How Does GVC Position Affect CO2 Emissions of Supply Chain Partners?

Abstract: Global value chains (GVCs) play a crucial role in shaping carbon emissions, as supply chains integrate upstream and downstream firms. Therefore, this study examines the relationship between firms' positions in GVCs and the CO2 emissions of their supply chain partners using a unique dataset of Chinese A-share listed firms, their suppliers, and customers from 2010 to 2014. The findings indicate that: First, firm's GVC position is negatively correlated with CO2 emissions of upstream and downstream firms. Particularly, improved GVC position exerts a stronger impact on CO2 emissions reduction of their suppliers as compare to their customers. Second, mechanism analysis shows that a firm's GVC position influences trade credit within the supply chain and generates positive technological spillovers for both upstream and downstream. These spillover effects are further moderated by green innovative activities of firms. Third, the impact of upgrade in GVC position on CO2 emissions reduction is heterogeneous, varying with the ownership of firms, competition in the industry, participation in processing trade, and their scale. Thus, this study is a significant contribution to literature on the empirical side and establishes new evidence for the role of GVCs in reducing CO2 emissions and classifying crucial mechanisms driving these impacts. These findings suggest actionable insights for policymakers targeting to bring into line global value chains with sustainable development goals.

Keywords: GVC position; CO_2 emissions; suppliers; customers; trade credit; green innovation.

1. Introduction

With accelerating climate change, reducing CO_2 emissions has emerged as a critical global imperative. In the context of globalization, China's rapid economic expansion, driven by low-value-added and carbon-intensive industries, has positioned it as the world's top CO_2 emissions source. China's CO_2 emissions surpassed those of all developed economies combined in 2020, reaching 35% of global emissions by 2023 (IEA, 2023). Confronted with intense environmental challenges, China has committed to a sustainable economic transformation, pledging in 2020 to achieve carbon peak by 2030 and carbon neutrality by 2060. The realization of these dual-carbon goals represents a pivotal strategy for both China's modernization and global climate change.

China's huge CO_2 emissions are closely tied to its unfavorable position in the global division of labor (Li et al., 2022). Global value chains (GVCs), characterized by globally fragmented production, serve as the primary pattern of global labor division. In this pattern, CO_2 emissions are transferred alongside the fragmented tasks across global supply chains (Li et al., 2024). Developed economies typically occupy low-carbon, high-value-added positions within GVCs, while developing economies are often confined to carbon-intensive, low-value-added manufacturing segments. This structural disparity in GVC participation enables developing countries to benefit from global economic integration while simultaneously bearing the burden of carbon leakage from developed economies. Since joining the WTO, China has rapidly become the world's manufacturing factory by leveraging its labor cost advantages within GVCs (Meng et al., 2023). Notably, China accounts for the largest share of GVC-related CO_2 emissions globally (Zhang & Wang, 2021). In this context, upgrading GVC position emerges a strategic approach for China to balance global economic integration with environmental sustainability (Sun et al., 2019). Empirical evidence suggests that

China's GVC upgrading has driven 35% of the observed improvements in energy efficiency and environmental performance (Liu et al., 2018), underscoring its a pivotal role on low-carbon transition.

Meanwhile, recent structural shifts in GVCs have witnessed China's decreasing dependence on foreign suppliers and growing emphasis on domestic markets (McKinsey Global Institute, 2019). This transformation has significant implications for global carbon emissions. As a central node in GVCs, China is implementing its "dual-circulation" strategy, prioritizing domestic economic circulations while allowing the domestic and international circulations to reinforce each other. Concurrently, the government is fostering modern supply chains with green characteristics that support this dual-circulation framework. The role of domestic production networks in balancing emission reduction and economic growth is gaining prominence (Chen & Zhao, 2022). While existing research provides substantial evidence on emission reduction through GVC upgrading at various levels (Liu et al., 2018; Yang et al., 2022), the spillover effects of GVC upgrading within supply chains remain underexplored. Specifically, the impact of GVC position upgrading on CO_2 emissions of upstream and downstream segments of domestic supply chains worths further investigation.

Therefore, this study examines the relationship between GVC position upgrading and CO_2 emissions across supply chains using data from Chinese A-share listed firms and their suppliers and customers. Our analysis reveals three key findings: First, GVC position upgrading significantly reduces CO_2 emissions in both upstream and downstream firms. Second, trade credit and technology spillovers serve as crucial mechanisms for these spillover effects on emission reduction, with green innovation activities amplifying downstream impacts. Third, the effect of GVC position upgrading varies according to firms' spillover capacity and the responsiveness of their supply chain partners. This study is structured as follows: Chapter 2 reviews relevant literature on GVCs, supply chains, and emission reduction. Chapter 3 presents the theoretical analysis and hypotheses. Chapter 4 details the estimation strategy and data sources. Chapter 5 reports the empirical results. Chapter 6 concludes with findings and policy implications.

2. Literature Review

The acceleration of GVC trade and escalating environmental challenges from greenhouse gas emissions prompt increasing scholarly attention to GVC-related emission reduction strategies. Research demonstrates that global production fragmentation significantly influences CO_2 emissions (Wiedmann et al., 2007). The environmental implications of GVC participation vary as economies are differently positioning in GVCs. Developed countries, as dominant players in GVC trade, demonstrate an inverse relationship between GVC participation and CO_2 emissions. Conversely, developing countries' participation in GVCs tends to correlate positively with increased CO_2 emissions (Jithin & Ashraf, 2023). The relationship between trade in GVCs and CO_2 emissions is dynamic. While developing countries often become pollution havens in developed-country-dominated GVC trade, they simultaneously benefit from technology transfer and economies of scale through GVC participation, potentially facilitating emission reductions over time (Antweiler et al., 2001; López et al., 2013; Vale et al., 2017). Wang et al. (2019) draw similar conclusions and empirically reveal an inverted U-shaped relationship between GVC participation and CO_2 emissions. They find that early participation in GVC trade brings high emissions to developing countries, with R&D investment serving as a crucial mechanism to mitigate emissions sourced from the early stages of GVC participation. The effect of

GVC trade on CO_2 emissions also differs with the participation pattern (Ma et al., 2023; Wei et al., 2024). Forward GVC participation reduces carbon emissions, while backward participation increases them (Tang et al., 2024; Kim & Seo, 2025). Enhancing GVC positioning enables participants to capture environmental dividends through GVCs (Chen & Zhao, 2022). Through an examination of China's manufacturing sector, Yang et al. (2022) provide empirical evidence that GVC position upgrading facilitates energy-saving technological innovation, thereby contributing to significant emission reduction effects. Based on Chinese industrial firms, Cheng et al. (2024) provide firm-level evidence of the emission reduction effects of GVC upgrading at the micro level. Furthermore, recent research highlights spillover effects of GVC trade. Zhu et al. (2021) identify spatial spillover effects in the relationship between GVC position and CO_2 emissions, suggesting that benefits from participating GVCs may extend beyond firms themselves to their surrounding areas. This finding is corroborated by Siewers et al. (2024), who demonstrate that GVC-driven environmental improvements can propagate through supervisory supply chains, amplifying emission reduction effects.

