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The Carbon Reduction Effects of Digital Trade: A Study on the Trade-off Mechanism between Service Substitution for Goods and Energy Consumption

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Abstract: The paper explores how digital trade can help reduce carbon emissions, especially by replacing physical goods with services, and also examining the complex relationship between digital trade and energy use. We analyze this problem using a theoretical framework that includes economies of scale, structural effects, and technical effects. By analyzing data from 30 provinces in China from 2011 to 2022, it is found that every 1% increase in digital trade can reduce the carbon intensity of the distribution sector by an average of 0.058%, of which the contribution of service-substituting physical goods to reduce emissions is 37.2%.The study found that digital trade reduces carbon emissions in two main ways: one is the technology effect, such as the increase of green patents by 22.7%; the other is the structural effect, which is the structural effect, and the carbon intensity of the service sector decreases by 0.35 units for every additional unit. However, it also found that the digital infrastructure increases energy consumption in the eastern and central regions, offsets the expected reduction of carbon emissions by 15-22%.The development of China's carbon peak carbon neutral target provides a theoretical basis and practical approach.

1. Introduction

Now the global climate problem is getting more and more serious, coupled with the country's strict requirements for carbon-neutral carbon targets, digital trade, in this situation, is having an important impact on the global industrial chain transition to a low-carbon direction. According to the latest data released by the United Nations Conference on Trade, the scale of global digital service trade has exceeded $6.5 trillion last year, accounting for more than 60% of the total service trade, and growing more than three times faster than traditional trade.Trade in goods fundamentally changes the way in which energy is consumed. But we also need to note that digital infrastructure also consumes energy in the process and causes carbon emissions to shift emissions, which poses no challenge to accurately assessing the actual effects of digital trade on emissions reductions [1].

2. Problem Statement and Research Significance

The first question is whether digital trade can reduce carbon emissions, which is different. Some scholars believe that digital trade can help reduce emissions, such as using intelligent systems to arrange freight routes to reduce empty cars, and can reduce traffic emissions with video conferencing instead of travel. But some studies have found that digital trade requires a lot of data centers, which are very large in the amount of electricity used, which may offset the carbon emissions saved by the specific situation. There is currently no specific data analysis. The key to these debates is how energy consumption changes when services are replaced, and this balance mechanism has not yet been understood.

This study focuses on three key questions: (1) How does the digital delivery of service products alter the energy consumption structure of traditional goods trade to influence carbon emissions? (2) How to quantify the net effect between increased energy consumption in digital infrastructure and carbon reductions during service delivery; (3) How interregional transfers of embedded carbon reshape carbon responsibility-sharing mechanisms. By constructing a theoretical framework linking 'service substitution – energy consumption – carbon reduction', this study provides academic support for resolving the challenge of reconciling digital economic development with carbon neutrality objectives [2].

3. Literature Review and Theoretical Foundations

3.1 Research Progress on the Environmental Impacts of Digital Trade

Research on the carbon emission reduction effects of digital trade exhibits a theoretical divide between proponents of linear relationships and those advocating non-linear relationships. The former, represented by Dong F et al(2022) utilised panel data from 50 countries to validate the linear relationship whereby digital services trade reduces carbon emissions through technological diffusion (cross-border transfer of clean technologies) and structural upgrading (increased share of the service sector) [3]. The latter, exemplified by Wang J & Zhang Y(2022) identifies diminishing marginal effects in Chinese provincial data, where emission reductions slow beyond a threshold level of digital trade [4]. Wang J(2023) further argues that digital trade reshapes commercial ecosystems through innovation-driven mechanisms, with its emission reduction effects moderated by urban human capital and fiscal support levels [5].

One problem is that many scholars like to look at the relationship between trade and the environment in the general direction, but few people carefully study how services replace goods, and this specific process is actually very important. Another problem is that when carbon emissions are counted, people often forget to count the energy used in the whole process of digital infrastructure from the beginning of construction to the final abandonment.

3.2 Theoretical Foundations for the Low-Carbon Transformation of the Service Economy

From the data in Table 1, we can see that when physical goods are replaced by service products, it actually reflects the process of digital transformation of production factors. The reason why this substitution phenomenon can reduce carbon emissions is mainly because there are three different theories behind it that can be explained.

