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Trade Openness, Renewable Energy, and Environmental Quality: The Role of Infrastructure in Developed and Developing Countries

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ABSTRACT

This study examines the relationship between trade openness, renewable energy, and environmental quality, with a specific focus on the role of infrastructure in developed and developing countries. To address this objective, we employ a comprehensive panel dataset covering 154 countries over the period 1990 to 2024. To account for heterogeneity across different stages of development, the full sample was divided into 112 developing countries and 42 developed countries, enabling a comparative analysis of the dynamics across contexts. We perform the two-step System Generalized Method of Moments (SGMM) estimator, which effectively addresses potential endogeneity, unobserved heterogeneity, and dynamic relationships among the variables. The findings provide insights that trade openness significantly increases the CO_2 emission; renewable energy significantly enhances the environmental quality, while the effect of infrastructure differs across samples. We also found that infrastructure moderates both the trade-CO_2 emission and renewable energy-CO_2 emissions relationships. Countries in the full sample and developing countries benefit from an interaction between trade, renewable, and infrastructure. These interactional relationships significantly decrease CO_2 emissions. Overall, this study contributes to the understanding of the trade–energy–infrastructure-environment nexus and offers policy implications for designing sustainable development strategies tailored to diverse national contexts.

Keywords: Trade Openness, Renewable Energy, Environmental Quality, CO_2 Emission, Infrastructure in Developed and Developing Countries
JEL Classifications: F18; Q43; Q56; O44

1. INTRODUCTION

In recent decades, policymakers have faced the challenge of balancing economy, trade, and sustainability (Bibi and Jamil, 2025; Le et al., 2016). Economic growth can be fueled, as well as trade, through globalization and trade openness (Saidi et al., 2016). However, this also increases energy use and resource exploitation, as well as environmental degradation and climate change. This situation necessitates the search for development paths which intertwine economic development and ecological integrity through clean energy, sustainable trade and resilient infrastructure. Trade openness has the potential to both enhance environmental quality as well as degrade it. It can lead to a "*pollution haven effect*"; meaning that countries will experience polluting industries moving to their lax regulations, or a "*technique effect*" in which promoting a cleaner technology innovation and efficiency is promoted (Padhan and Bhat, 2024; Hakimi and Hamdi, 2019; Antweiler et al., 2001; Grossman and Krueger, 1991). The ultimate effect will vary depending on the level of regulations (or lack thereof) the country has, technological ability, and the commitment towards sustainability.

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Concerns surrounding climate change, evident in global policy discussions and economic debates, led climate change adaptation and mitigation into public discourse. Rising global temperatures, extreme weather events, and depletion of resources make it clear that current economic growth must be reconciled with ecological sustainability (Lai et al., 2025; Mehta, 2024; Jacob and Winner, 2009). Globalization's effects, along with increased energy demand for modern lifestyles, account for higher carbon emissions and pollution. These factors present a compelling case for sustainability as a central issue to tackle. Considering the need to address some of these demands through renewable energy, transitioning to renewable energy is seen as a major step towards reducing carbon emissions in efforts to mitigate climate change. Potentially, wind energy, solar energy, and hydropower combine to create cleaner sources of energy with increased energy security and sustainable development. While global energy consumption continued to increase, if solar, wind, and hydropower become an accepted and adopted part of the energy structure, sustainable development, low-carbon development, potentially improved health outcomes, and reaching climate targets are all possible outcomes (Raghutla and Kolati, 2023). Additionally, taking into infrastructure, renewable energy technology will be imperative for essentially all countries to deploy energy-efficient structures and use trade networks to monitor transportation systems. Integrated energy systems such as smart grids can provide reliability for the deployment of renewable energy systems, and transportation systems can improve the use of goods and energy. In addition, engaged digital infrastructure will improve energy efficiency, and promote the implementation of disruptions. All these factors should support sustainable, interconnected economies (Li and Yang, 2025; Ma et al., 2025).

While trade openness offers opportunities to encourage technological diffusion and cleaner production, its implications for the environment may depend crucially on the quality of the infrastructure needed to support energy efficiency and renewable integration. Under some channels, trade openness can influence environmental quality: the *scale effect*, the *composition effect*, and the *technique effect* (Padhan and Bhat, 2024; Hakimi and Hamdi, 2019; Fan and Hossain, 2018; Antweiler et al., 2001). In addition, growth in renewable energy provides gains in environmental quality by decreasing dependence on fossil fuels and emissions of greenhouse gases. However, the extent to which they do so is often dependent on the quality of infrastructure, since effective energy, and digital networks can enhance the positive effects of trade openness and renewable energy by promoting technology diffusion, decreasing energy losses, and enabling cleaner production and delivery systems (Dai et al., 2025; Yu and Du, 2025).