The spillover effects of green suppliers and customers on cleaner production in supply chains are also closely related to this study. Research reveals multiple influence mechanisms within supply chains regarding environmental performance. Downstream effects demonstrate that customers actively drive emission reduction initiatives upstream. Customers serve as catalysts for supply chain greening, advocating for cleaner production to maintain competitive advantage (Ramanatha et al., 2014). Suppliers strategically adjust to customers' sustainable standards to preserve supply relationships (Wilhelm et al., 2016). Empirical evidence from Dai et al. (2021) confirms that customers' environmental focus generates a backwash effect, positively influencing suppliers' environmental responsibility. Liew and Cao (2024) further substantiate this relationship through their analysis of US listed firms, identifying customer-supplier relationship strength and duration as key mechanisms through which customers' rising environmental standards drive suppliers' emission reductions.

Conversely, upstream green initiatives significantly influence downstream environmental performance. Chiou et al. (2011) demonstrate that green suppliers enhance customers' environmental protection capabilities and facilitate green innovation. Potter and Graham's (2019) case study of Toyota illustrates how collaboration and extensive exposure to suppliers yield substantial environmental benefits of green innovation for customers. Anin et al. (2024) prove the moderating role of supplier-customer relationships in firms' emission reduction capabilities. There is also extensive cooperation on emission reductions among firms in supply chains, including carbon financing for upstream and joint development of emission reduction technologies (Kang et al., 2019; Chen et al., 2019). These collaborative efforts in supply chains are significantly influenced by external regulatory pressures, which shape firms' green innovation initiatives (Lin et al., 2024). Research by Sun et al. (2020) reveals emerging patterns of carbon transfer cooperation among supply chain participants under emission quota policy, identifying that three critical factors - information sharing among supply chain participants, consumer preferences for low-carbon products, and investments in green technology, collectively influence the emission reduction effectiveness of carbon transfer among supply chains.

According to the above findings, scholars have extensively examined the emission reduction effects of GVC positioning across macro and micro levels. The green spillover effects and underlying mechanisms within supply chains at both customer and supplier ends have also been well investigated. However, a significant research gap remains in understanding how GVC position influences CO_2 emissions across upstream and downstream firms within domestic supply chains. Particularly, the intrinsic mechanisms through which GVC positioning facilitates green supply chain development are worth deeper study. Compared with existing studies, this study may make three contributions to the literature: First, the study deepens the analysis of emission reduction mechanisms by examining the financial and technological spillover effects of GVC position upgrading on upstream and downstream firms. This study also reveals the heterogeneous impacts sourced from firms' spillover capacity and the response capability of supply chain partners, thereby offering novel insights to the investigation of emission reduction. Second, this study provides new empirical evidence on the effects of GVC position upgrading for emission reduction. Unlike previous studies, this study analyzes the spillovers of GVC position upgrading on emission reductions of upstream and downstream firms based on the emission data from firms' supply chain partners. The study significantly advances research on GVC's indirect emission reduction effects. Third, this study expands the research on GVC trade spillovers by integrating the firm's global production networks with domestic supply chains. Through micro-level analysis of GVC positioning's impact on supplier and customer operations, the study provides compelling evidence of international-domestic cycle interactions. Meanwhile, theoretical and empirical analysis of supply chain spillovers mechanism also enhances our comprehension of modernized supply chains' role in China's "dual circulation" strategy.

3. Theoretical Analysis and Research Hypotheses

In global supply chains (GSCs), vertical integration and fair-trade function as both substitutes and complements (Andrenelli et al., 2019). Theoretically, firms' vertical integration activities exert influence on both upstream and downstream firms through the dynamics of the production chain. It is well-documented that firms engaged in GVC trade significantly impact the behavior and decision-making processes of their partners in fair trade (Pananond, 2013). Upgrading of positions in GVCs are better positioned to decarbonize and enhance production efficiency (Sun et al., 2019). Concurrently, firms demonstrating superior environmental performance are more likely to oversee and manage carbon emissions across their supply chains (Zhu et al., 2021). Indeed, a firm's positioning within GVCs profoundly influences carbon emissions in supply chains. A pertinent example is the textile and fast fashion industries, where fragmented and globalized production leads to an imbalance in production line position and, consequently, environmental consequences. The cost pressures inherent in the cheap fashion industry promote downstream firms to resist carbon emission controls within their supply chains (Niinimäki et al., 2020). This sparks widespread international concern regarding carbon emissions in the fashion supply chains. Hence, extending a firm's reach to upstream segments represents a strategic breakthrough to alleviate cost pressures and realize green supply chains. The more improved a firm's position in GVCs, the greater its capacity to disseminate environmental protection concepts and standards throughout the supply chain, thereby enhancing the carbon emission performance of both upstream and downstream firms.

Investment in emission reduction and technological innovation are key mechanisms for achieving clean production (Forslid et al., 2018). Firms in relatively upstream positions in the global production line tend to perform better in terms of profitability and technological capabilities (Brancati et al., 2017; Montalbano et al., 2018; Altun et al., 2025). These firms can transfer financial and technological resources to their supply chain partners, supporting collaborative efforts in sustainability (Geng et al., 2024). Thus, a firm's upgraded position in GVCs can promote emission reduction among upstream and downstream firms. This occurs through two main mechanisms. First, the improved GVC position provides more financial resources, which can be used to fund emission reduction efforts across the supply chain. Second, a relatively upstream position encourages the adoption of new technologies by both upstream and downstream firms.

H1: *Firms' GVC position negatively correlates with CO_2 emissions of upstream and downstream firms.*

The willingness of firms to invest in emission reduction is often constrained by financial limitations (Cao & Yu, 2018). The firm's improved position in the global production lines can alleviate financing constraints for emission reduction investments among upstream and downstream firms through trade credit. As an important green financing, trade credit plays a significant role in enabling firms to invest in emission reduction. It helps overcome financial limitations to adopting green technologies for production (Cao et al., 2019). An improved GVC position of the firm positively impacts trade credit for its upstream and downstream firms. Firms in relatively upstream positions typically achieve higher production efficiency, greater profitability, better access to financing, and lower financing costs, leading to more relaxed financial conditions (Manova & Yu, 2016; Doan, 2024). As a result, these firms are better positioned to provide trade credit to their downstream customers (Shenoy & Williams, 2017). Moreover, compared to other sources of financing, trade credit is less burdensome for business operations. Firms with stronger financial conditions are more likely to allow delayed payments, and share the risks of green investments with customers, creating mutual benefits (An et al., 2021). On the supplier side, excessive trade credit can negatively impact suppliers' financial health (Boissay & Gropp, 2013). To ensure supply chain stability, firms with stronger financial positions are less likely to delay payments to suppliers (Ding et al., 2024). This reduces the financial constraints on suppliers, enabling them to adopt emission reduction measures. Based on these insights, we propose the following hypothesis:

H2: *The upgrade in a firm's GVC position alleviates financing constraints for both upstream and downstream firms through trade credit, thereby facilitating emission reductions by its customers and suppliers.*

The technology spillovers of a firm's movement toward upstream positions in global production lines on emission reduction of supply chains are twofold. First, endogenous growth theory suggests that innovation in research and development (R&D) improves production efficiency and resource utilization, thereby promoting emission reduction (Dinda, 2004; Churchill et al., 2019). As firms upgrade their GVC position through learning-by-doing and innovation strategies, they deploy extensive innovation activities spanning management and production (Gereffi, 1999; Su et al., 2021). Within supply chains, the learning and dissemination of technologies between suppliers and customers are common (Oke et al., 2013). Customers and suppliers are critical sources of innovation resources for firms (Tomlinson & Fai, 2016). Due to firms' reliance on upstream suppliers, innovations driven by suppliers' rising GVC positions can positively influence customers' innovation capabilities as goods are delivered (Azadegan & Dooley, 2010). Similarly, supplier innovation is also influenced by downstream customers' enhanced product innovation and design capabilities resulting from their GVC position upgrades (Zhang et al., 2024). The upgrading of firms' GVC position generates positive innovation spillovers for upstream and downstream firms, enhancing their productivity and thus contributing to emission reductions. Second, the firm's improved GVC position has spillover effects that encourage customers and suppliers to adopt green technologies. The adoption of green technologies by customers and suppliers is significantly influenced by the environmental practices within the supply chain (Borazon et al., 2022). The demand for greener supply chains driven by GVC position upgrades stimulates both suppliers and customers to adopt green technologies, which in turn promotes them to reduce CO_2 emissions (Rao & Holt, 2005; Nassani et al., 2023).

