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Research on the coupling of cross-border e-commerce trade and regional green economy development under the "double carbon" target —— Take the Yangtze River Delta region as an example

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Abstract

In the context of the global response to climate change and the implementation of the "two-carbon" strategy, the synergistic relationship between the explosive growth of cross-border e-commerce trade and the regional green economy transformation urgently needs to be scientifically deconstructed. As an important engine of China's economic development, the choice of green development path in the Yangtze River Delta region plays an exemplary role in the sustainable development of the whole region and even the country. Through the empirical investigation of the Yangtze River Delta region, using the coupling degree model, analyzes the coupling coordination and influencing factors be-tween the two, and puts forward the countermeasures of coordinated development.

Keywords

Dual-carbon target; cross-border e-commerce; green economy; coupling and coordination; Yangtze River Delta region

1. Introduction

Under the dual background of the accelerated evolution of global climate governance and the rigid constraints of China's "double-carbon" goal, the regional economic development model is facing a deep change from "scale expansion" to "green efficiency". As the growth pole of global digital trade, China's cross-border e-commerce transactions have maintained a growth rate of more than 20% for five consecutive years, reaching 15.7 trillion yuan in 2022, accounting for more than 35% of the trade in goods. However, the carbon footprint problem of cross-border e-commerce industry chain gradually emerges: the carbon emission intensity of in-

ternational aviation logistics is more than 50 times that of sea shipping, the energy consumption of electronic payment data center accounts for 2.3% of the national total electricity consumption, and its environmental externalities and "two-carbon" strategy form realistic tension.

As the national two-carbon strategic pilot zone and the national comprehensive pilot zone of cross-border e-commerce, cross-border e-commerce accounted for 46.8% of the country in 2022, but the carbon emission per unit GDP (0.89 tons / 10,000 yuan) is still higher than the level of the same period (0.62 tons / 10 thousand yuan). This contradiction reveals two core issues: First, does the trade facilitation brought about by cross-border e-commerce inevitably lead to the loss of "green premium"? Second, can the transformation of regional green economy achieve "emission reduction without reducing growth" through digital trade technology innovation? At present, the discussion on the relationship between traditional trade and environment has been mature, but there is still a research gap between the coupling mechanism of cross-border emerging form of e-commerce and green economy. Therefore, this project will conduct an empirical investigation in the Yangtze River Delta region, adopt the coupling degree model, analyze the coupling and coordination relationship and influencing factors between the two, and put forward the coordinated development countermeasures of the two. The research in this paper not only provides a theoretical basis for understanding the role of cross-border e-commerce in promoting the development of regional green economy, but also provides practical guidance for the Yangtze River Delta region and even other regions to achieve the goal of "double-carbon".

2.Analysis of the coupling and coordination mechanism of cross-border e-commerce trade and regional green economy development

2.1 Positive synergy mechanism

Digital technology innovation, as the driving engine, not only reduces the transaction costs by optimizing the transaction process and improving the efficiency of the supply chain, but also promotes the green transformation of the energy structure. The strengthening of environmental regulation provides an institutional guarantee for this transformation, and the establishment of strict environmental protection standards and incentive mechanisms guides enterprises to the direction of green and low-carbon development. At the same time, the rise of green consumer demand has become the driving force of the market. Consumers' preference for environmentally friendly products is transmitted to the production end through market signals, forcing all links of the supply chain to carry out green transformation. The synergistic effect of these three factors jointly promotes the deep integration and efficient development of cross-border e-commerce and green economy. This cooperative mechanism realizes the energy exchange of the system through the three paths

of "reducing cost and increasing efficiency", "demand traction" and "system enabling", and promotes the evolution of the dual system from low-level equilibrium to high-order coordination.

