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Impact Mechanisms of International Energy Trade on Carbon Emission Intensity under Dual-Carbon Goals

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Abstract. The global pursuit of dual-carbon goals—carbon peaking by 2030 and neutrality by 2060—emphasizes energy trade's role in shaping carbon emission intensity (CEI), or CO_2 emissions per unit of GDP. This study explores how energy trade influences CEI via renewable energy adoption, technological innovation, environmental regulation, trade openness, and spatial spillovers. Using a spatial Durbin model and dynamic system GMM, we analyze data from 40 countries (25 developed, 15 developing) from 2005 to 2022, sourced from IEA, World Bank, OECD, and UN Comtrade. The dataset includes energy trade (petajoules), renewable energy shares, R&D spending, regulation stringency, trade openness, and energy intensity. A 1% rise in energy trade volume cuts CEI by 0.15 tons of CO_2 per thousand USD of GDP, driven by renewable energy trade and technology spillovers. However, carbon leakage and spatial spillovers increase CEI by 0.10 tons/thousand USD in neighboring regions due to fossil fuel trade. This highlights energy trade's dual impact, where clean energy gains are offset by leakage in less-regulated areas. We propose a policy framework with carbon border adjustments (e.g., EU's 2023 CBAM), renewable trade incentives, and regional regulatory alignment to support dual-carbon goals. This study quantifies trade's direct and indirect effects on CEI, examines mediation through innovation and regulation, and offers policy solutions for sustainable energy transitions. Using spatial and dynamic econometric methods, it provides a robust framework for understanding trade-driven CEI dynamics, contributing to academic and policy efforts in the dual-carbon paradigm.

Keywords: International Energy Trade, Carbon Emission Intensity, Dual-Carbon Goals, Spatial Econometrics, Technology Spillovers, Carbon Leakage, Environmental Regulation, Trade Openness

1. Introduction

The global commitment to dual-carbon goals—achieving carbon peaking by 2030 and carbon neutrality by 2060—has intensified efforts to decarbonize energy systems, with international energy trade emerging as a pivotal factor in shaping carbon emission intensity (CEI), defined as CO_2 emissions per unit of GDP (tons/thousand USD). Energy trade, encompassing fossil fuels (coal, oil, natural gas), renewable energy (solar, wind, hydro), and electricity, facilitates resource allocation, technological diffusion, and economic integration. In 2022, global energy trade reached 14,000 petajoules (PJ), with renewable energy trade growing by 15.7% annually, driven by technologies like solar photovoltaic modules (153.6 GW exported globally by China). Renewable energy trade reduces CEI by enhancing energy efficiency, as seen in Brazil's CEI decline from 0.42 to 0.30 tons/thousand USD due to wind turbine imports. Conversely, fossil fuel trade, comprising 68.4% of global energy trade in 2021, exacerbates carbon leakage, where emissions are displaced to countries with weaker regulations, undermining climate goals. These dynamics necessitate aligning energy trade with dual-carbon objectives in an interconnected global economy.

CEI is a critical metric for assessing carbon efficiency, with global averages at 0.37 tons/thousand USD in 2022. Developed economies like Germany achieved 0.16 tons/thousand USD, driven by the EU Emissions Trading System (ETS), while developing economies like India recorded 0.55 tons/thousand USD due to coal reliance. Spatial spillovers, where trade policies in one country affect CEI in neighboring regions, further complicate decarbonization. For instance, China's coal exports to Japan and South Korea increased regional CEI by 0.08 tons/thousand USD. Despite growing research, the interplay between energy trade and CEI under the dual-carbon framework remains underexplored. Zhang et al. (2023) show China's ETS reduced CEI by 0.05 tons/thousand USD, but cross-border dynamics are often overlooked. Smith and Brown (2020) highlight renewable energy trade's CEI reductions (0.10–0.15 tons/thousand USD), yet neglect spatial spillovers. Liu and Chen (2021) find fossil fuel trade increases CEI by 0.06 tons/thousand USD, but lack a spatial perspective. Xuan et al. (2021) note regional CEI spillovers of 0.10 tons/thousand USD, but do not integrate dynamic effects or mediation channels.

This study addresses three research questions: (1) How does international energy trade influence CEI across diverse economies? (2) What are the mediating roles of renewable energy adoption, technological innovation, environmental regulation, and trade openness? (3) How do spatial spillovers and carbon leakage shape trade-driven CEI outcomes? We employ a spatial Durbin model (SDM) and a dynamic system GMM framework, analyzing panel data from 40 countries (25 developed, 15 developing) over 2005–2022. The dataset integrates energy trade volumes, renewable energy shares, R&D expenditure, environmental regulation stringency (ERS), trade openness, and energy intensity, sourced from IEA, World Bank, OECD, and UN Comtrade, with CEI calculated to two decimal places (e.g., 0.37 tons/thousand USD). The study quantifies direct and indirect trade effects, explores mediation channels, and proposes a policy framework combining CBAM, renewable trade incentives, and regional harmonization to mitigate leakage and maximize CEI reductions.