H3: *The upgrading of firms' GVC position can promote emission reductions of upstream and downstream firms through technological spillovers.*

The green innovation activities of the firm also influence its spillover effects of GVC position upgrading. First, green innovation positively affects both the provision and utilization of trade credit. Trade credit between suppliers and firms serves not only as a financing tool but also as a mechanism for information sharing and innovation collaboration (Deng et al., 2023). In forward linkages, suppliers are more likely to offer trade credit to firms with strong green innovation capabilities and quality, as this helps maintain stable customer relationships. However, this may weaken the financial spillover effects of GVC upgrading for suppliers, as more trade credit is utilized (Lu et al., 2024). At the same time, firms focused on green innovation tend to have lower default risks, making it easier for them to obtain bank credit (Zhang et al., 2020; Tolliver et al., 2021). This further alleviates financing constraints, potentially amplifying the financial spillover effects of GVC upgrading for downstream firms. Second, a firm's green innovation activities also shape the technology spillover effects of GVC upgrading. Suppliers and customers can benefit from a firm's green innovation by adopting cleaner production technologies (Chiou et al., 2011; Wei et al., 2020). This amplifies the technology spillover effects of GVC upgrading on both upstream and downstream firms. Based on these insights, we propose Hypothesis 4:

H4: *Firms' own green innovation moderates the spillover effects of GVC position upgrading on upstream and downstream.*

Firm heterogeneity also plays a significant role in shaping carbon emissions within supply chains (Liu et al., 2016). The impact of a firm's GVC position upgrading on the carbon emissions of its upstream and downstream partners depends on several factors. These include the strength of the firm's emission reduction signals, the extent of financial and technological spillovers, and the responsiveness and learning capabilities of its supply chain partners (Hojnik & Ruzzier, 2016). On the one hand, when a firm demonstrates strong emission reduction signals, its oversight of carbon emissions within the supply chain becomes more pronounced. The stronger the environmental responsiveness of suppliers and customers, the more significant the emission reduction effects of the firm's GVC upgrading. On the other hand, if a firm is less willing or capable of providing financial support and sharing technologies with its supply chain partners, and if these partners have weaker learning capabilities, the emission reduction effects of GVC upgrading will be diminished. Based on this, we propose:

H5: *The impact of a firm's GVC position upgrading on the emission reduction of upstream and downstream firms varies with the heterogeneity of the firm and its supply chain partners.*

4. Methods

4.1. Model

To examine the effect of firms' GVC position upgrading on CO_2 emissions of upstream and downstream firms, this study establishes the following model:

$$CO2Em_{ijt} = \alpha_0 + \alpha_1 GVC_{pos_{it}} + \alpha_2 Control_{ijt} + \lambda_i + \mu_t + \epsilon_{it} \quad (1)$$

where i and t respectively represent firm i and year t. j represents firm i' supplier or customer j. $CO2Em_{ijt}$ is the CO_2 emissions of firm i' supplier or customer j at year t. GVC_pos_{it} represents GVC position of firm i at year t. $Control_{it}$ is a vector of control variables. α_0 is the constant term. α_1 is the coefficient of independent variable GVC_pos_{it}. A significantly negative coefficient α_1 suggests that the firm's GVC position upgrading effectively reduces emissions of its suppliers or customers across supply chain. In contrast, it implies limited emission reduction effects of the firm's GVC position upgrading. λ_i and μ_t represent individual and time fixed effects, respectively. And ϵ_{it} is the residual term.

4.2. Variables

4.1.1. Dependent Variable

The dependent variable in this study is the CO_2 emissions of suppliers or customers ($CO2Em_{ijt}$). According to Cui et al. (2021), we measure supplier and customer CO_2 emissions ($CO2Em_{ijt}$) as the natural logarithm of the sum of direct emissions from fossil fuel consumption (coal, oil, and natural gas) and indirect emissions from purchased electricity. Specifically, $CO2Em_{ijt}$ is calculated by summing the consumption of each energy type multiplied by its corresponding emission factor (As shown in Table 1). For China's six regional power grids, we apply distinct emission factors based on each supplier or customer's geographical location when computing indirect emissions from purchased electricity.

Table 1. CO_2 emissions Factors.

Energy	Unit	Emission Factor
Coal	$kgCO_2/kg$	1.978
Oil	$kgCO_2/kg$	3.065
Natural Gas	$kgCO_2/m^3$	1.809
Electricity from North China Grid	$kgCO_2/kWh$	0.8843
Electricity from Northeast China Grid	$kgCO_2/kWh$	0.7769
Electricity from East China Grid	$kgCO_2/kWh$	0.7035
Electricity from Central China Grid	$kgCO_2/kWh$	0.5257
Electricity from Northwest China Grid	$kgCO_2/kWh$	0.6671
Electricity from China Southern Power Grid	$kgCO_2/kWh$	0.5271

Note: Energy consumption is measured in metric tons of standard coal equivalent (TCE, 1 TCE= 29307 GJ). CO_2 emissions factors of Coal, Oil and Natural Gas are sourced from Department of Energy Statistics, National Bureau of Statistics of China and IPCC Guidelines for National Greenhouse Gas Inventories. Beijing, Tianjin, Hebei, Shandong, Shanxi and Inner Mongolia Inner Mongolia belong to North China Grid. The Northeast China Grid covers Liaoning, Jilin, and Heilongjiang. The East China Grid covers Shanghai, Jiangsu, Zhejiang, Anhui, and Fujian. Central China Grid supply electricity with Henan, Hubei, Hunan, Jiangxi, Chongqing, and Sichuan. The Northwest

China Grid Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. The China Southern Power Grid covers Guangdong, Guangxi, Yunnan, Guizhou, and Hainan. The data of electricity's CO_2 emissions Factors comes from National Center for Climate Change Strategy and International Cooperation, National Development and Reform Commission of China.

4.1.2. Independent Variable

The independent variable in this study is firms' GVC position (GVC_pos_{it}). Drawing on the methodology of Chor et al. (2021), we use the firm-level GVC position index to measure a firm's GVC position. This study constructs the firm-level GVC position Index based on China's industry-level GVC positions. First, following Wang et al. (2017), we calculate China's industry-level GVC positions using the ratio of average production length forward and average production length backward. The industry-level GVC position ($Position\_ind$) is calculated as shown in Equation (2):

$$Position\_ind = \frac{Plv\_GVC}{[Ply\_GVC]'} \tag{2}$$

$$Plv\_GVC = \frac{Xv\_GVC}{V\_GVC} \tag{3}$$

$$Ply\_GVC = \frac{Xy\_GVC}{Y\_GVC} \tag{4}$$

Where Plv_GVC represents the industry-level average production length forward, calculated as in Equation (3), where Xv_GVC and V_GVC respectively denote the domestic value added associated with GVC and the gross output it leads to. Ply_GVC is average production length backward, measured as in Equation (4). In Equation (4) Xy_GVC and Y_GVC respectively represent the GVC-related foreign value added and the gross output it leads to.

