Production*, *142*, 1347-1367.

Tamura, R., Kobayashi, K., Takano, Y., Miyashiro, R., Nakata, K., & Matsui, T. (2018). Mixed integer quadratic optimization formulations for eliminating multicollinearity based on variance inflation factor. *Journal of Global Optimization*, *73*(2), 431-446.

Thomas, L. D. W., Autio, E., & Gann, D. M. (2022). Processes of ecosystem emergence. *Technovation*, *115*, 102441.

Wang, J., Wan, G., & Wang, C. (2019). Participation in GVCs and CO2 emissions. *Energy Economics*, *84*, 104561.

Wang, P., Wang, H., Chen, W.-Q., & Pauliuk, S. (2022). Carbon neutrality needs a circular metal-energy nexus. *Fundamental Research*, *2*(3), 392-395.

Weko, S., & Goldthau, A. (2022). Bridging the low-carbon technology gap? Assessing energy initiatives for the Global South. *Energy Policy*, *169*, 113192.

Xie, X., & Wang, H. (2020). How can open innovation ecosystem modes push product innovation forward? An fsQCA analysis. *Journal of Business Research*, *108*, 29-41.

Xin, Z., Xiaowei, M., Boyang, C., Yuping, S., & Malin, S. (2022). Challenges toward carbon neutrality in China: Strategies and countermeasures. *Resources, Conservation and Recycling*, *176*, 105959.

Yang, Z., Chen, H., Du, L., Lin, C., & Lu, W. (2021). How does alliance-based government-university-industry foster cleantech innovation in a green innovation ecosystem? *Journal of Cleaner Production*, *283*, 124559.

Yu, C., Zhao, J., & Cheng, S. (2023). GVC trade and business cycle synchronization between China and belt-road countries. *Economic Modelling*, *126*, 106417.

Zhao, J., Jiang, Q., Dong, X., Dong, K., & Jiang, H. (2022). How does industrial structure adjustment reduce CO2 emissions? Spatial and mediation effects analysis for China. *Energy Economics*, *105*, 105704.

Zhou, C. (2019). Can intellectual property rights within climate technology transfer work for the UNFCCC and the Paris Agreement? *International Environmental Agreements: Politics, Law and Economics*, *19*(1), 107-122.

Appendix A

IPC code of renewable energy patents

Classification	Subclass	IPC code
Non-renewable alternative energy sources	Nuclear engineering	G21B，G21C，G21D
	Nuclear fuel	F02C-005/00
	Fuel cell	H01M-004，H01M-008，H01M-012
	Garbage power	A62D-003，B09B，B01D-053/02，B01D-053/14，B01D-053/22，B01D-053/24，C02F-011，C10L-005/00，C10J-003/02，C10J-003/46，C21B-005/06，D21C-011，F23G-007，F23B90，F23G-005
	Waste heat	C02F-001/02，C10J-003/86，D21F-005/20，F01K-017，F01K-027，F01K-023，F01N-005，F02C-006/18，F02G-005，F22B-001/02，F24F-012，F25B-027/02，F27D-017，F28D-017，F28D-019，F28D-020
Renewable energy	Hydro energy	B63H19/02，B63H19/04，E02B9/00，F03B，F03C
	Ocean energy	F03G7/05
	Geothermal energy	F01K，F03G4/00，F03G7/04，F24F5/00，F25B30/06，H02N10/00，
	Wind energy	B60K16/00，B60L8/00，B63B35/00，B63H13/00，E04H12/00，F03D，H02K7/18
	Solar energy	C01B33/02，C02F1/14，C23C14/14，C23C16/24，C30B29/06，E04D13/00， F21L4/00，F21S9/03，F24D17/00，F24D3/00，F24D5/00，F24D11/00，F24D19/00，F03D1/04，F03D9/00，F03G6/00，F02C1/05，F22B1/00，F24J1/00，F25B27/00，F26B3/00，3/28，F24J 2/06，G02B7/183，G05F1/67，H01L27/142，H01L31/00，H01G9/20，H01L27/30，H01L51/42，H01L51/44，H01L51/46，H01L51/48，H01L25/00，H01M14/00，H02J7/35
	Biofuels	A01H，C02F3/28，C02F11/04，C07C67/00，C07C69/00，C10B53/02，C10G，C10L1/00，C10L3/00，C10L5/00，C10L9/00，C11C3/10，C12P7/06，C12P7/08，C12P7/10，C12P7/12，C12P7/14，C12P7/64，C12M1/107，C12N1/13，C12N1/15，C12N1/21，C12N5/10，C12N9/24，C12N15/00，C12P5/02，
	Biomass energy	C10B53/00， C10J
Low carbon energy storage technology	Electric energy storage	B60K6/28，B60W10/26，H01G9/15，H01M10/44，H01M10/46，H02J3/28，H02J7/00，H02J15/00
	Thermal energy preservation	C09K5/00，F24H7/00，F28D20/00
	Green lighting	F21K99/00，H01L33/00，H01L51/50，H05B33/00
	Building thermal insulation	E04B1/62，E04B1/74–1/80，E04B1/88，E04B1/90，E04B2/00，E04B5/00，E04B7/00，E04B9/00，E04C1/40，E04C1/41，E04C2/284–2/296，E04D1/28，E04D3/35，E04D13/16，E04F13/08，E04F15/18，E06B3/263
	Mechanical energy	B60K6/10，B60K6/30，B60L53/00，F03G7/08

Appendix B

Index of LCIEs in various countries over the years

Country	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
China	0.5025	0.5292	0.5864	0.5821	0.6081	0.6279	0.6862	0.7365	0.7731	0.8673	0.9124
Argentina	0.1042	0.1118	0.1162	0.1186	0.1253	0.1263	0.1273	0.1278	0.1283	0.133	0.1286
Brazil	0.1454	0.1515	0.1587	0.1724	0.1773	0.1807	0.1842	0.189	0.1961	0.2003	0.207
Chile	0.0643	0.0686	0.0767	0.0795	0.0951	0.1036	0.1001	0.0957	0.098	0.1039	0.1096
Colombia	0.029	0.0397	0.0437	0.0466	0.055	0.048	0.0499	0.054	0.0559	0.059	0.0628
Mexico	0.0827	0.0787	0.0851	0.0843	0.098	0.1004	0.092	0.0966	0.1063	0.1081	0.1109
Peru	0.0631	0.0678	0.0426	0.0448	0.0349	0.0393	0.04	0.047	0.0513	0.0626	0.062