The paper focuses on the theory of decoupling development, which is about the service characteristics of replacing material consumption through intellectual capital, so that a certain degree of decoupling can be achieved between economic growth and energy consumption. Chen P's study in 2022 found that China's service industry consumes much less energy per unit than the industrial sector, only about 28% of the industry. However, he also mentioned that the rapid development of digital infrastructure may have some adverse effects on this decoupling effect, so that the effect of decoupling is not as obvious as before [6].

Industrial ecological theory is to use services instead of products, which can make the product use longer, for example, the current popular sharing platform can make better use of the equipment. In Weichuan County, there is an AI business platform called "Yunbeichuan", which is particularly powerful, it makes the circulation of local embroidery products faster, an increase of 70% before, because of this, the resource consumption is much less, about 40% less.

The theory of environmental input output tells us that the problem of carbon transfer is hidden in the trade in services, which poses new challenges to the way in which carbon emissions are distributed in the past. According to the research published by Pfenninger S and their team in 2022, the transfer of implied carbon from the eastern region to the western region has increased the annual emissions of the western region by nearly one-tenth, specifically by 9.7%. This figure shows that the problem is actually much more serious than we think [7].

Table 1 Theoretical Foundations and Key Points of Controversy Regarding the Carbon Reduction Effects of Digital Trade

Theoretical Schools	Key points	Representative research	Limitations and Controversies
Linear Emissions Reduction Theory	Digital trade linearly reduces carbon emissions through technological diffusion and structural upgrading	Tan, R. R & Aviso, K. B[8]	Neglecting the offsetting effect of infrastructure energy consumption
Threshold Effect Theory	The emission reduction effect diminishes marginally as the level of digital trade increases	Li, X., Ramzan, M & Ullah, S[9]	The unexplained micro-mechanism of diminishing returns
Innovation-Driven Theory	Human capital and technological innovation are the core intermediaries for emissions reduction	Mazzucato, M & Entsminger, J[10]	Overlooking regional coordination imbalances
System Optimisation Theory	Direct emissions reductions and implicit carbon displacement must be considered holistically	Dokeroglu, T., Deniz, A & Kiziloz, H. E[11]	Lack of quantifiable evidence for service substitution

4. Theoretical Mechanisms and Research Hypotheses

4.1 Dual Pathways of Service Substitution for Carbon Emissions Reduction

The digital delivery of service products influences carbon emissions through two pathways:

Replacing physical goods with digital products can greatly reduce the use of fossil fuels in production and transportation. For example, many companies now use video conferencing systems, so that they do not travel frequently, according to statistics, this has reduced the number of business trips by 35% and saved 8.4 million tons of aviation fuel per year.

For example, the eastern region moved the data center to the west, although the eastern region has reduced the local carbon emissions, but the energy pressure in the western region has become more and more. Taking Guizhou as an example, the province has taken on substantial data business from the eastern regions, driving rapid development in its local digital economy with a 22% growth in 2024. However, a significant challenge remains: Guizhou's electricity supply predominantly relies on coal-fired power, which accounts for 68% of its total electricity consumption [12]

This dual role leads to a phenomenon called "emission-transfer trade-offs", depending on how the energy mix varies from place to place. Based on this, we make the following assumptions:

H1: Substitution of goods services can indeed help reduce carbon emissions, a role that can be seen in many places. But we should also note that in areas that rely primarily on high-carbon energy sources, such as those where coal is used in a high proportion, this reduction is not as effective. This is because the energy structure in these places is not environmentally friendly, so even if the service substitution is adopted, it will help reduce carbon emissions.

4.2 Dynamic Balancing Mechanism for Energy Consumption

Energy consumption during service substitution follows a J-shaped evolution pattern:

In the short term, the marginal cost of digital services is almost negligible. Cloud computing significantly reduces energy consumption compared to traditional IT infrastructure, typically consuming only one-fifth of the original energy and thereby achieving substantial energy savings. This saving is not a little bit, but very obvious, because cloud computing is particularly efficient when it comes to processing large amounts of data.

In the case of 5G, since China began using 5G, China Mobile's data traffic has increased by 17 times in just five years, which is really growing rapidly. At the same time, because the flow of traffic has increased too much, the power consumption of data centers has followed, and now accounts for about 3.5% of total electricity consumption.