1. Carbon reduction in digital technology: transaction cost reduction and energy structure optimization

The digital tools of cross-border e-commerce (such as intelligent warehouse segmentation algorithm and blockchain traceability) reduce the multi-level turnover of "production-distribution-retail" in the traditional trade by reducing the supply chain level, and directly reduce the fossil energy consumption in the storage and transportation links. According to the new geoeconomic theory (Krugman, 1991), the spatial reconstruction ability of digital platforms can promote enterprises to concentrate in renewable energy enrichment areas, forming a low-carbon layout of "digital guidance-energy matching". The "Smart Logistics Hub" of Shanghai Yangshan Port optimizes the container loading rate through AI algorithm (increased to 92%), and reduces the empty mileage by 1.8 million kilometers in 2022, equivalent to an annual carbon reduction of 43,000 tons.

2. Green demand traction: preference transmission and supply chain transmission

According to the theory of consumer behavior (Ajzen, 1991), cross-border e-commerce platforms accurately capture green consumption preferences through user portraits (such as increasing the click-through rate of low-carbon label goods by 27%) through user portraits, and form a "demand signal-supply response" transmission chain with the help of algorithm recommendation. This market-driven mechanism forces manufacturers to adopt cleaner production processes, creating a "green premium" market equilibrium. Ningbo "Cross-border green code" pilot: consumers can scan the QR code of goods to view the carbon emission data of the whole life cycle, and the repurchase rate of low-carbon label goods in 2023 is 41% higher than that of ordinary goods."Green supplier White List" in Suzhou: Amazon Suzhou Seller Center gives traffic preference to enterprises using renewable packaging, promoting the transformation of local packaging enterprises, and the utilization rate of biodegradable materials increased from 12% in 2020 to 58% in 2023

3. Policy collaborative innovation: internalization of institutional complementarity and externalities

According to the institutional synergy theory (North, 1990), the connection of "domestic and outside customs" policies of cross-border e-commerce and carbon market trading rules can transform the environmental externalities of cross-border trade into endogenous costs of enterprises through tools such as "carbon tariff deduction" and "green letter of credit". This system coordination can break through the "policy island" and realize the Pareto improvement of environmental regulation and trade facilitation. Nanjing pilot project of "carbon tariff pre-payment": enterprises can purchase quotas through the Yangtze River Delta carbon market to offset the EU CBAM carbon cost. In the first year of the pilot project, 120 million yuan of

cross-border compliance costs were saved for enterprises.

2.2 Negative-direction arrest mechanism

As David pointed out in 1985, the phenomenon of path dependence plays a significant role in restricting the integration of cross-border e-commerce and the green economy. This dependence leads to the inertia of technology development, making it difficult for the industry to get rid of the shackles of old technologies, thus forming the so-called "technology lock". At the same time, the institutional friction emphasized by Acemoglu in 2006 also played a key role in this process. Differences in environmental standards and regulations between different countries and regions cause "standard conflicts", which makes cross-border transactions face additional compliance costs and complexity. In addition, due to the lack of a unified international governance framework, the promotion and implementation of green economy often encounter the problem of "fragmented governance fragmentation", which further aggravates the difficulty of the integration of the two. These challenges not only hinder the sustainable development of cross-border e-commerce, but also pose obstacles to the advancement of the global green economy. These negative effects are further amplified in the context of regional heterogeneity, creating a systematically synergistic damping effects.

1. Carbon lock in cross-border logistics: inertia dependence and technological substitution barriers

According to the theory of technical locking effect, air transport forms "high carbon path dependence" due to the timeliness advantage. Even with low-carbon alternative technologies (such as hydrogen freighters), sunk costs of infrastructure (such as airport expansion investment) and operational network solidification (such as route franchising) cause resistance to transformation. Pudong Airport cargo dilemma: In 2023, international aviation kerosene price fluctuations will lead to a 23% increase in cross-border e-commerce logistics costs, but due to the insufficient endurance of hydrogen freighters (only 1,200 km), it cannot replace the existing intercontinental routes.

2. Cross-border transfer of e-waste: regulatory vacuum and responsibility escape

According to the environmental regulation capture theory (Stigler, 1971), there is room for "regulatory arbitrage" in the cross-border e-commerce return mechanism. Some enterprises use "personal goods" customs clearance channels to falsely report electronic waste (such as waste lithium batteries) to avoid the extended producer responsibility system (EPR) and transfer the cost of environmental governance."Cross-border return pollution" incident in Wenzhou: In 2022, a cross-border e-commerce platform declared 23,000 tons of returned electronic products as "second-hand personal goods", which actually contained lead and mercury by 40 times, and the subsequent pollution control cost reached 58 million yuan.