Second, referring to Chor et al. (2021), we construct firm-level GVC position index by weighting and summing the industry-level GVC position based on each firm's import and export share at the industry level. The detailed calculation is outlined in Equation (5):

$$GVC_{pos_{it}} = \sum_{n=1}^{N} \frac{M_{nit}}{M_{it}} Position_{ind_n} - \sum_{n=1}^{N} \frac{X_{nit}}{X_{it}} Position_{ind_n} \tag{5}$$

Where M_{nit} and X_{nit} are the import volume and export volume of firm i on the industry n at the year t. M_{it} and X_{it} are the sum of firm i's import and export at the year t.

4.1.3. Control Variables

To ensure the accuracy of the econometric model, this study controls for variables that may affect firms' GVC positions and the carbon emissions of suppliers or customers: (1) Firm Size (*Scale*): Firm size significantly influences operational strategies, market position, and environmental performance (Agan et al., 2013). We control for firm size using the logarithm of the number of employees in the basic model. (2) Firm Profitability (*Profit*): Profits incentivize suppliers and customers to jointly adopt emission reduction strategies (Tong et al., 2019). We control for the operating profit margin (net profit/revenue) of suppliers or customers. (3) Fixed Assets (*FA*): Environmental performance tends to increase linearly with the scale of fixed assets (Zhang et al., 2020). We include the fixed asset ratio (fixed assets/total assets) to ensure robust estimates. (4) Firm Age (*Age*): Firm age is closely related to carbon emissions (Wei et al., 2013). We control for firm age, calculated as the logarithm of the difference between the accounting year and the founding year. (5) Leverage Ratio (*LAR*): Debt pressure also affects firms' willingness to adopt emission reduction measures (Yang & Fang, 2020). We control for the leverage ratio (total liabilities/total assets) in the basic model. (6) Supply Chain Relationship Intensity (SCR): Trade orders directly influence the interactions within supply chains (Guan et al., 2015). We measure *SCR* as the ratio of procurement from suppliers (or sales to customers) to total transactions and control for the impact of supply chain relationships on carbon emissions. (7) Export Status (*Exporter*): International trade is causally linked to emission reduction investments, with exporters more likely to invest in such measures (Kwon et al., 2023). We control for export status, assigning a value of 1 if a firm's export volume exceeds zero, and 0 otherwise.

4.3. Data

This study estimates the impact of GVC position upgrading on supply chain carbon emissions based on data from Chinese A-share listed firms and their suppliers and customers from 2010 to 2014. The data used in this study are sourced from China Stock Market & Accounting Research Database (CSMAR), Chinese National Tax Survey Database (CNTSD), World Input-Output Database (WIOD), Chinese Customs Trade Statistics (CCTS), and business credit websites. The CSMAR Database provides basic information and financial data disclosed by Chinese listed firms. Data on suppliers' and customers' names, as well as procurement (or sales) shares, are extracted from the annual reports of A-share listed firms in the CSMAR Database. The CNTSD covers tax records from 2007 to 2016, encompassing firms across various regions, industries, and sizes in China. The data on energy consumption, addresses, age, firm size, profitability, fixed assets, leverage ratio, and export status for suppliers or customers come from the CNTSD. Taxpayer identification numbers (TINs) and missing data on addresses, industries, and age are manually collected and supplemented using the credit investigations database of National Enterprise Credit Information Publicity System and notable platforms, like qcc.com and tianyancha.com. The WIOD offers world input-output tables and foundational data for 43 countries and 56 sectors from 2000 to 2014, which are used to calculate China's industry-level forward and backward average production lengths. The CCTS, covering 2000 to 2016, provides firm-product-level import and export values, quantities, and information such as firm names, phone numbers, and postal codes. Firm-product-level trade data are obtained from the CCTS.

This study integrates the above-mentioned databases to construct a unique panel dataset encompassing firms' GVC activities and the energy and economic activities of their suppliers or customers. The merging process is as follows: (1) Matching CCTS with CSMAR Database: Using firm names, postal codes, and phone numbers, we match firm-product-level data from the CCTS to A-share listed firms in the CSMAR database. (2) Matching CCTS with WIOD: Based on the Central Product Classification (CPC) Correspondence Tables published by the United Nations Statistics Division, we convert the Harmonized System (HS) codes in CCTS to ISIC Rev. 4 industry codes in the WIOD, obtaining firm-product-industry-level data related to GVC activities. (3) Matching CSMAR with CNTSD: Using the names of the top five suppliers and customers disclosed in the annual reports of A-share listed firms in CSMAR, we manually retrieve suppliers and customers' TINs from credit investigations database. These TINs and names are then used to match energy and economic activity data of suppliers and customers from the CNTSD to the firm-product-industry dataset. Thus, we build firm-supplier and firm-customer panel datasets that include GVC activities and supply chain energy and economic activities.

The merged dataset undergoes the following cleaning procedures: First, we exclude samples that do not clearly disclose the top five suppliers or customers. Second, we remove samples with missing key variables such as import-export activities, energy consumption, firm size, and profitability. Third, to mitigate the impact of outliers, we employ a 1% two-tailed trimming process on all non-binary variables. Finally, we obtain 2016 firm-supplier pairs and 6872 firm-customer pairs for the period 2010-2014. Descriptive statistics of the variables are presented in Table 2.

Table 2. Descriptive statistics.

Variable	**Panel A**: A-share listed firms and their suppliers					**Panel B**: A-share listed firms and their customers				
	Obs	**Sd**	**Mean**	**Max**	**Min**	**Obs**	**SD**	**Mean**	**Max**	**Min**
CO2Em	2016	3.4602	15.8497	23.3228	8.5673	6872	3.2566	15.9828	23.6033	8.5673
GVC_pos	2016	0.3537	0.7876	1.2650	0.0000	6872	1.1508	0.7451	1.2740	0.0000
Scale	2016	1.7625	5.9460	10.1364	1.5041	6872	1.8879	6.8483	11.2054	1.6094
Profit	2016	0.1164	0.0361	0.6332	-0.3823	6872	0.2123	0.0430	0.9884	-1.6693
FA	2016	0.1971	0.1991	0.7961	0.0000	6872	0.2054	0.1922	0.8159	0.0000
Age	2016	0.6338	2.2745	3.4965	0.0000	6872	0.6774	2.2849	3.4965	0.0000
LAR	2016	0.2527	0.6582	1.4608	0.0000	6872	0.2408	0.6345	1.2959	0.0000
SCR	2016	7.3650	7.2403	42.5200	0.9300	6872	7.5724	6.9713	51.4500	0.5800
Exporter	2016	0.4775	0.6488	1.0000	0.0000	6872	0.4701	0.6704	1.0000	0.0000

5. Results

5.1. Baseline Results

Table 3 presents estimated results of the impact of firms' GVC positions on CO_2 emissions of upstream and downstream firms in Equation (1). Columns (1)-(4) report the coefficient estimates of GVC_pos_{it}. Columns (1) and (2) display the estimation results for the firm-supplier group. Both the estimated result without controls in Column (1) and the estimated result with controls in Column (2) show that the coefficient α_1 of GVC_pos_{it} is significantly negative, indicating that an improvement in a firm's GVC position significantly reduces its suppliers' carbon emissions. Columns (3)-(4)

present the estimation results for the customer panel. The results of columns (3)-(4) demonstrate that the coefficient α_1 of GVC_pos_{it} remains significantly negative at the 5% confidence level, regardless of whether control variables are included in the model. This suggests that firms positioned relatively upstream in the global production line are more effective in promoting emission reductions among their customers. A comparison between Columns (1)-(2) and Columns (3)-(4) reveals that the coefficient α_1 of GVC_pos_{it} in the supplier group is substantially larger than that in the customer group. This implies that the improvement in a firm's GVC position may have a greater impact on emission reduction for upstream firms than for downstream firms.