While there has been a growing focus on environmental sustainability, existing literature has notable gaps regarding trade openness, renewable energy, and infrastructure in the same framework. In particular, how trade openness and renewable energy impact environmental quality, and whether infrastructure moderates these relationships, has been addressed relatively poorly, resulting in limited understanding of how these variables influence environmental quality. Furthermore, comparative evidence between developing and developed countries is also limited, even though the nature of differences in the economy, technological advances, and institutions may lead to different environmental outcomes. These gaps should be addressed to better understand how trade, energy, and infrastructure can be effectively coordinated for sustainable development in different contexts. Therefore, this study aims to answer the following research question: *How do trade openness and renewable energy affect environmental quality in developed and developing countries? Does infrastructure moderate these relationships?*

The objective of this study is to examine the relationship between trade openness, renewable energy, and environmental quality, focusing on the role of infrastructure in developed and developing countries. To this end, we use a panel of 154 countries from 1990 to 2024, and split this full sample into 112 developing and 42 developed countries to allow comparative analysis. We employ the two-step System GMM estimator as an econometric approach. Overall, the findings show that trade openness increases CO_2 emissions, renewable energy improves environmental quality, and the effect of infrastructure varies across samples. We also found that infrastructure moderates the trade–CO_2 and renewable energy–CO_2 relationships, with interactions in the full and developing country samples significantly reducing emissions.

This study contributes significantly to the literature in several ways. First, it integrates trade openness, renewable energy, and environmental quality into one analytical framework that explores their joint effects. Second, it explores how infrastructure is critical in either supporting or limiting the environmental gains from renewable energy and trade openness. Third, it determines how the relationships among the development of energy transitions and their environment differ between countries at distinct stages of economic development (developed and developing countries). Finally, we provide insights for policymakers to develop propositions for sustainable and equitable approaches to trade, renewable energy, and infrastructure development that will, in turn, spur green and inclusive economic growth.

The rest of the paper is structured as follows: Section 2 sheds light on the relevant literature and theoretical framework. Section 3 outlines the data and methodology. Section 4 discusses empirical results. Section 5 concludes and addresses some policy implications.

2. LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

The association between trade openness, renewable energy, environmental quality, and infrastructure development is essential to understand sustainable economic development (Jóźwik et al., 2025; Abdi et al., 2025). Trade openness, which refers to the degree a country engages in international trade can affect environmental quality through various pathways (Copeland and Taylor, 2024; Hakimi and Hamdi, 2019; Frankel and Rose, 2005). Trade may increase the transfer of clean technology and lead to economic growth, with the potential implications for environmental quality.

Conversely, trade openness may exacerbate environmental degradation, which is particularly the case in countries with weaker environmental governance, called the "*pollution haven effect*." The logic behind the pollution heaven hypothesis is that trade liberates polluting industries in developed countries and relocates to countries with limited environmental legal protections, leading to increases in CO_2 emissions and environmental deterioration. There has been varying evidence regarding the link between trade openness and environmental quality. For example, Pham and Nguyen (2024) examined this relationship in developing countries and found no relationship between trade openness and environmental pollution. On the contrary, Bernard and Mandal (2016) found that trade openness and poor infrastructure could increase CO_2 emissions in Africa, thereby showing a need for strong regulatory policies in mitigating the effects of trade openness.

Renewable energy adoption has emerged as a critical strategy for mitigating environmental degradation and enhancing environmental quality (Avazkhodjaev et al., 2022; Bhattacharya et al., 2016; Sadorsky, 2009). The transition to renewable energy sources, such as solar, wind, and hydropower, can reduce reliance on fossil fuels, decrease greenhouse gas emissions, and improve air quality. However, the effectiveness of renewable energy adoption is closely linked to the development and quality of infrastructure (Dai et al., 2025; Yu and Du, 2025). Energy infrastructure is essential for integrating renewable energy sources into national grids, ensuring reliability and efficiency. Additionally, transport infrastructure plays a crucial role in reducing emissions associated with the movement of goods and people, while digital infrastructure enables real-time monitoring and management of energy consumption, facilitating the implementation of energy-efficient practices and technologies. In this vein, Nchofoung and Asongu (2022) emphasized the significant role of infrastructure in moderating the environmental impacts of trade openness, suggesting that robust energy infrastructure can facilitate the adoption of cleaner energy technologies.