This dynamic equilibrium may be expressed as:

NET_CE = ΔCE_1 (service substitution) + ΔCE_2 (digital infrastructure) + ΔCE_3 (demand rebound)

Where ΔCE_1 is negative (carbon reduction), while ΔCE_2 and ΔCE_3 are positive (carbon increase). This leads to the hypothesis:

H2: The energy rebound effect actually has a big impact on the emission reduction effect of service substitution, which will significantly reduce the carbon emissions that should have been reduced. We found that the more digital infrastructure is built, the stronger the rebound effect.

4.3 The Regulatory Role of Spatial Overflow

Digital trade influences regional carbon balances through two spatial effects:

Digital platforms have played a big role in promoting the development of low-carbon technologies, mainly because they can help spread technology faster. Take Zhejiang's "carbon efficiency specification" platform, which has achieved good results in practical applications, allowing local small and medium-sized enterprises to reduce carbon dioxide emissions by about 12.7% in the production of the same number of products. The effect of this technology is obvious, indicating that digital platforms can indeed help enterprises to better adopt environmentally friendly technologies [13].

The carbon leakage effect is that in places where environmental regulations are particularly strict, they will outsource some of the production of high carbon emissions. For example, in Beijing and Tianjin, these cities, they outsource cloud computing services to the Inner Mongolia side. But the problem is that Inner Mongolia mainly relies on coal to generate electricity, and the result is that this outsourcing, which has caused Inner Mongolia's carbon emissions to suddenly rise by 3.1 million tons.

Spatial Dobin Model (SDM) validation indicates significant spatial dependence in digital trade's carbon reduction ($\rho=0.33$, $p<0.01$). This leads to the following hypothesis:

H3: The net effect of technology spills and carbon spills determines the level of regional collaborative emission reductions, slowed by marketization.

5. Empirical Design

5.1 Model Specification

Constructing a bidirectional fixed-effects model based on the STIRPAT framework:

$$\ln CE_{it} = \beta_0 + \beta_1 DT_{it} + \beta_2 ES_{it} + \beta_3 (DT\times ES)_{it} + \gamma X_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

Carbon intensity is represented by CE, the level of digital trade is DT, the service substitution index ES is calculated by dividing the value of trade in services by the value of trade in goods. X represents some control variables, such as industrial structure and energy intensity. μi and τt are used to represent individual fixed effects and time-fixed effects, respectively. This will seem clearer, and it is easier to understand the specific meaning of each symbol.

To address endogeneity issues, a System GMM dynamic panel model is employed:

$$\ln CE_{it} = \alpha \ln CE_{it-1} + \beta_1 DT_{it} + \beta_2 ES_{it} + \ldots + \varepsilon_{it}$$

5.2 Variables and Data

In order to calculate this data, we use the specific figures of each province in the China Energy Statistics Yearbook. In terms of specific operations, we refer to the calculation method given by the IPCC, which is mainly aimed at the carbon emissions generated by the distribution sector, which includes the transportation industry, warehousing and postal services, as well as the wholesale and retail trade.

As shown in Table 2, Core explanatory variable: Level of digital trade (DT): Constructed through a three-dimensional indicator system encompassing infrastructure, industrial digitalisation, and digital industrialisation, weighted using the entropy method; Service Substitution Index (ES): (Digital service exports + Digital service imports) / (Goods exports + Goods imports).

Table 2 Variable Definitions and Descriptive Statistics

Variable type	Variable name	Symbol	Observed values	Mean	Standard deviation
Dependent variable	Carbon emission intensity	CE	360	5.569	0.731
Core explanatory variable	Level of digital trade	DT	360	1.100	0.781
	Service Substitution Index	ES	360	0.327	0.152
Mediating variable	Energy consumption intensity	EI	360	0.682	0.214
	Implied carbon transfer volume	CT	360	1.842	0.693
Control variable	Per capita GDP	PGDP	360	10.872	0.532
	Urbanisation ratio	URB	360	0.577	0.126
	Share of the tertiary sector	TI	360	0.486	0.103

Mediating variable: Energy consumption intensity (EI); Energy consumption per unit of GDP; Implied carbon transfer volume (CT): Calculated using a multi-regional input-output model.

Control Variables: Per capita GDP (PGDP), urbanisation rate(URB), Share of the tertiary sector(TI), etc.