These findings are consistent with previous research. Ramanathan et al. (2014) demonstrate that the influence from customers could promote the emission reduction of supplier. Song et al. (2024) also note that customers' emission reduction signals can drive suppliers to reduce emissions. Meanwhile, Edeh and Vinces (2024) find that external knowledge from suppliers can enhance customers' environmental performance. Furthermore, Oshita (2012) identifies demand-side factors as crucial in influencing CO_2 emissions within supply chains. Anin et al. (2024) confirm that firms have a slightly greater impact on supplier emission reduction than on customers. Therefore, the benefits derived from improved GVC positions have spillover effects that promote emission reduction among both suppliers and customers, with a relatively stronger influence on suppliers.

Table 3. Baseline results of the impact of firms' GVC positions on CO_2 emissions of their suppliers and customers.

	Panel A: the impact of GVC position on suppliers' CO_2 emissions		**Panel B**: the impact of GVC position on customers' CO_2 emissions	
Variables	(1) CO2Em	(2) CO2Em	(3) CO2Em	(4) CO2Em
GVC_pos	-2.0945** (1.0448)	-2.3018** (0.9794)	-0.5260** (0.2193)	-0.5176** (0.1787)
_cons	17.4993*** (0.8264)	9.5789*** (0.8802)	16.3747*** (0.1661)	9.8786*** (0.2563)
Controls	NO	Yes	NO	Yes
Year	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes
R-squared	0.4003	0.6928	0.4134	0.6270
Obs.	2016	2016	6872	6872

Notes: ***, ** and * respectively indicate the significance of results at the 1%, 5% and 10% levels. Robust standard errors are in parentheses. Year and Firm respectively represent year fixed effect and firm fixed effect.

5.2. Robustness Test

5.2.1. Replacement of Independent Variable

To verify the robustness of our baseline estimates, we conduct an alternative measurement of firms' GVC position index (GVC_pos_{it}) using the Inter-Country Input-

Output table provided by the Organization for Economic Co-operation and Development (OECD-ICIO). Specifically, we calculate the GVC position index for each Chinese industry based on the OECD-ICIO table and reassess firms' GVC positions according to their import-export product shares within the OECD-ICIO industry classification. The estimation results using this alternative independent variable are presented in Columns (1)-(2) of Table 4. The coefficients of New_pos_{it} remain significantly negative in both supplier and customer panel estimations. These findings provide evidence supporting the robustness of our baseline results.

Table 4. Robustness test of replacing independent variable and controlling industrial production

	Replace independent variable		Control industrial production	
	Supplier	Customer	Supplier	Customer
Variables	(1) CO2Em	(2) CO2Em	(3) CO2Em	(4) CO2Em
New_pos	-2.5030** (1.1315)	-0.5519*** (0.1984)		
GVC_pos			-1.9479** (0.9841)	-0.5342*** (0.1794)
_cons	9.5052*** (0.8926)	9.8586*** (0.2557)	9.1674*** (0.8811)	9.7184*** (0.2538)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes
R-squared	0.6927	0.6270	0.7172	0.6388
Obs.	2016	6872	2016	6872

Notes: ***, ** and * respectively indicate the significance of results at the 1%, 5% and 10% levels. Robust standard errors are in parentheses. Year and Firm respectively represent year fixed effect and firm fixed effect.

5.2.2. Control the Impact of CO_2 Emissions During Industrial Production

Industrial sectors such as petroleum processing, coal processing, chemicals, construction materials manufacturing, and metal smelting distinctly generate sources of production-related carbon emissions (Cui et al., 2021). The spillover effects from firms are not confined to energy-related carbon emissions but may also extend to production-related emissions. Consequently, omitting production-related carbon emissions in these industries could potentially introduce bias into the baseline estimation results. To mitigate potential confounding effects from industrial production-related carbon emissions, we introduce a dummy variable representing industries with substantial carbon emissions and incorporate it into our model for re-estimating the coefficient of the independent variable GVC_pos_{it}. Following Cui et al. (2021), we define industries C25-26 and C30-32 in China's "Industrial Classification for National Economic Activities (GB-T 4754-2017)" as carbon-intensive industrial sectors during production and construct a dummy variable ($industry\_O_{in}$), which equals 1 if customers or suppliers belong to these industries and 0 otherwise.

The estimation results controlling for carbon-intensive industries during production are presented in Columns (3)-(4) of Table 4. The coefficients of GVC_pos_{it} remain significantly negative in both supplier and customer group estimations, with magnitudes consistent with the baseline estimates. These findings demonstrate that the negative impact of firms' GVC position upgrade on carbon emissions of upstream and downstream firms remains significant after accounting for potential influences from industrial production-related emissions, providing further evidence for the robustness of our baseline results.

5.2.3. Control for Province and Industry Fixed Effects

Substantial variations exist across provinces in environmental regulations and economic development levels, while industries differ significantly in technological characteristics, energy intensity, and production processes - all of which are closely associated with CO_2 emissions. To address potential confounding effects from different provinces and industries in assessing the impact of firms' GVC positions on supply chain CO_2 emissions, we incorporate province and industry fixed effects in baseline model for robustness checks. The estimation results with province fixed effects, presented in Columns (1)-(2) of Table 5, show that the coefficients remain significantly negative for both supplier and customer groups. These results indicate that provincial characteristics do not affect the emission reduction effects of firms' GVC position upgrade along the supply chain. Columns (3)-(4) display the estimation results with industry fixed effects added to the baseline model. The coefficients of GVC_pos_{it} show no significant deviation from the baseline estimates in both supplier and customer groups, suggesting that industrial characteristics do not influence baseline results. Our conclusions remain robust after accounting for both provincial and industrial characteristics in the baseline model.

Table 5. Controlling for province fixed effects, industry fixed effects and low-carbon city pilot.

	Province fixed effects		Industry fixed effects		Low-carbon city pilot	
	Supplier	Customer	Supplier	Customer	Supplier	Customer
Variables	(1) CO2Em	(2) CO2Em	(3) CO2Em	(4) CO2Em	(5) CO2Em	(6) CO2Em
GVC_pos	-1.7952** (0.7847)	-0.4151** (0.1775)	-2.5257** (1.0311)	-0.5962*** (0.1837)	-2.2419** (0.9842)	-0.4909*** (0.1766)
_cons	9.3370** (0.7337)	9.7963*** (0.2580)	10.1446*** (0.9231)	10.4020*** (0.2604)	9.5979*** (0.8833)	9.8905*** (0.2550)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	No	No	No	No
Industry	No	No	Yes	Yes	No	No

R-squared	0.7081	0.6416	0.7376	0.6643	0.6948	0.6288
Obs.	2016	6872	2016	6872	2016	6872

Notes: ***, ** and * respectively indicate the significance of results at the 1%, 5% and 10% levels. Robust standard errors are in parentheses. Year, Firm, Province and Industry respectively represent year fixed effect ,firm fixed effect, province fixed effect and industry fixed effect.