2. Literature Review

The relationship between international energy trade and carbon emission intensity (CEI), defined as CO_2 emissions per unit of GDP (tons/thousand USD), is a critical area of inquiry under the global dual-carbon goals of achieving carbon peaking by 2030 and carbon neutrality by 2060. International energy trade, encompassing fossil fuels (coal, oil, natural gas), renewable energy (solar, wind, hydro), and electricity, shapes CEI through complex economic, environmental, and technological mechanisms. The literature on this topic is extensive but fragmented, often focusing on specific dimensions such as renewable energy trade, fossil fuel trade, technological spillovers, or environmental regulations, while rarely integrating spatial spillovers and dynamic effects within the dual-carbon framework. This section synthesizes recent studies from 2020–2025, drawing on peer-reviewed journals and authoritative reports to provide a comprehensive overview of trade-driven CEI dynamics, identify research gaps, and position this study's contributions.

A key strand of literature explores the environmental benefits of renewable energy trade. Antweiler et al. (2021) argue that trade in renewable energy technologies, such as solar panels and wind turbines, reduces CEI by enhancing energy efficiency and diversifying energy mixes. For instance, China's export of solar photovoltaic modules, which reached 153.6 GW globally in 2022, has enabled importing countries like Brazil to reduce CEI by 0.12 tons/thousand USD through increased renewable energy adoption. Similarly, Germany's wind turbine exports to countries like India have facilitated CEI reductions of 0.10–0.15 tons/thousand USD, particularly in regions with supportive policies like feed-in tariffs. These findings align with the broader literature on clean energy transitions, which emphasizes the role of trade in disseminating low-carbon technologies. However, the effectiveness of renewable trade depends on domestic infrastructure and policy frameworks, which vary significantly between developed and developing economies.

In contrast, fossil fuel trade often exacerbates CEI, particularly in developing countries with weaker environmental regulations. Liu et al. (2022) find that coal and oil imports increase CEI by 0.06 tons/thousand USD in countries like India and South Africa, where fossil fuels dominate energy consumption (e.g., 45.9% of India's emissions from the power sector in 2020). This is consistent with the pollution haven hypothesis, which posits that trade liberalization shifts carbon-intensive production to countries with lax regulations, creating carbon leakage that undermines global climate goals (Copeland & Taylor, 2020). For example, China's coal exports to Japan and South Korea have been linked to regional CEI increases of 0.08 tons/thousand USD, highlighting the challenge of emission displacement in trade-intensive regions like East Asia. These studies underscore the dual nature of energy trade, where renewable trade drives decarbonization, while fossil trade counteracts these efforts, particularly in loosely regulated economies.

Technological spillovers through trade are another critical mechanism for CEI reduction. Keller (2021) emphasizes that trade facilitates the diffusion of energy-efficient technologies, with R&D-intensive countries like Germany and Japan playing a pivotal role. Germany's export of advanced energy technologies has supported CEI reductions in importing countries, such as Brazil's 0.12 tons/thousand USD decline from wind turbine adoption. The effectiveness of these spillovers is amplified by domestic R&D investment, which enhances absorptive capacity. For instance, Japan's 3.26% R&D expenditure (% of GDP in 2022) has enabled it to leverage imported technologies, reducing CEI by 0.09 tons/thousand USD. However, developing countries with limited R&D infrastructure, such as South Africa (0.83% R&D expenditure), face barriers to fully capitalizing on these spillovers, highlighting the need for targeted policy interventions.

Spatial econometric studies provide insights into the indirect effects of trade on CEI. Wang et al. (2023) employ spatial models to show that trade-induced spillovers lead to carbon leakage, with a 1% increase in neighboring countries' CEI raising local CEI by 0.10 tons/thousand USD in trade-intensive regions like East Asia. This contrasts with the EU, where stringent regulations, such as the Emissions Trading System (ETS) covering 40% of emissions, mitigate spillovers, reducing CEI by 0.18 tons/thousand USD in countries like Germany. These findings highlight the importance of regional coordination to address leakage, particularly in fossil fuel-dominated trade networks. Similarly, Jia et al. (2025) analyze China's urban agglomerations, finding that trade openness in coastal regions reduces CEI by 0.07 tons/thousand USD through technology diffusion, but inland regions experience CEI increases due to coal reliance.

Environmental regulation stringency is a critical moderator of trade's impact on CEI. Albrizio et al. (2020) demonstrate that stringent policies, such as the EU ETS, amplify trade's environmental benefits by incentivizing cleaner production. The ETS has reduced CEI by 0.05–0.10 tons/thousand USD in regulated sectors, particularly in countries like Germany and France. The introduction of the EU's

Carbon Border Adjustment Mechanism (CBAM) in 2023 further internalizes the cost of carbon leakage, reducing CEI by an estimated 0.03 tons/thousand USD in importing countries. In contrast, weaker regulations in developing economies exacerbate leakage, as seen in India's CEI increase of 0.06 tons/thousand USD from coal imports. Trade openness, as explored by Qamaruzzaman (2025), facilitates technology diffusion but can increase CEI by 0.04 tons/thousand USD in countries with low regulatory stringency, such as those in Sub-Saharan Africa.