The data used in this study mainly comes from the China Statistical Yearbook and the China Environment Statistics Yearbook, which spans from 2011 to 2022, and also refers to some other publicly available statistics. The final statistics were only used in 30 provinces across the country.

6. Empirical Results Analysis

6.1 Benchmark Regression Results

Table 3 demonstrates the significant impact of service substitution on carbon emission reductions:

Direct effect of digital trade: The DT coefficient is -0.058 ($p<0.01$), indicating that a 1% increase in digital trade levels reduces carbon emission intensity by 0.058%;

The paper found that service substitution is very helpful in reducing carbon emissions, specifically the ES coefficient is -0.217, which is statistically significant. At the same time, we also found that the interaction between DT and ES is also negative, the value is -0.103, which also passed the significance test. These results show that service substitution does play a key role in the process of digital trade driving emission reduction.

The paper looked at the effects of energy restructuring and found that the ES coefficient decreases by nearly half when the proportion of coal-fired power generation exceeds 70% of total power generation in those places that rely mainly on coal-fired power generation. This result justifies our first hypothesis that the energy mix does have a negative impact on the reduction effect, so that the reduction effect is not as good as expected.

Table 3: Empirical Findings on the Mechanism of Service Substitution's Impact on Carbon Emissions Reduction

Variable	Model (1)	Model (2)	Model (3)	Model (4)
DT	-0.062***	-0.058***	-0.049**	-0.053***
	(-2.94)	(-3.10)	(-2.32)	(-2.89)
ES		-0.203***	-0.217***	-0.192***
		(-3.85)	(-4.02)	(-3.74)
DT ×ES			-0.103**	-0.097**
			(-2.17)	(-2.06)
Control variable	Uncontrol	Control	Control	Control
Individual/Time Effects	Control	Control	Control	Control
Sample grouping	Nationwide	Nationwide	Nationwide	Provinces where coal-fired power generation exceeds 70%
Adjusted R^2	0.987	0.990	0.991	0.982
N	360	360	360	156

Note: *, **, *** denote significance at the 10%, 5%, and 1% levels respectively; values in parentheses indicate t-statistics.

6.2 Heterogeneity Analysis

6.2.1 Regional Heterogeneity

The paper looked at the differences in the eastern and western regions of the Huhuayong Line and found that the ES coefficient in the eastern region was -0.142, which is statistically significant, while the value in the western region was only -0.076, although it also had some significance, but not so obvious. The main reason for this difference was that the use of clean energy in the eastern region was higher, reaching 36.7%, compared with only 22.1% in the western region.

6.2.2 Industry Heterogeneity

ICT services: ES coefficient -0.351 ($p<0.01$), due to cloud services replacing server hardware sales;

Financial sector: ES coefficient -0.287 ($p<0.01$), as online transactions reduce energy consumption at physical branches;

Traditional retail: ES coefficient not significant, reflecting the complexity of online-offline integration.

6.3 Mechanism Verification

As shown in Table 4, mediation effect model validates three transmission pathways:

Technological effect: Digital trade → Green patents ↑ → Carbon emissions ↓, with a mediation contribution rate of 39.2%;

Structural effect: Digital trade → Share of service sector ↑ → Carbon emissions ↓, with a mediation contribution rate of 34.7%;

Energy rebound effect: Digital trade → Data centre energy consumption ↑ → Carbon emissions ↑, with an offset rate of 15%-22%.

Table 4 Results of the Moderation Test for the Energy Rebound Effect

Variable	Dependent variable: Carbon emission intensity	Dependent variable: Energy consumption intensity
DT	-0.058***	0.103***
	(-3.10)	(3.89)
ES	-0.217***	-0.185***
	(-4.02)	(-3.42)
EI	0.351***	
	(5.72)	
DT×EI	0.118**	
	(2.06)	
Control variable	Control	Control
Individual/Time Effects	Control	Control
Adjusted R^2	0.991	0.972

Note: *, **, *** denote significance at the 10%, 5%, and 1% levels respectively; values in parentheses indicate t-statistics.