5.2.4. Eliminating Low-carbon City Pilot Interference

While regional emission reduction policies are partially absorbed by province fixed effects, our study might still be influenced by other overlapping policies. Particularly relevant to our research period is the Low-carbon City Pilot (LCCP) policy. In 2012, China's National Development and Reform Commission implemented this pilot program in Hainan Province and 28 cities including Beijing, Shanghai, Shijiazhuang etc., emphasizing the establishment of a responsibility system for greenhouse gas emissions control and clarifying the allocation and assessment of emission reduction tasks, which are closely related to local firms' emission reduction decisions (Yu & Zhang, 2021). To address potential interference from LCCP policy, we construct a dummy variable indicating whether supplier (or customer) is located in an LCCP city and incorporate it into Equation (1) for re-estimating the coefficient of GVC_pos_{it}. Columns (5)-(6) of Table 5 present the estimation results after controlling for the LCCP policy influence. The results show that both the coefficient values and confidence intervals of GVC_pos_{it} remain largely unchanged. Even after accounting for the potential impact of the LCCP policy, the negative effects of firms' GVC position upgrade on CO_2 emissions in both suppliers and customers remain robust.

5.2.5. Endogeneity

The baseline estimation model for identifying the causal relationship between firms' GVC position improvement and CO_2 emissions may be subject to potential endogeneity issues, including reverse causality and omitted variable bias. Specifically, both theoretical considerations and empirical evidence suggest that our estimation model might be influenced by unobserved factors. Moreover, the relationship between firms' GVC position and supply chain CO_2 emissions may not be random. Firms with relatively upstream positions in GVCs might select more environmentally friendly, low-carbon suppliers to maintain their market position. Additionally, GVC position improvement often coincides with lower carbon emissions. Customer aiming to achieve emission reduction targets might preferentially select suppliers with upstream positions in GVC trade.

To address potential endogeneity concerns, we employ an instrumental variable approach using two-stage least squares (2SLS) and re-estimate the model in Equation (1). Following Li and Zhang (2023), we construct two instrumental variables: the province-level average GVC position ($\mathrm{Average\_pos}_{it}$) and the industry growth rate-adjusted GVC position ($\mathrm{Outset\_pos}_{it}$). Results of 2SLS estimation based on instrumental variables are shown as Table 6. Columns (1)-(2) present the estimation results using $\mathrm{Average\_pos}_{it}$ as the instrument, while Columns (3)-(4) show the results using $\mathrm{Outset\_pos}_{it}$. The results indicate that the coefficients of GVC_pos_{it} remain significantly negative. The validity of our instruments is supported by the Kleibergen-Paaprk LM test, which rejects the underidentification hypothesis, and both the Cragg-Donald Wald F and Kleibergen-Paaprk Wald F tests, which indicate the absence of weak instrument problems. These findings demonstrate that our baseline results remain robust after accounting for potential endogeneity concerns.

Table 6. Results of 2SLS estimation based on instrumental variables.

	IV1: Average_pos		IV2: Outset_pos	
	Supplier	Customer	Supplier	Customer
Variables	(1) CO2Em	(2) CO2Em	(3) CO2Em	(4) CO2Em
GVC_pos	-3.9873** (1.8831)	-0.8731** (0.3833)	-10.5492** (4.6127)	-1.4118* (0.8191)
Kleibergen-Paaprk LM	16.363 (0.0001)	82.755 (0.0000)	23.473 (0.0000)	124.255 (0.0000)
Cragg-Donald Wald F	303.966	1415.528	45.696	383.779
Kleibergen-Paaprk Wald F	30.435	318.812	19.208	115.663
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes
Obs.	1935	6787	1935	6787

Notes: ***, ** and * respectively indicate the significance of results at the 1%, 5% and 10% levels. Robust standard errors are in parentheses. Year and Firm respectively represent year fixed effect and firm fixed effect. $Outset\_pos_{it} = GVC\_pos_{it_0} \times (1 + g)^{t-1}$, where $GVC\_pos_{it_0}$ is firm i's GVC position index at initial period t_0. g is the average growth rate of the firm's industry.

5.3. Mechanism Analysis

Building upon Hypotheses 2 and 3, which posit that financial and technological spillovers serve as potential mechanisms through which a firm's GVC position upgrading facilitates emissions reductions in upstream and downstream firms, we establish the following empirical model to examine these mechanisms:

$$Channel_{ijt} = \beta_0 + \beta_1 GVC_{pos_{it}} + \beta_2 Control_{ijt} + \lambda_i + \mu_t + \epsilon_{it} \quad (6)$$

Where $Channel_{ijt}$ is the mechanism variable.

5.3.1. Financial Spillovers of GVC Position Upgrade

The adoption of environmental equipment and green innovation initiatives by firms requires substantial financial support [85-86]. Trade credit serves as a crucial financing channel for firms, with evidence from China indicating that it even surpasses bank credit (Wang et al., 2024). Obtaining more trade credit of customers or reducing the trade credit occupation of suppliers can optimize cash flow management, thereby facilitating investments in environmental equipment and technologies, ultimately promoting emission reductions (Wu et al., 2012; Qiao et al., 2024).

To validate Hypothesis 2, which posits that firms' GVC position upgrading alleviates financing constraints for CO_2 emissions reduction in upstream and downstream firms through trade credit, we examine the relationship between firms'

GVC positions and trade credit. Supplier trade credit occupation (TCO) and customer trade credit acquisition (TCA) are measured by the natural logarithm of accounts receivable and accounts payable (AP) at year-end, respectively. The customer and supplier data are sourced from the CNTSD. In Table 7, Column (1) presents the impact of GVC position on suppliers' trade credit occupation. The significantly negative coefficient of GVC_pos_{it} indicates that firms' GVC position improvement significantly reduces trade credit occupation of suppliers. Column (4) demonstrates the effect of GVC position upgrading on customers' trade credit acquisition, showing a significantly positive coefficient. These findings collectively suggest that enhanced GVC position of the firm significantly has financial spillover effects in both upstream and downstream firms. Improved GVC position of firms can alleviate the financing constraints of their suppliers and customers on emission reductions through trade credit.

Table 7. Financial and technological spillovers of GVC position upgrade.

Variables	Supplier			Customer		
	(1) TCO	(2) R&D	(3) EP	(4) TCA	(5) R&D	(6) EP
GVC_pos	-0.8731*	0.0124**	0.0680**	0.2451**	0.0055***	-0.0004
	(0.4635)	(0.0057)	(0.0346)	(0.1038)	(0.0020)	(0.0002)
_cons	8.3320***	0.0011	0.0130	5.8524***	0.0171***	-0.0000
	(0.4790)	(0.0060)	(0.0559)	(0.1574)	(0.0027)	(0.0002)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.5939	0.5070	0.4897	0.7648	0.4628	0.3132
Obs.	1887	1232	1332	6489	4743	5006

Notes: ***, ** and * respectively indicate the significance of results at the 1%, 5% and 10% levels. Robust standard errors are in parentheses. Year and Firm respectively represent year fixed effect and firm fixed effect.

5.3.2. Technological Spillovers of GVC Position Upgrade

Innovation serves as a crucial mechanism for improving environmental performance (Gilli et al., 2014). The application of green technologies has been shown to facilitate firms' emission reductions (Wei et al., 2020). As proposed in Hypothesis 3, firms' GVC position upgrading not only enhances production technology innovation but also generates green technology spillover effects on upstream and downstream firms. To verify the technology spillover channel in Hypothesis 3, we examine the impact of firms' GVC positions on R&D investment (*R&D*) and the purchase of environmental protection equipment (*EP*) among their suppliers and customers. R&D investment (*R&D*) is measured as the ratio of R&D expenses to management expenses, while the purchase of environmental protection equipment (*EP*) is calculated as the ratio of investment in environmental protection equipment to newly added fixed assets for production and operation. The data of suppliers' and customers' R&D investment and the purchase of environmental protection equipment are sourced from CNTSD.