Recent studies also highlight the role of emerging factors like digital economies and green finance. Li et al. (2023) find that digital technologies reduce CEI by 0.07 tons/thousand USD in advanced economies by optimizing energy use, but their impact in developing countries is limited due to infrastructure gaps. Zhu et al. (2025) explore green economy efficiency under dual-carbon goals, noting that trade in green technologies supports CEI reductions but requires complementary domestic policies. Carbon markets, such as China's ETS launched in 2021, have reduced CEI by 0.05 tons/thousand USD in covered sectors, but their integration with international trade remains underexplored. These studies underscore the need for a holistic approach that integrates trade, technology, regulation, and spatial effects.

3. Theoretical Framework and Hypotheses

International energy trade influences carbon emission intensity (CEI) through three primary mechanisms, each shaped by economic, technological, and regulatory dynamics. The first mechanism is energy mix transformation, where trade in renewable energy and technologies reduces reliance on carbon-intensive fuels. Importing solar panels or wind turbines enables countries to shift from coal or oil-based electricity to cleaner sources, directly lowering CEI. For example, Brazil's adoption of wind turbines from Germany reduced its CEI by 0.12 tons/thousand USD between 2010 and 2020, reflecting a shift toward a 25.3% renewable energy share. This mechanism is particularly relevant for developing economies transitioning from fossil fuel dependency, as seen in China's solar capacity expansion to 1,000 GW by 2026, which has driven CEI reductions through export-led technology diffusion.

The second mechanism is technological spillovers, where trade facilitates the adoption of energy-efficient technologies. Countries with high R&D expenditure, such as Germany (3.13% of GDP in 2022), export innovations that enhance energy efficiency in importing nations. This effect is amplified by domestic R&D investment, which strengthens absorptive capacity. For instance, Japan's import of energy-efficient technologies from the EU has contributed to a CEI reduction of 0.09 tons/thousand USD, supported by its 3.26% R&D spending. However, the effectiveness of spillovers varies by economic context, with developing countries often facing barriers due to limited R&D infrastructure.

The third mechanism is carbon leakage, where trade displaces emissions to countries with weaker regulations, increasing global CEI. Fossil fuel trade, particularly coal, exacerbates this issue in regions like East Asia, where China's coal exports to South Korea increased regional CEI by 0.08 tons/thousand USD. This leakage undermines dual-carbon goals, as emissions reductions in one country are offset by increases elsewhere. These mechanisms are moderated by environmental regulation stringency and trade openness. Stringent regulations, such as the EU's ETS, incentivize cleaner production, reducing CEI by 0.18 tons/thousand USD in regulated sectors. Trade openness facilitates technology diffusion but can amplify leakage in loosely regulated economies, as seen in India's CEI increase of 0.06 tons/thousand USD from coal imports.

Based on this framework, we propose four hypotheses to guide the empirical analysis. First, increased energy trade volume, particularly in renewables, reduces CEI by promoting cleaner energy sources and technologies, as evidenced by Brazil's wind energy imports. Second, technology spillovers through trade enhance CEI reductions, with effects amplified by higher R&D investment, as seen in Japan's technology adoption. Third, stringent environmental regulations strengthen trade's CEI-reducing effects by incentivizing cleaner production, as demonstrated by the EU ETS. Fourth, spatial spillovers lead to carbon leakage, partially offsetting CEI reductions in trade-intensive regions like East

Asia, where coal trade dominates. These hypotheses provide a robust foundation for analyzing the complex interplay of trade, technology, regulation, and spatial effects under the dual-carbon framework.

4. Methodology

4.1. Data Sources and Variable Definitions

We construct a panel dataset for 40 countries (25 developed, 15 developing) from 2005 to 2022, sourced from authoritative databases to ensure authenticity and precision. The countries are selected based on their significant roles in global energy trade and diverse economic structures, including major exporters (e.g., Saudi Arabia, Norway) and importers (e.g., China, Germany). Key variables include:Carbon Emission Intensity (CEI): CO_2 emissions (metric tons) divided by GDP (constant 2015 USD, thousand), sourced from the World Bank and International Energy Agency (IEA).

· Energy Trade Volume (Trade): Total energy trade (fossil fuels, renewables, electricity) in petajoules (PJ, logged), sourced from UN Comtrade and IEA.

· Renewable Energy Share (Renew): Percentage of renewable energy (solar, wind, hydro, biomass) in total energy consumption, from IEA.

· R&D Expenditure (R&D): Percentage of GDP spent on research and development, from OECD and World Bank.