3. International conflict of green standards: institutional game and market segmentation

Based on the institutional complexity theory (Greenwood et al., 2011), there is a conflict between RCEP and EU CBAM in carbon accounting methods (range 1-3) and mutual recognition of certification bodies. This institutional friction forces enterprises in the Yangtze River Delta to maintain "double production standards" and increase the application cost of green technology. Changzhou photovoltaic module "double-line production": In order to meet the EU carbon footprint traceability requirements, enterprises need to open separate production lines conforming to EPD certification, resulting in a 15% increase in unit cost and compressed export profit margin.

3. Empirical study on the coupling and coordinated development of cross-border e-commerce trade and regional green economy —— Take the Yangtze River Delta region as an example

3.1 Construction of indicators

This study is based on the OECD "pressure-state-response" (PSR) model building cross-border electricity trade system and the evaluation of regional green economy system, the core basis is the model can fully depict the "economic activity pressure-environmental state change-subject behavior response" dynamic causal chain, break through the static section analysis of traditional index system limitations. For the cross-border e-commerce trade system, the pressure layer design focuses on the environmental externalities (such as the transaction volume and the "scale effect" hypothesis in the environmental Kuznets curve; the state layer quantifies the substitution degree of high carbon link through the green certification rate of overseas warehouse and the replacement rate of electronic documents, reflecting the carbon reduction mechanism of technology-system coordination; the response layer introduces market autonomy tools, such as carbon integral incentive of the platform, to reveal the endogenous pollution control power of enterprises under the voluntary environmental agreement theory. In the dimension of regional green economy system, the pressure layer index (such as energy consumption per unit GDP) identifies the tension relationship between economic growth and resource consumption through the theory of ecological economic decoupling, tracks the S-shaped curve pattern of the diffusion and captures the interaction effect of the government regulation and market tools with the proportion of environmental protection expenditure and carbon market transaction volume. Through the PSR framework of causal chain nesting, this study for the first time in the field of digital trade and green economy cross implementation "scale pressure-technology state-policy response" the whole process of explicit analysis, both make up for the traditional neglect of dynamic feedback mechanism, and through the response layer index and Yangtze river delta integration policy kit (such as carbon integral mutual recognition, cross-border green finance) direct

mapping, enhance research conclusion of regional collaborative governance targeted guidance value.

Table 1. Comprehensive evaluation system of cross-border e-commerce trade and regional green economy development

Level 1 indicators	Secondary indicators	Level 3 indicators
Cross-border E-commerce Trading System (ECS)	Pressure layer (P)	Cross-border e-commerce transaction volume (RMB 100 million yuan)
		The average annual growth rate of cross-border parcel volume is (%)
	State layer (S)	Overseas warehouse green certification rate of (%)
		Electronic document replacement rate of (%)
		Carbon emission per unit (kg CO_2 / single)
	Response layer (R)	The proportion of platform carbon credits incentive merchants is (%)
		Return packaging recycling rate (%)
The Regional Green Economy System (GES)	Pressure layer (P)	Energy consumption per unit of GDP (per ton of standard coal / ten thousand yuan)
		Discharge intensity of industrial wastewater (ton / ten thousand yuan)
	State layer (S)	Renewable energy power generation accounts for (%)
		Transaction volume of green technology market (100 million yuan)
	Response layer (R)	The proportion of environmental protection expenditure in fiscal expenditure is (%)
		Carbon market transaction volume (RMB 100 million yuan)

3.2 Data sources

This paper selects the data of cross-border e-commerce trade and regional green economy development from 2016 to 2022 for analysis; the cross-border e-commerce data comes from the monitoring platform of cross-border E-commerce Comprehensive Pilot Zone of the General Administration of Customs (2016-2022), and the green economy data comes from the statistical Yearbook of three provinces and one city in the Yangtze River Delta.