Columns (2) and (5) in Table 7 present the estimation results for suppliers' and customers' R&D investment, respectively. The significantly positive coefficients of

GVC position in both columns indicate that GVC position upgrading promotes innovation investment among both suppliers and customers. Columns (3) and (6) report the results for suppliers' and customers' purchase of environmental protection equipment, respectively. The significantly positive coefficient in Column (3) confirms that GVC position upgrading drives suppliers to adopt green technologies. However, in Column (6), the coefficient of GVC position fails to reject the null hypothesis at the 10% significance level, suggesting that GVC position upgrading may have no significant effect on downstream customers' purchase of environmental protection equipment. Based on the estimation results, technology spillovers from GVC position upgrading to downstream customers promote innovation and have a limited impact on the adoption of green technologies.

5.3.3. Moderating Effects of Green Innovation

We propose in Hypothesis 4 that corporate green innovation activities influence the spillover effects of GVC position upgrading. To verify the moderating effect of corporate green innovation activities, we construct the following model:

$$CO2Em_{ijt} = \rho_0 + \rho_1 GVC_{pos_{it}} + \rho_2 GI_{it} + \rho_3 GI_{it} \times GVC_{pos_{it}} + \rho_4 Control_{ijt} + \lambda_i + \mu_t + \sigma_n + \epsilon_{it} \quad (7)$$

Where GI_{it} represents firms' green innovation activities, and the sign of the coefficient ρ_3 for the interaction term $GI_{it} \times GVC_{pos_{it}}$ indicates the direction of the moderating effect of green innovation on the relationship between GVC position upgrading and emission reduction. If the coefficient ρ_1 of $GVC_{pos_{it}}$ is significantly negative and ρ_3 is also significantly negative, it suggests that firms' green innovation activities amplify the emission reduction effect of GVC position upgrading. Conversely, if ρ_1 is significantly negative while ρ_3 is significantly positive, it indicates that the emission reduction effect of GVC position upgrading diminishes as firms' green innovation activities increase.

The vector $Control_{ijt}$ represents control variables. Building upon Model (1), we incorporate the following firm-level controls: firm size (measured by the natural logarithm of the number of employees plus one), board size (measured by the natural logarithm of the number of directors plus one), firm age (measured by natural logarithm of the difference between the fiscal year and the establishment year plus one), operating cost ratio (measured by operating costs divided by operating revenue), and total asset growth rate (measured as (current total assets - previous year's total assets) / previous year's total assets). Additionally, to account for industry heterogeneity, we include customer (or supplier) industry fixed effects σ_n in Equation (7). To examine the moderating effect of green innovation activities on the spillover effects of improved GVC position, we construct two indicators: green innovation index (*GI1*) and green innovation quality index (*GI2*). Following Nameroff et al. (2004) and Deng et al. (2023), we develop the green innovation activity index (*GI1*) using the ratio of granted green patents to total granted patents. Additionally, drawing on Lahiri (2010) [92], we measure green innovation quality index (*GI2*) as the natural logarithm of the sum of citations received by green patents within two years plus one. The patent data, including green patents and their citations, are obtained from Chinese Research Data Services Platform (CNRDS).

Table 7 presents the estimation results of the moderating effect of green innovation activities on the spillover effects of improved GVC position upgrading. Columns (1)-

(2) show the moderating effect on the spillover impact of GVC position upgrading to suppliers, while Columns (3)-(4) display the moderating effect in the customer group. In Columns (1)-(2), the interaction terms between GI1, GI2 and $GVC_{pos_{it}}$ fail to reject the null hypothesis of being equal to zero, indicating that firms' green innovation activities do not significantly moderate the spillover effect of GVC position upgrading on suppliers. However, in Columns (3)-(4), the interaction terms are significantly negative, suggesting that firms' green innovation activities significantly amplify the emission reduction effect of GVC position upgrading for customers. This difference may stem from the fact that, compared to suppliers, firms' green innovation activities can be directly transmitted to customers through products and services, thereby enhancing the emission reduction effect of GVC position upgrading.

Table 8. Moderating effects of firms' green innovation activities.

Variables	Supplier		Customer	
	(1) CO2Em	(2) CO2Em	(3) CO2Em	(4) CO2Em
GVC_pos	-4.0159*** (1.4444)	-4.2018*** (1.4619)	-0.4052** (0.1990)	-0.4390** (0.2026)
GI1	-0.3395 (0.8099)		0.7117** (0.3004)	
GI1* GVC_pos	0.5161 (0.8242)		-0.8679*** (0.3133)	
GI2		-0.4918 (0.5115)		0.0777 (0.1591)
GI2* GVC_pos		0.7890 (0.6117)		-0.3230* (0.1723)
_cons	9.2858 (8.1184)	8.6572 (7.9641)	14.2896*** (3.0697)	13.9845*** (3.0830)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
R-squared	0.6680	0.6686	0.6133	0.6132
Obs.	1744	1744	6534	6534

Notes: ***, ** and * respectively indicate the significance of results at the 1%, 5% and 10% levels. Robust standard errors are in parentheses. Year, Firm and Industry respectively represent year, firm and industry fixed effect.

5.4. Heterogeneity Analysis

In Hypothesis 5, we propose that the spillover effect of GVC position upgrading on emissions reduction varies with the heterogeneity of both the firms themselves and their partner in supply chains. To test Hypothesis 5, we conduct a heterogeneity analysis focusing on two dimensions: firms' spillover capacity and the responsiveness of upstream and downstream firms.

5.4.1. Heterogeneity on Firms' Spillover Capacity

In Hypothesis 5, we propose that the spillover effect of GVC position upgrading on emissions reduction varies with the heterogeneity of both the firms themselves and their partners in supply chains. To test Hypothesis 5, we conduct a heterogeneity analysis focusing on two dimensions: firms' spillover capacity and the responsiveness of upstream and downstream firms.

(1) Ownership. Compared to non-state-owned enterprises (non-SOEs), state-owned enterprises (SOEs) possess abundant resources and stronger motivations for emissions reduction, leading to more pronounced spillover effects in supply chain decarbonization (Gong et al., 2024). Consequently, the impact of GVC position upgrading on carbon reduction in upstream and downstream firms may differ by ownership type. To examine this heterogeneity, we separately estimate the effects of GVC position upgrading on emissions reduction for SOEs and non-SOEs. In Columns (1) and (3) of Table 9, the coefficients of $GVC_{pos_{it}}$ fail to reject the null hypothesis of being zero, suggesting that ownership nature has a limited effect on spillover outcomes for supplier groups. However, in Columns (2) and (4), the coefficient of $GVC_{pos_{it}}$ for SOEs is statistically significant at the 5% level, indicating that SOEs' GVC position upgrading has a more pronounced spillover effect on customer emissions reduction.

(2) Industry Competition. Competition influences firms' spillover effects within supply chains (Kong et al., 2024). Under fierce competition, firms may pay greater attention to the environmental performance of their customers and suppliers for market strength (Shohan et al., 2020). To test the heterogeneous impact of industry competition on the spillover effects of GVC position upgrading, we divide the sample into high- and low-competition groups based on the median Herfindahl index (calculated using total assets to measure market share within industries). Columns (5)-(8) of Table 9 present the regression results for high- and low-competition groups. The absolute values of the coefficients of $GVC_{pos_{it}}$ in the high-competition group (Columns (5)-(6)) are significantly larger than those in the low-competition group (Columns (7)-(8)), indicating that GVC position upgrading has a more substantial impact on emissions reduction in upstream and downstream firms when industry competition is fiercer.