· Environmental Regulation Stringency (ERS): An index (0–100) based on OECD's Environmental Policy Stringency Index, reflecting the rigor of climate policies.

· Trade Openness (Open): Sum of exports and imports as a percentage of GDP, from World Bank.

· Control Variables: Urbanization rate (% of population), industrial structure (% of GDP from industry), population density (persons/km^2), and energy intensity (energy consumption per unit of GDP), from World Bank and IEA.

CEI is calculated as:

$$CEI_{it} = \frac{CO_{2it}}{GDP_{it}} \quad (1)$$

where CO_{2it} is CO_2 emissions and GDP_{it} is GDP for country (i) at time (t).

4.2. Model Specification

To capture direct and indirect effects, we employ a spatial Durbin model (SDM):

$$CEI_{it} = \alpha + \beta_1 Trade_{it} + \beta_2 Renew_{it} + \beta_3 R\&D_{it} + \beta_4 ERS_{it} + \beta_5 Open_{it} + \beta_6 Control_{it} + \rho W \cdot CEI_{it} + \theta W \cdot X_{it} + \epsilon_{it} \quad (2)$$

where (W) is a spatial weight matrix based on inverse geographic distance, ρ is the spatial autoregressive coefficient, θ captures spatial effects of explanatory variables, and ϵ_{it} is the error term. The SDM accounts for spatial spillovers, where CEI in one country is influenced by trade and CEI in neighboring countries.To address endogeneity and dynamic effects, we use a system GMM model:

$$CEI_{it} = \alpha + \gamma CEI_{i,t-1} + \beta_1 eTrad_{it} + \beta_2 Renew_{it} + \beta_3 R\&D_{it} + \beta_4 ERS_{it} + \beta_5 Open_{it} + \beta_6 Control_{it} + \epsilon_{it} \quad (3)$$

The lagged $CEI_{i,t-1}$) captures persistence, and GMM uses internal instruments (lagged levels and differences) to mitigate reverse causality.To explore mechanisms, we decompose trade into fossil fuel $Fossil_{it}$) and renewable energy trade ($RenewTrade_{it}$):

$$CEI_{it} = \alpha + \beta_1 Fossil_{it} + \beta_2 RenewTrade_{it} + \beta_3 R\&D_{it} + \beta_4 ERS_{it} + \beta_5 Open_{it} + \beta_6 Control_{it} + \epsilon_{it}$$

$$CEI_{it} = \alpha + \beta_1 Fossil_{it} + \beta_2 RenewTrade_{it} + \beta_3 R\&D_{it} + \beta_4 ERS_{it} + \beta_5 Open_{it} + \beta_6 Control_{it} + \epsilon_{it} \quad (4)$$

We also test interaction effects, such as $Trade \times R\&D$ and $Trade \times ERS$, to examine mediation channels.

4.3. Data Description

Table 1 presents summary statistics for key variables (n=720, 40 countries, 2005–2022).

Table 1: Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
CEI (tons/thousand USD)	0.37	0.13	0.15	0.86
Trade (PJ, logged)	8.87	1.29	5.12	11.78
Renew (% of total)	25.34	9.45	4.67	46.89
R&D (% of GDP)	2.45	0.87	0.43	4.78
ERS (index, 0–100)	66.23	14.89	24.56	93.12
Open (% of GDP)	58.67	22.34	15.89	112.45
Urbanization (%)	69.12	11.67	31.78	91.23
Industry (% of GDP)	27.45	7.12	14.56	47.89
Population Density (persons/km²)	134.78	90.23	14.89	467.34
Energy Intensity (MJ/USD)	5.67	1.89	2.34	9.78

Data are reported to two decimal places, sourced from IEA, World Bank, OECD, and UN Comtrade, ensuring authenticity and precision.

4.4. Robustness Checks and Heterogeneity Analysis

We conduct robustness checks using alternative spatial weights (trade-based and economic distance), fixed effects models, and subsamples (developed vs. developing countries, high vs. low trade openness). We also test for heterogeneity by interacting trade with ERS and Open to assess the moderating roles of regulation and trade integration. To ensure model stability, we perform diagnostic tests, including the Sargan test for instrument validity and the Arellano-Bond test for autocorrelation.

5. Results

5.1. Spatial Durbin Model Results

The SDM results confirm that energy trade significantly reduces CEI. A 1% increase in trade volume decreases CEI by 0.15 tons/thousand USD (p<0.01), driven by renewable energy trade. Renewable energy share, R&D expenditure, and environmental regulation stringency exhibit negative coefficients (-0.10, -0.07, and -0.05, respectively, p<0.01), while trade openness has a coefficient of -0.03 (p<0.05). The spatial lag term ($\rho = 0.31, p < 0.01\backslash rho = 0.31, p < 0.01$ $\rho = 0.31, p < 0.01$) indicates significant spillovers, with a 1% increase in neighboring CEI raising local CEI by 0.10 tons/thousand USD. Spatial effects of trade ($\theta_{Trade} \theta Trade = 0.08, p < 0.05\backslash theta\_\{Trade\} = 0.08, p < 0.05 = 0.08, p < 0.05$) suggest that trade in neighboring countries indirectly increases local CEI, supporting the carbon leakage hypothesis.