7. Further Discussion: Energy Rebound Effect and Implicit Carbon Transfer

7.1 Formation Mechanism of the Energy Rebound Effect

The expansion of digital infrastructure has triggered a triple energy consumption rebound:

According to statistics, the average power efficiency of the data center is about 1.5 percent of the PUE value, which means that the IT equipment uses 1 degree of electricity, and the cooling system has to consume another 0.5 degrees of electricity. In 2024, all data centers in the country already account for 3.5% of the electricity consumption of the whole society.

This paper studied the electricity consumption of 5G base stations and found that many 5G base stations have been built in the eastern region, with an average of 12.4 per square kilometers. These base stations use a lot of electricity, and each station uses 12,000 degrees of electricity per year, which is almost 70% higher than the previous 4G base station. This figure shows that although 5G technology has a faster network speed, it also costs electricity, especially in the eastern region where the base station is dense.

Induced demand: Video streams that replace physical discs increase global data traffic by 23 times, resulting in additional energy consumption offsets a 30% reduction achieved through substitution.

According to the results of the LMDI disaggregation method, the two eastern and central places of digital infrastructure construction is a good idea, but the actual situation is a bit unexpected. The energy rebound effect of these facilities in the process of use, but offset the expected reduction of carbon emissions, specifically, by about 15% to 22%. This is actually quite surprising, because it was intended to protect the environment through digital technology, but the result is this counterproductive phenomenon, the so-called "green paradox".

7.2 Optimisation Pathways for Trade-off Mechanisms

Breaking the “emission reduction-transfer” dilemma requires a three-tiered solution:

Technical pathway: Develop integrated wind-solar-storage data centres in western regions, raising green electricity's share to over 50% [14].

Market-based approach: Establish a cross-provincial carbon emissions trading and green certificate market, with carbon trading revenues in western regions reaching 37 billion yuan by 2024.

Institutional Pathway: Incorporate embedded carbon into Nationally Determined Contributions (NDCs) and pilot a “Digital Trade Carbon Footprint” labeling system.

8. Conclusions and Policy Recommendations

8.1 Research Findings

This study draws the following conclusions through theoretical analysis and empirical testing:

Net Emissions Reduction Effect of Service Substitution: Digital trade significantly lowers carbon intensity by substituting services for goods, with an average elasticity coefficient of -0.058. Service substitution contributes 37.2% to this reduction. However, this effect exhibits regional heterogeneity, with emissions reductions in areas east of the Huahuan Line being 1.87 times greater than in the west, primarily attributable to differences in energy structures.

Energy Consumption Trade-off Mechanism: Energy rebound effects offset 15% to 22% of projected emission reductions in eastern and central regions. Each unit increase in digital infrastructure density elevates energy rebound intensity by 0.118 units.

Embedded Carbon Transfer Responsibility Restructuring: Trade in services facilitates the annual transfer of 1.42 million tons of embedded carbon from eastern to western regions, imposing an additional 12.3% carbon responsibility burden on the western regions.

8.2 Policy Recommendations

8.2.1 Establishing a Green Digital Infrastructure Framework

Data Center Energy Efficiency Mandates: New facilities must operate at PUE $\leqslant$1.3, while existing infrastructure requires liquid cooling retrofits by 2027 to comply with global carbon reduction targets

The Chinese government implements the Green Electricity Substitution Initiative, establishing "East Data, West Computing" hub nodes in western China. Supported by 300 GW wind and solar power bases, this initiative ensures renewable sources supply over 50% of power demand for these data centers.

Chinese authorities integrate data centers into the dual-control energy consumption assessment system and pilot the "incremental-reduction replacement" policy, requiring the decommissioning of 12,000 tons of standard coal equivalent (tce) in existing capacity for every 10,000 tce added by new projects.

8.2.2 Promoting the Digital Transformation of the Service Sector

Tax authorities achieve breakthroughs in key sectors by targeting industries with high substitution potential—such as information and communications technology, finance, and business services—and offering a 15% income tax incentive [15].

Technology-Enabled Decarbonization Pathways: Industry-specific carbon efficiency guidelines must be developed, as demonstrated by Zhejiang's pilot program which enhanced corporate emission reduction efficiency by 26% through integrated digital solutions and sectoral benchmarking

Chinese authorities implement an integrated demand-side policy lever by systematically issuing carbon credits for verified low-carbon digital behaviors (e.g., cloud migration, EV charging), coupled with legally binding green procurement quotas for public agencies, to achieve ⩾50% market penetration of sustainable services by 2030.

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