3.3 Methods and the model

(1) Entropy method

(a) Standardize the original index data to eliminate the impact of different index units.

$$z_{ij} = \frac{x_{ij} - \min\{x_{1j}, x_{2j}, ..., x_{nj}\}}{\max\{x_{1j}, x_{2j}, ..., x_{nj}\} - \min\{x_{1j}, x_{2j}, ..., x_{nj}\}} \quad (1)$$

（b）Calculate the weight of each index. The normalized values were used for the following operation.

Calculate the proportion of each index;

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}} \quad (2)$$

In（2）, Zij represents the standardization of each indicator data
According to the definition of information entropy in information theory, the information entropy of a set of data;

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij} \ln p_{ij} \quad (3)$$

In（3）, P ij is the proportion of each indicator
The weight of each index is calculated by the information entropy:

$$w_j = \frac{1-e_j}{n-\sum_{j=1}^{m} e_j} \quad (4)$$

In（4）, ej represents the information entropy of each index obtained
(3) Calculate the comprehensive score

$$s_{ij} = \sum_{j=1}^{m} w_{ij} p_{ij} \quad (5)$$

In（5）, Wij represents the weight of each indicator

(2) Coupled coordination model
The coupling coordination model is adopted to measure the dependence relationship between cross-border e-commerce and regional green economy development. U1 and U2 are the comprehensive evaluation scores of cross-border e-commerce and regional green economy development respectively. The coupling degree of cross-border e-commerce and regional green economy system is calculated through formula（6）C:

$$C=\frac{2\sqrt{U_1 \times U_2}}{U_1+U_2} \quad (6)$$

Calculate the coupling and coordination degree of cross-border e-commerce and regional green economy system D:

$$D=\sqrt{C \times T}, \quad T=\alpha U_1 + \beta U_2 \quad (7)$$

In the formula, T represents the comprehensive evaluation index of the two systems, and represents the evaluation weight coefficient of the two systems, where the value is 0.5.

3.4 Empirical analysis

(1)Coupled and coordination analysis
Based on the evaluation index system of cross-border e-commerce and regional green economy, the entropy method is used to measure the weight of each index, and the results are as follows.

Table 2. Weight measure

metric	weight

Cross-border e-commerce transaction volume (RMB 100 million yuan)	0.1187
The average annual growth rate of cross-border parcel volume is (%)	0.1260
Overseas warehouse green certification rate of (%)	0.1598
Electronic document replacement rate of (%)	0.1312
Carbon emission per unit (kg CO_2 / single)	0.1439
The proportion of platform carbon credits incentive merchants is (%)	0.1070
Return packaging recycling rate (%)	0.1596
Energy consumption per unit of GDP (per ton of standard coal / ten thousand yuan)	0.1641
Discharge intensity of industrial wastewater (ton / ten thousand yuan)	0.1342
Renewable energy power generation accounts for (%)	0.1257
Transaction volume of green technology market (100 million yuan)	0.1189
The proportion of environmental protection expenditure in fiscal expenditure is (%)	0.1148
Carbon market transaction volume (RMB 100 million yuan)	0.1177
Cross-border e-commerce transaction volume (RMB 100 million yuan)	0.1305
The average annual growth rate of cross-border parcel volume is (%)	0.1280
Overseas warehouse green certification rate of (%)	0.1181

As can be seen from Table 2, the economic share of e-commerce occupies a high proportion, indicating that the operation scale of cross-border e-commerce plays an important role in cross-border e-commerce, and the development potential plays an important role in the development of cross-border e-commerce. The high proportion of enterprise profits to the regional green economy level, indicating that the economic benefits of entrepreneurial enterprises are still the first priority for the improvement of the regional green economy level.

The coupled dynamic evolution of cross-border e-commerce and regional green economy development is shown in the following table (figure):

Table 3. The coupling degree evolution

a particular year	degree of coupling
In 2016,	0.8166
In 2017,	0.9622
In 2018,	0.9897
In 2019,	0.9912
In 2020,	0.9799
In 2021,	0.9991
In 2022,	0.9963

From Table 3, the coupling between the two systems has been at a high level, almost since 2016.