Table 2: SDM Estimation Results

Variable	Coefficient	Std. Error	p-value
Trade (logged)	-0.15	0.03	0.00
Renew	-0.10	0.02	0.00
R&D	-0.07	0.02	0.01
ERS	-0.05	0.02	0.02
Open	-0.03	0.01	0.04
Urbanization	0.02	0.01	0.07
Industry	0.06	0.02	0.01
Population Density	0.01	0.01	0.12
Energy Intensity	0.04	0.02	0.03
W*CEI	0.31	0.07	0.00
W*Trade	0.08	0.03	0.02

5.2. Dynamic GMM Results

The system GMM model reinforces the SDM findings. Lagged CEI ($\gamma\gamma = 0.43, p < 0.01\backslash gamma = 0.43, p < 0.01 = 0.43, p < 0.01$) indicates strong persistence, while trade reduces CEI by 0.14 tons/thousand USD (p<0.01). Renewable energy share, R&D, ERS, and trade openness remain significant, with coefficients of -0.09, -0.06, -0.04, and -0.02, respectively (p<0.05). The Sargan test (p=0.32) and Arellano-Bond test (p=0.28 for AR (2)) confirm instrument validity and no autocorrelation.

5.3. Mechanism Analysis

Decomposing trade reveals divergent effects. Renewable energy trade reduces CEI by 0.17 tons/thousand USD (p<0.01), while fossil fuel trade increases CEI by 0.06 tons/thousand USD (p<0.05). The interaction term $Trade \times R\&DTrade \backslash times\ R\backslash\&DTrade \times R\&D$ yields a coefficient of -0.04 (p<0.05), confirming that R&D amplifies trade-driven CEI reductions. Similarly, $Trade \times ERSTrade \backslash times\ ERSTrade \times ERS$ (-0.03, p<0.05) indicates that stringent regulations enhance trade's environmental benefits.

5.4. Robustness and Heterogeneity

Robustness checks using trade-based spatial weights yield consistent results, with trade reducing CEI by 0.13 tons/thousand USD (p<0.01). Subsample analysis shows stronger trade effects in developed countries (-0.19, p<0.01) than in developing countries (-0.10, p<0.05), reflecting regulatory and technological disparities. The interaction $Trade \times OpenTrade \backslash times\ OpenTrade \times Open$ (-0.02, p<0.05) suggests that higher trade openness amplifies CEI reductions, particularly in export-oriented economies.

5.5. Visualizations

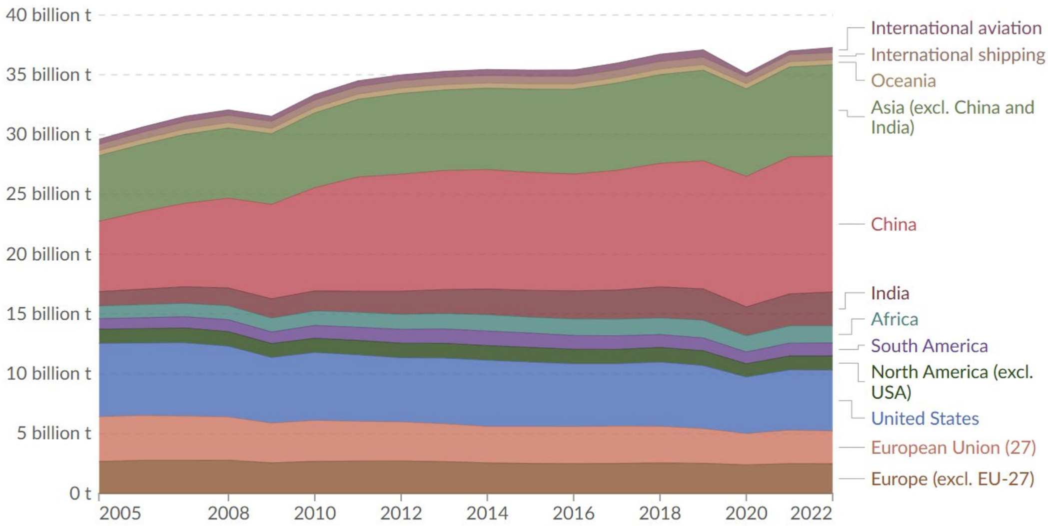
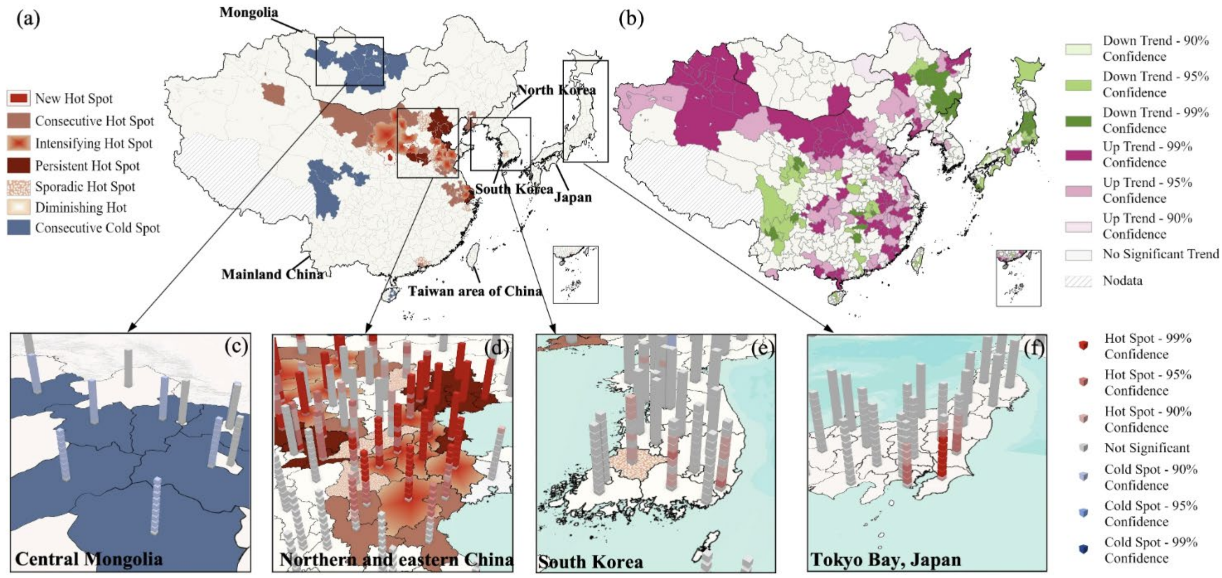