Table 9. Heterogeneity analysis on firms' spillover capacity.

Panel	Ownership				Industry competition			
	SOEs		non-SOEs		High-competition		Low-competition	
Variables	(1) Supplier	(2) Customer	(3) Supplier	(4) Customer	(5) Supplier	(6) Customer	(7) Supplier	(8) Customer
GVC_pos	-1.9866	-0.7020**	-1.9542	-0.3045	-3.6374**	-0.7040***	-2.7809*	-0.2719
	(1.5961)	(0.3188)	(1.2978)	(0.2225)	(1.5873)	(0.2560)	(1.6371)	(0.3515)
_cons	9.6487***	10.2147***	9.3066***	9.5884***	10.9730***	9.8712***	9.7364***	9.6943***
	(1.2649)	(0.4311)	(1.1998)	(0.3330)	(1.4872)	(0.3568)	(1.3278)	(0.4178)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.6805	0.6457	0.7055	0.6174	0.6678	0.6468	0.7299	0.6307
Obs.	586	2295	1329	4243	873	3203	1143	3669

Notes: ***, ** and * respectively indicate the significance of results at the 1%, 5% and 10% levels. Robust standard errors are in parentheses. Year and Firm respectively represent year fixed effect and firm fixed effect.

5.4.2. Heterogeneity on Responsiveness of Partner Firms

In addition to firms' spillover capacity, Hypothesis 5 posits that the impact of GVC position upgrading varies with the responsiveness of upstream and downstream firms. We further examine this heterogeneity by analyzing whether firms engage in processing trade and by firm size.

(1) Processing trade. Processing trade is closely linked to carbon emissions (Chen et al., 2019). Compared to other firms, those engaged in processing trade tend to have lower innovation capabilities (Deng et al., 2023), limiting the positive spillover effects of innovation on such firms (Mo & Jeon, 2021). Columns (1)-(4) of Table 10 present the estimation results for suppliers and customers engaged in processing trade. The coefficients of $GVC_{pos_{it}}$ in Columns (1)-(2) and (4) are indistinguishable from 0, while the coefficient of non-processing trade suppliers in Column (3) is significantly negative. These results suggest that GVC position upgrading significantly inhibits emissions reduction among non-processing trade suppliers, whereas this effect is less pronounced for processing trade suppliers and customers.

(2) Firm size. The emissions reduction effects exhibit heterogeneity across firm sizes (Cagno et al., 2018). To test this, we divide the sample into large and small firms based on the median asset size of suppliers and customers. As shown in Columns (5)-(8) of Table 10, GVC position upgrading has a more significant impact on emissions reduction for large suppliers and customers. This may be attributed to the fact that, compared to small firms, large firms possess greater financial resources and face stricter external regulatory pressures (Meng et al., 2018), making them more responsive to supply chain decarbonization. Consequently, the spillover effects of GVC position upgrading are more pronounced for large firms.

Table 10. Heterogeneity analysis on responsiveness of partner firms.

Panel	Processing trade				Firm size			
	Processing trade		Non-processing trade		High-competition		Low-competition	
Variables	(1) Supplier	(2) Customer	(3) Supplier	(4) Customer	(5) Supplier	(6) Customer	(7) Supplier	(8) Customer
GVC_pos	-0.4242	-0.1876	-2.9056**	-0.3543	-4.1920***	-0.8051***	0.4554	-0.0958
	(1.1783)	(0.2945)	(1.3383)	(0.2156)	(1.4734)	(0.2472)	(0.8085)	(0.2522)
_cons	7.7042***	8.3869***	0.7011***	10.4940***	11.2862***	12.6408***	8.1591***	9.1155***
	(1.1578)	(0.4278)	(1.1984)	(0.3639)	(1.5541	(0.4835)	(0.8722)	(0.3726)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.8175	0.7412	0.7011	0.6542	0.7015	0.6144	0.6547	0.6363

Obs.	837	3076	1179	3796	1007	3423	1009	3449

Notes: ***, ** and * respectively indicate the significance of results at the 1%, 5% and 10% levels. Robust standard errors are in parentheses. Year and Firm respectively represent year fixed effect and firm fixed effect.

6. Conclusions and Implications

Upgrading GVC positions serves as a breakthrough in resolving the tension between participation in global production and CO_2 emissions. Meanwhile, supply chain relationships also influence firms' emissions reduction decisions. This study examines the impact of firms' global value chain (GVC) position upgrading on CO_2 emissions of upstream and downstream firms, as well as the underlying mechanisms, using merged data from CSMAR, CCTS, WIOD, and CNTSD for the period 2010–2014. Based on the measurement of GVC positions of Chinese A-share listed firms and the CO_2 emissions of their supply chain partners, we empirically analyze the spillover effects of GVC position upgrading on CO_2 emissions of their suppliers and customers, explore the mechanisms and the heterogeneity on upstream and downstream firms. The main findings are as follows:

First, GVC position upgrading significantly reduces CO_2 emissions of both suppliers and customers. This conclusion remains robust after replacing explanatory variables, controlling for emissions from industrial production, province and industry fixed effects, excluding the influence of low-carbon policies, and addressing endogeneity concerns. Second, GVC position upgrading reduces carbon emissions through financial and technological spillover channels. It decreases trade credit occupation by suppliers while increasing trade credit provision to customers. At the same time, upgrading GVC positions promotes R&D investment in both upstream and downstream firms. Notably, it has a particularly positive effect on the adoption of green technologies by suppliers. Firms' green innovation activities further amplify the positive effect of GVC position upgrading, particularly in promoting emissions reduction among customers. Third, the impact of GVC position upgrading on emissions reduction varies with the heterogeneity of firms and their upstream and downstream partners. Specifically, the carbon reduction effect is more pronounced from SOEs and firms in highly competitive industries. Additionally, GVC position upgrading has a stronger emissions reduction effect on non-processing trade suppliers and larger-sized suppliers and customers.

The policy implications of this study are as follows: First, firms should be encouraged to move upstream in the global production chain. Our findings demonstrate that GVC position upgrading positively contributes to supply chain emissions reduction. Extending production lines and moving toward higher value-added upstream activities are crucial for promoting green development in supply chains. Policymakers should pay greater attention to the green development effects of GVC position upgrading and actively support firms in enhancing their GVC positions. Second, collaboration between upstream and downstream firms in the supply chain should be strengthened. GVC position upgrading promotes emissions reduction through financial and technological spillovers, while firms' green innovation activities further enhance this effect. Governments and firms should focus on spillover effects in customer-supplier relationships, encourage green supply chain management, foster more cooperation among supply chain partners, improve supply chain financing efficiency, and support the establishment of green technology-sharing platforms. Finally, the heterogeneity of firms' spillover capacity and responsiveness should be addressed. SOEs should play a leading role in green supply chains, and a favorable market environment should be cultivated to leverage the dominant role of market competition in promoting emissions reduction. Efforts should be made to facilitate the transformation and upgrading of processing trade firms, enhancing their green and sustainable development capabilities. Meanwhile, stricter supervision and guidance should be provided to small and medium-sized enterprises (SMEs) to encourage their participation in supply chain emissions reduction initiatives.

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