Comparative analyses between developed and developing countries reveal notable differences in the dynamics between these factors. Developed countries possess advanced infrastructure and strong environmental regulations, enabling them to leverage trade openness and renewable energy adoption to improve environmental outcomes (Deng et al., 2024; Al-Mulali and Ozturk, 2016). In contrast, developing countries often face challenges related to weak infrastructure and ineffective regulatory frameworks, which can hinder the positive impacts of trade openness and renewable energy adoption on environmental quality (Khan et al., 2021; Azimi and Mollah, 2024). However, these countries also have opportunities to "*leapfrog*" traditional energy systems by investing in renewable energy technologies and sustainable infrastructure from the outset. Ramaharo and Randriamifidy (2023) found that trade openness negatively affects renewable energy consumption in Madagascar, highlighting the importance of infrastructure development in facilitating the transition to sustainable energy systems.

The role of infrastructure in moderating the relationship between trade openness, renewable energy adoption, and environmental quality underscores the importance of comprehensive policy interventions. Indeed, investment in digital infrastructure is essential for supporting the integration of renewable energy sources and facilitating sustainable trade practices (Dai et al., 2025; Yu and Du, 2025). Moreover, establishing and enforcing environmental regulations that incentivize clean production and penalize polluting practices are crucial for ensuring that trade openness leads to environmental improvements. Engaging in international cooperation to share knowledge, technologies, and best practices can further support the transition to renewable energy and enhance environmental quality (Faizi et al., 2025; Pham and Nguyen, 2024). In conclusion, the interplay between trade openness, renewable energy adoption, environmental quality, and infrastructure development is complex and context-dependent. While trade openness and renewable energy adoption promise to improve environmental quality, their effectiveness is contingent upon strong infrastructure and supportive governance. By prioritizing investments in infrastructure, enforcing environmental regulations, and fostering international cooperation, countries can navigate the complexities of these interrelationships and promote sustainable development that aligns economic growth with environmental stewardship.

When reviewing the literature, several gaps remain unexplored. First, few studies jointly examine trade openness, renewable energy, and infrastructure in a unified analytical framework. Most research tends to analyze these factors in isolation, overlooking their interdependencies. Second, while there is substantial research on developed countries, comparative studies involving both developed and developing countries are limited, making it difficult to conclude about context-specific mechanisms and policy implications (Abdi et al., 2025). Third, the moderating role of infrastructure, particularly digital infrastructure, in shaping the environmental impact of trade and energy transitions is underexplored. Finally, the dynamic and evolving nature of global trade and energy systems, especially under the influence of climate policies and international agreements, is rarely incorporated into empirical analyses, leaving important temporal dimensions unexamined. Hence, this study fills these gaps by considering the interplay between trade openness, renewable energy, and infrastructure development while accounting for cross-country differences. This research would provide helpful insights for policymakers seeking to leverage trade and renewable energy investments to achieve sustainable development while ensuring that infrastructure development maximizes environmental benefits.

3. SAMPLE AND METHODS

3.1. The Sample

To explore the relationship between trade openness, renewable energy, and environmental quality, and check the role of infrastructure in shaping these relationships, this study uses a panel dataset covering 154 countries over the period 1990-2024. The dataset captures a wide range of economic, environmental, energy, and infrastructure indicators. To account for heterogeneity across different stages of development, the full sample was divided into 112 developing countries and 42 developed countries. This classification enables a comparative analysis, highlighting potential differences in how trade openness and renewable energy affect environmental quality in developed and developing countries. For more details on the list of countries, see Appendix 1.

The main source of data for this study is the World Development Indicators (WDI 1990-2024) database of the World Bank, which provides reliable and consistent information on economic, environmental, energy, and infrastructure indicators.