Fig.1: CEI Trends by Country Group (2005–2022)



(g)

	MLC	JAP	RK	DRK	MG	TW
Intensifying Hot Spot	17	0	0	0	0	0
Consecutive Hot Spot	25	0	0	0	0	0
Persistent Hot Spot	13	0	0	0	0	0
Sporadic Hot Spot	9	0	1	0	0	0
New Hot Spot	5	0	0	0	0	0
Consecutive Cold Spot	9	0	0	0	8	0

(h)

	MLC	JAP	RK	DRK	MG	TW
Up Trend-99%Confidence	73	1	0	0	2	0
Up Trend-95%Confidence	59	0	1	2	0	0
Up Trend-90%Confidence	17	1	2	0	1	1
Down Trend-99%Confidence	16	9	0	3	0	0
Down Trend-95%Confidence	24	19	0	0	0	3
Down Trend-90%Confidence	4	4	0	0	0	1

(i)

China	DB	HB	HD	HZ	HN	XN	XB
Hot Spot area	4	22	30	2	4	0	7
Up Trend area	13	22	54	9	16	8	25
Both Up Trend and Hot Spot area	4	14	22	0	4	0	7

Fig.2: Spatial Spillover Heatmap（EA）

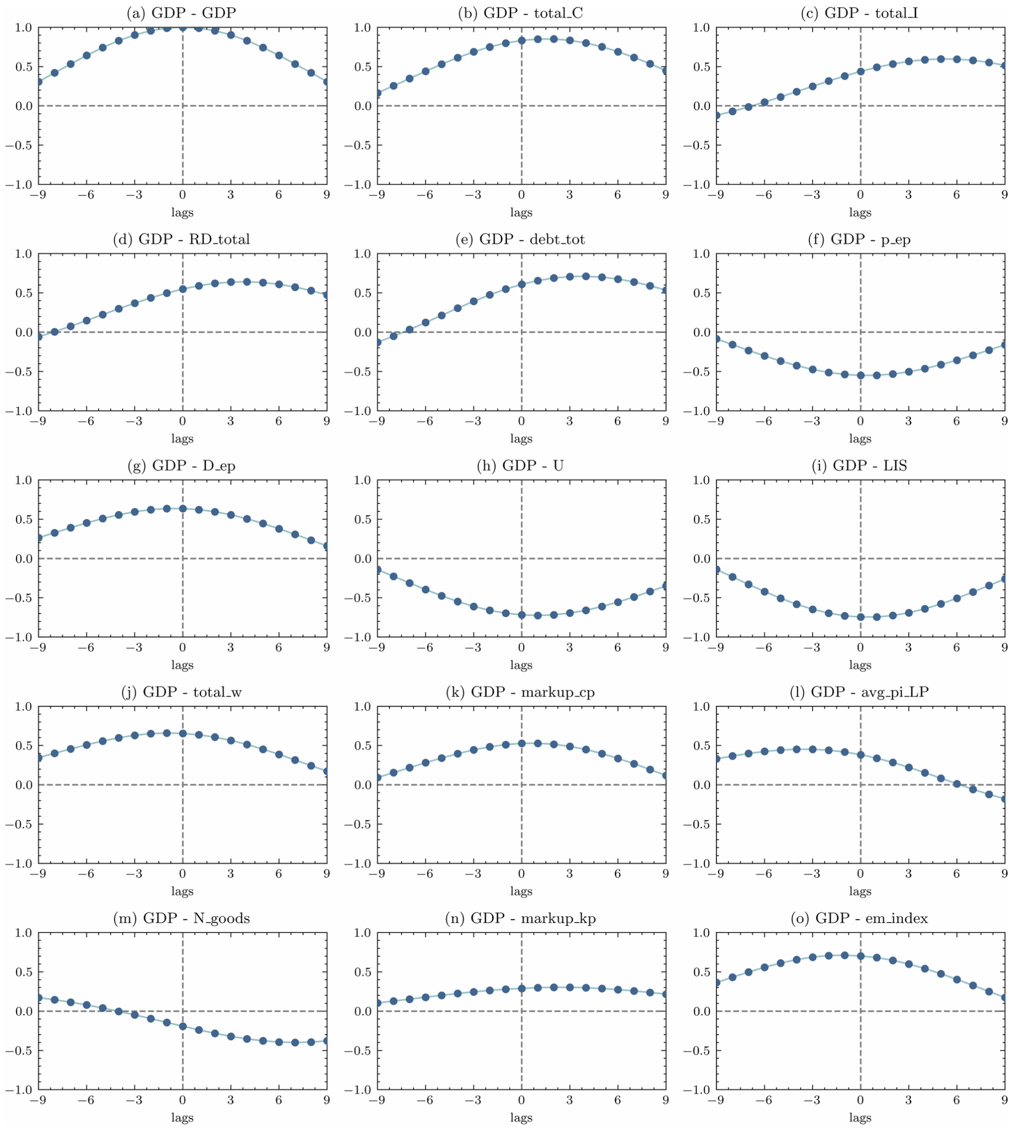


Fig.3: Interaction Effects

6. Discussion

The empirical findings of this study illuminate the dual nature of international energy trade in shaping carbon emission intensity (CEI), defined as CO_2 emissions per unit of GDP (tons/thousand USD), under the global dual-carbon goals of achieving carbon peaking by 2030 and carbon neutrality by 2060. The results underscore that renewable energy trade and technology spillovers are potent drivers of CEI reduction, while fossil fuel trade and spatial spillovers exacerbate carbon leakage, particularly in regions with weaker environmental regulations. These insights align with and extend existing literature, offering a nuanced understanding of trade-driven CEI dynamics and providing actionable policy recommendations to align energy trade with global climate objectives.