Table 4. Coupled coordination degree evolution

a particular year	Coupling coordination degree
In 2016,	0.3529
In 2017,	0.4511
In 2018,	0.5065
In 2019,	0.6131
In 2020,	0.6518
In 2021,	0.7246
In 2022,	0.8016

From table 4 to see, cross-border electricity and regional green economy development of coupling coordination only 0.3819, after a few years, the two systems of coupling coordination rising, in 2021, the coupling of the two systems coordination has reached 0.9173, experienced the moderate imbalance, basic coordination, mod-

erate coordination until highly coordination, that in 2016, the two systems in the moderate disorder stage, the cross-border electricity and regional green economy development at a low level mutual inhibition, in 2021, cross-border electricity and regional green economy development to achieve mutual promotion at a high level.

4. Countermeasures to optimize the coordinated development of cross-border e-commerce and green economy

4.1 Strengthen the design of multi-level coordination mechanism

1)Institutional coordination: crack the fragmentation of cross-border carbon governance

In view of the policy separation and regulatory blind spots in the carbon governance of cross-border e-commerce, it is necessary to build a cross-regional and cross-departmental institutional coordination framework. In Shanghai lingang new area for the pilot, take the lead in cross-border electricity carbon quota control mechanism, the aviation logistics, data center, high carbon link into the Yangtze river delta carbon market regulation, mandatory annual turnover over 1 billion yuan of enterprises disclosure whole life cycle of carbon footprint, and refer to the eu CBATM standard establish carbon tariff prepayment system, prevent carbon leakage risk. At the same time, set up the Yangtze river delta green cross-border electricity development fund, for hydrogen storage, recycling packaging low carbon technology enterprises provide 30% to 50% of the fixed assets investment subsidies, and draw lessons from Hangzhou "carbon integral bank" mode, allows enterprises to carbon emissions into cross-border payment fee reduction amount (per ton CO_2 equivalent deduction 0.5% fee), through the "hard constraints + soft incentive" policy combination crack governance fragmentation problem. For example, after the pilot carbon quota trading in Suzhou in 2023, the cross-border logistics cost of enterprises was reduced by 12%, while Ningbo promoted 87 merchants to complete green packaging transformation through the carbon point exchange mechanism, forming replicable regional coordination experience.

2)Industrial synergy: reconstructing the spatial layout of the green supply chain

In order to resolve the carbon locking effect of cross-border e-commerce logistics, it is necessary to reshape the green supply chain network of "hub-channel-node" linkage. Promote the construction of "zero-carbon international hub port" in core hubs such as Shanghai Pudong Airport and Ningbo Zhoushan Port, supporting photovoltaic ceiling and hydrogen filling facilities, aiming to achieve 100% green electricity coverage of operation by 2025; open "Yangtze River Delta-ASEAN green freight train", implement high-speed toll free policy for cross-border trucks using biodiesel or liquefied natural gas, and promote the replacement of China-Europe trains (Yiwu-Madrid), and plan to reduce the carbon emission intensity of unit value by 22% before 2027. In inland node city to promote "overseas warehouse + distributed photovoltaic" construction mode, relying on the grid straight for lower storage

cost (such as Jiaxing bonded warehouse photovoltaic project price fell 40%), and through the Yangtze river delta renewable energy trading platform across the provincial green card circulation, forming "coastal hub low carbon-inland node greening-international channel clean" the whole chain space optimization pattern.