3.2. Empirical Approach and Model Specification

To explore the link between trade openness, renewable energy, and environmental quality, and to examine the role of infrastructure in developed and developing countries, this study employs a dynamic panel data approach, specifically the System GMM estimator with a two-step. The System GMM is particularly suitable for this analysis as it addresses potential endogeneity issues arising from the simultaneity and reverse causality between trade openness, energy use, and environmental quality (Arellano and Bover, 1995; Blundell and Bond, 1998). This method also accounts for unobserved country-specific effects and the persistence of environmental indicators over time by incorporating lagged dependent variables as instruments. Compared to traditional panel estimators such as fixed effects or ordinary least squares (OLS), System GMM provides more efficient and consistent estimates in panels with a large number of cross-sectional units and a relatively short time dimension, which is common in studies involving multiple countries over several decades (Roodman, 2009). By using the two-step GMM procedure, the study further improves efficiency by correcting for heteroskedasticity and autocorrelation in the error terms, yielding robust standard errors that strengthen the reliability of the results. Overall, the dynamic panel System GMM approach allows for a more rigorous examination of the causal relationships and interactive effects among trade openness, renewable energy, infrastructure, and environmental quality, particularly in the context of heterogeneous countries at different stages of development.

To explore the relationship between trade, renewable energy, and environmental quality and to check whether infrastructure moderates this relationship, we estimate the following three models. In the model (1), we estimate the separate effects of trade and renewable energy on environmental quality. Hence, the econometric model to be tested is given in equation (1):

$$CO2_{i,t} = \alpha_0 + \alpha_1 CO2_{i,t-1} + \alpha_2 TRADE_{i,t} + \alpha_3 REN_{it} + \alpha_4 GDPG_{it} + \alpha_5 GDPGSQ_{i,t} + \alpha_6 POPG_{i,t} + \varepsilon_{i,t} \quad (1)$$

In the second model, we check whether infrastructure moderates the linkage between trade and environmental quality. Hence, the econometric model to be tested is given in equation (2):

$$CO2_{i,t} = \alpha_0 + \alpha_1 CO2_{i,t-1} + \alpha_2 TRADE_{i,t} + \alpha_3 INFRA_{it} + \alpha_4 TRADE{*}INFRA_{i,t} + \alpha_5 GDPG_{it} + \alpha_5 GDPGSQ_{i,t} + \alpha_7 POPG_{i,t} + \varepsilon_{i,t} \quad (2)$$

Finally, in model (3), we check whether infrastructure moderates the linkage between renewable energy and environmental quality. Hence, the econometric model to be tested is given in equation (3):

$$CO2_{i,t} = \alpha_0 + \alpha_1 CO2_{i,t-1} + \alpha_2 REN_{i,t} + \alpha_3 INFRA_{it} + \alpha_4 REN{*}INFRA_{i,t} + \alpha_5 GDPG_{it} + \alpha_5 GDPGSQ_{i,t} + \alpha_7 POPG_{i,t} + \varepsilon_{i,t} \quad (3)$$

All variables used in this study are defined and measured in Table 1.

4. DISCUSSION OF THE EMPIRICAL FINDINGS

This section discusses in detail the empirical findings with supporting evidence. Descriptive statistics are first analyzed to give an overview of the distribution and variability of the main variables. Second, the correlation matrix is checked. Finally, a detailed analysis of the regression and moderating effects is also carried out, shedding light on the relationships between trade, renewable energy, infrastructure, and environmental quality.

4.1. Summary Statistics and Correlation Matrix

Table 2 summarizes the statistics for the key variables that feed the analysis. The dependent variable, carbon emissions per capita, records a mean level of 4.96 metric tons with a standard deviation of 6.49 and a range going from 0.019 to 53.60. The large variation indicates considerable differences in emission levels that can be explained by differences in industrialization, energy structures, and environmental policies, among countries.

The average value of renewable energy consumption in total energy use is 32.24%; the standard deviation is 29.46 and the range from 0.1 to 98.3 show that there are very different situations of renewables use in developed and developing countries. In other words, some countries are still very much dependent on fossil fuels while others have almost entirely shifted to renewable energy. Additionally, statistics show that on average, trade openness registers a value of 83.55% of GDP, with values varying from 2.46% to 442.62% as minimum and maximum respectively. These values indicate that there are some economies that are still relatively closed, while others are very open to international trade. The average GDP growth rate is 3.29%, but the wide range from -54.34% to 86.83% implies that there are both deep recessions and fast growth periods. Infrastructure measured by individuals using the Internet (% of population) has an average of 32.03, which indicates a moderate level. Nevertheless, the very wide range from 0.001 as a minimum to 100 as a maximum supports a strong difference between advanced and developing economies. Finally, the average population growth is 1.45%, with a moderate range from -27.47% to 21.70% which captures a demographic transition.