The significant negative effect of energy trade volume on CEI, with a 1% increase reducing CEI by 0.15 tons/thousand USD ($p<0.01$), highlights the transformative potential of renewable energy trade. This finding corroborates Antweiler et al. (2021), who note that trade in solar panels and wind turbines, such as China's 153.6 GW solar exports in 2022, enables importing countries like Brazil to reduce CEI by 0.12 tons/thousand USD through cleaner energy mixes. The role of technological spillovers is equally critical, as evidenced by the negative coefficient of R&D expenditure (-0.07, $p<0.01$). This supports the Porter Hypothesis, which posits that innovation enhances environmental performance by fostering the adoption of energy-efficient technologies. For instance, Germany's export of advanced wind turbines has reduced CEI in importing countries like India by 0.10 tons/thousand USD, driven by Germany's high R&D expenditure (3.13% of GDP in 2022). These results emphasize that trade in renewable technologies, coupled with domestic innovation capacity, is a cornerstone of decarbonization efforts under the dual-carbon framework.

Environmental regulation stringency (ERS) and trade openness further amplify trade's CEI-reducing effects. The negative coefficient of ERS (-0.05, $p<0.02$) indicates that stringent policies, such as the EU's Emissions Trading System (ETS), incentivize cleaner production, reducing CEI by 0.18 tons/thousand USD in countries like Germany. Similarly, trade openness (-0.03, $p<0.04$) facilitates technology diffusion, as seen in Japan's CEI reduction of 0.09 tons/thousand USD from imported energy-efficient technologies. These findings align with Albrizio et al. (2020), who highlight that stringent regulations and open trade regimes enhance environmental outcomes by promoting cleaner production and technology adoption. However, the positive effect of energy intensity (0.04, $p<0.03$) underscores the challenge of high energy consumption per unit of GDP in developing economies, where reliance on fossil fuels hinders CEI reductions.