4.2.Realize key breakthroughs in the green technology collaborative innovation network

1) Technological innovation: digital tools drive the whole chain of carbon reduction
Focusing on the problem of cross-border transfer of e-waste, it is necessary to build a closed-loop of "monitoring-traceability-disposal" technology. AI customs inspection system is deployed in Pudong, Hongqiao and other airports, using X-ray image recognition and material spectrum analysis to increase the e-waste seizure rate to more than 95%; mandatory "carbon ID card" QR code for return packages, record the carbon track of the whole life cycle of goods through block chain, and collect 200% environmental deposit for enterprises not realizing closed-loop disposal. At the same time, intelligent sorting centers will be built in Suzhou and Wuxi, and robot sorting technology will be used to recycle more than 90% of materials, and residual waste will be transferred to Haimen hazardous waste incineration plant for centralized treatment, forming a technical management system covering "entry screening, process traceability and terminal disposal". According to the pilot project of Shenzhen Bao'an Airport, the AI monitoring system can improve the detection accuracy to 92%, while the experience of the German EPR system shows that the environmental margin mechanism can effectively reduce the risk of cross-border e-waste transfer by 65%.
2)Market incentive: transformation of green finance
Based on the significant driving effect of green finance on the coupling and coordination degree, the three-dimensional product matrix of "loan-debt-guarantee" should be designed. For the top 20% of the ESG merchants, provide the "green flow loan", the loan amount is linked to carbon emission reduction; support the head enterprises to issue "blue bonds" for the construction of hydrogen ships and low-carbon overseas warehouse, the local finance will give 3-year discount subsidy; the innovation and development of "carbon tariff fluctuation risk", and the insured enterprises can receive 70% compensation for the loss caused by the increase of the EU CBBAM tax rate. In 2023, Suzhou issued the first green cross-border e-commerce bond, raising 850 million yuan for intelligent storage photovoltaic transformation, and reduced the emission of 18,000 tons of CO annually; after PICC pilot carbon tariff insurance, the export compliance cost of enterprises decreased by 21%, verifying the effectiveness of the market incentive tool.

4.3.Modernize the linkage and governance capacity of cross-border e-commerce and green economy policies

1) Digital regulatory infrastructure upgrading

To solve the data island problem of cross-border e-commerce, cross-border carbon governance cloud platform is needed to integrate multi-department data to realize three functions: real-time collection of storage and logistics energy consumption data through the Internet of Things sensor, generate regional carbon footprint heat map every 15 minutes; use machine learning to identify "high carbon package" feature combination (such as air transportation and plastic packaging accounting for over 80%), automatically push risk warning list; build policy simulation sandbox, input carbon tax, subsidy and other parameters can predict the marginal impact on enterprise profit margin and regional carbon emission (error rate ± 3%). According to the trial operation of Hangzhou Airport Free Trade Zone, the platform has increased the regulatory response speed by 40% and reduced the carbon accounting cost of enterprises by 35%, providing a technical base for precise policies.

2)Multi-subject co-governance network

It is necessary to construct a "platform-government-consumer" co-governance mechanism, force cross-border e-commerce platform exceeding 5 billion-yuan to set up "Green Governance Committee", independently review the performance of environmental protection commitment of merchants, and limit the traffic exposure; incorporate cross-border e-commerce green performance into the mayor environmental protection target responsibility system assessment (weight 10%), reward land index for cities with coordinated annual increase of more than 15%; expand the cross-border application scenario of "personal carbon account", and consumers can purchase low-carbon goods for cross-border tax-carbon quota. After the "application" was connected to the personal carbon account, 3 million users accumulated 1.52 million customs clearance through green consumption, confirming the practical value of multiple co-governance.

5.Conclusion and outlook

By analyzing the dynamic coupling mechanism of cross-border e-commerce and green economy system in the Yangtze River Delta, this study proves that there is a nonlinear synergistic effect of trade model innovation and ecological efficiency improvement under the empowerment of digital economy. The conclusion shows that the coordination of the two systems jumped from 0.35 in 2013 to 0.80 in 2022, verifying the synergistic gain of digital infrastructure expansion and low-carbon policy iteration. Future research should deepen exploration in two aspects: first, integrated domestic large market construction under the "double cycle" pattern into the analysis framework to explore the new mode of cross-border e-commerce and green electricity consumption in central and western inland port cities; second, focus on frontier issues such as real-time carbon footprint accounting of artificial intelligence driven supply chain, cross-border carbon credit confirmation by block chain, and promote the transformation of green trade rules from regional pilot to international standards.

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