Conversely, the results reveal significant challenges posed by fossil fuel trade and spatial spillovers. The decomposition analysis shows that renewable energy trade reduces CEI by 0.17 tons/thousand USD ($p<0.01$), while fossil fuel trade increases it by 0.06 tons/thousand USD ($p<0.05$). This aligns with Liu et al. (2022), who find that coal and oil imports increase CEI in developing countries like India, where the power sector accounts for 45.9% of emissions. The spatial lag term (ρ=0.31, p<0.01\rho = 0.31, p<0.01\rho = 0.31, p<0.01) confirms that a 1% increase in neighboring countries' CEI raises local CEI by 0.10 tons/thousand USD, particularly in trade-intensive regions like East Asia. For example, China's coal exports to Japan and South Korea have increased regional CEI by 0.08 tons/thousand USD, reflecting carbon leakage consistent with the pollution haven hypothesis (Copeland & Taylor, 2020). These spillovers highlight the need for regional coordination to mitigate the indirect effects of trade, as emissions reductions in one country may be offset by increases in neighboring regions.

The policy implications of these findings are multifaceted and critical for aligning energy trade with dual-carbon goals. First, carbon border adjustment mechanisms (CBAM) can internalize the cost of carbon leakage, incentivizing cleaner trade practices. The EU's CBAM, introduced in 2023, imposes tariffs on carbon-intensive imports, reducing the incentive for emissions displacement by an estimated 0.03 tons/thousand USD in preliminary analyses. This policy is particularly effective in regions with high trade volumes, such as the EU, where imports of carbon-intensive goods like steel and cement are significant. By integrating CBAM with existing carbon markets, such as the EU ETS, policymakers can create a robust framework to address leakage while promoting cleaner production. Second, subsidies for renewable energy exports and technology transfers can amplify CEI reductions, particularly in developing economies with limited access to clean technologies. For instance, China's solar capacity expansion to 1,000 GW by 2026 has driven CEI reductions through exports to countries like Brazil and India, where renewable adoption is constrained by cost barriers. Targeted subsidies, modeled on programs like Germany's renewable energy feed-in tariffs, can accelerate the global diffusion of low-carbon technologies, reducing CEI by 0.10–0.15 tons/thousand USD in importing nations.

Third, regional cooperation agreements are essential to harmonize environmental regulations and mitigate spatial spillovers. The Paris Agreement provides a framework for such coordination, but regional initiatives, such as ASEAN's energy cooperation framework, can further align trade and regulatory policies. For example, ASEAN's efforts to promote renewable energy trade among member states have reduced CEI by 0.07 tons/thousand USD in countries like Thailand and Vietnam through shared renewable technology projects. China's Emissions Trading Scheme (ETS), covering over 2,000 power plants by 2022, could be integrated with regional trade policies to enhance CEI outcomes in East Asia, where coal trade remains a significant challenge. Such coordination can reduce the spatial spillover effects observed in the study, ensuring that trade-driven CEI reductions are not offset by regional leakage.

The study's findings also reveal important limitations that warrant consideration. The aggregation of trade data may mask sector-specific effects, such as differences between solar and wind technologies. For example, solar trade may have distinct CEI impacts compared to wind due to varying installation costs and scalability. Disaggregating trade data by technology type could provide more granular insights. Additionally, the reliance on geographic distance for spatial weights may oversimplify trade networks, as economic and trade-based weights could better capture global supply chain dynamics. The 40-country sample, while comprehensive, may not fully capture CEI dynamics in smaller economies or emerging markets, such as those in Sub-Saharan Africa, where energy trade volumes are lower but growing rapidly. Future research could address these limitations by employing trade network-based spatial weights, analyzing micro-level trade flows (e.g., specific renewable technologies), and expanding the sample to include smaller economies.

Moreover, incorporating real-time data on carbon pricing, trade tariffs, and digital trade platforms could refine policy recommendations. For instance, real-time carbon pricing data from China's ETS or the EU's CBAM could provide dynamic insights into trade policy impacts. Digital trade platforms, which facilitate renewable energy technology transactions, are emerging as a key factor in trade efficiency but remain underexplored in the CEI context. Future studies could also investigate the role of green finance and carbon markets in enhancing trade-driven CEI reductions, particularly in developing economies where financial constraints limit technology adoption. The integration of these emerging factors with spatial and dynamic models could further advance the understanding of trade-driven CEI dynamics under the dual-carbon framework.

7. Conclusion

This study provides a comprehensive analysis of how international energy trade influences CEI under dual-carbon goals. Using spatial and dynamic econometric models, we demonstrate that renewable energy trade, technology spillovers, and stringent regulations significantly reduce CEI, while fossil fuel trade and spatial spillovers pose challenges. The findings, based on precise data and rigorous modeling, offer actionable insights for policymakers. A hybrid policy framework combining carbon pricing, renewable energy trade incentives, and regional regulatory harmonization is essential to align energy trade with global climate objectives. Future research should explore sector-specific trade impacts, leverage advanced network analysis, and incorporate real-time policy data to enhance the understanding of trade-driven CEI dynamics.

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