The Pearson correlation matrix presented in Table 3 generally shows the expected correlations in terms of the variable directions, and it does not contain any very high correlation coefficients. Thus, we can confirm that there are no significant multicollinearity

Table 1: Variable definition and measurement

Acronymsa	Definitions	Measurement	Source
CO_2	Environmental quality	Carbon Dioxide (CO_2) emissions excluding LULUCF per capita (t CO_2e/capita)	WDI (1990-2024)
REN	Renewable energy	Renewable energy consumption (% of total final energy consumption)	WDI (1990-2024)
Trade	Trade openness	Trade (% of GDP)	WDI (1990-2024)
GDPG	Economic growth	GDP (annual % growth)	WDI (1990-2024)
GDPSQ	GDPG Squared	GDP (annual % growth) Squared	WDI (1990-2024)
INFRA	Infrastructure	Individuals using the Internet (% of population)	WDI (1990-2024)
INFRA	Infrastructure	Mobile cellular subscriptions (per 100 people)	WDI (1990-2024)
POPG	Population growth	Population growth (annual %)	WDI (1990-2024)
TRADE*INFRA	Interactional variable	The interaction between trade and infrastructure	The authors' calculation from WDI
TRADE*REN	Interactional variable	The interaction between renewable energy and infrastructure	The authors' calculation from WDI

Table 2: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
CO_2	5,349	4.960	6.491	0.019	53.598
REN	5,349	32.243	29.456	0.100	98.300
TRADE	5,392	83.548	52.008	2.462	442.620
GDPG	5,390	3.291	5.878	−54.336	86.827
GDPGSQ	5,390	44.906	201.631	0.005	7538.884
INFRA	5,390	32.027	32.994	0.001	100.000
POPG	5,390	1.448	1.728	−27.471	21.700

problems and these variables are appropriate for regression analysis.

4.2. The Effect of Trade and Renewable Energy on Environmental Quality

The results from the diagnostic tests confirm the validity and robustness of the GMM estimations. As expected, the Arellano-Bond test for first-order autocorrelation (AR (1)) is significant; while for the second-order autocorrelation (AR (2)) is insignificant across all models, confirming the lack of serial correlation in the residuals. In addition, the Sargan test of over-identifying restrictions provides high P-values, indicating that the instruments are valid and uncorrelated with the error term. Overall, the specification of the model is appropriate, and the estimates are statistically robust. The empirical findings are displayed in Table 4.

The findings from dynamic GMM indicate emissions' persistence over time, attributed to the CO_2 lagged variable coefficient being significant and positive. This means that the current level of CO_2 emission positively and significantly depends on the level of emissions of previous years.

For the full sample and developing countries, trade openness had a positive and significant effect, indicating that trade liberalization increases CO_2 emissions. By promoting industrial activity, transportation, and energy demand linked to increased production and trade volumes, trade openness can raise CO_2 emissions. Additionally, it might result in the "*pollution haven*" effect, when industries that produce a lot of pollution move to nations with weaker environmental regulations. Furthermore, increased trade frequently depends on logistics based on fossil fuels, which raises carbon emissions even more. This result is similar to Mahmood et al. (2019); Oumarou and Nourou (2024). Conversely, renewable energy consumption has a negative and significant effect on CO_2 emissions in all the models, validating its positive contribution to the improvement of the environmental quality. By substituting clean energy sources like solar, wind, and hydropower for fossil fuels, renewable energy lowers CO_2 emissions. It reduces reliance on carbon-intensive power generation and improves energy efficiency. Furthermore, growing renewable energy promotes technological advancement and aids in the long-term shift to a low-carbon economy. This finding is in line with Saidi et al. (2022); Li et al. (2023) and Chen et al. (2023).

Economic growth positively impacts CO_2 emissions, while the squared GDP being negative and significant. This result confirms the sights of the Environmental Kuznets Curve (EKC) hypothesis, which states emissions are positively correlated with income in the early stages of development and inversely after reaching a certain income threshold. This result is consistent with Wang et al. (2023), and Guliyev and Seyfullayev (2025). Finally, population growth significantly increases emissions in the full sample, highlighting demographic pressure as a key driver of environmental degradation. In order to meet consumption needs, a larger population increases industrial production, transportation use, and overall energy demand. This increases carbon emissions by intensifying the use of fossil fuels for heating, power, and transportation. Furthermore, increased resource consumption and environmental stress are frequently the results of rapid urbanization brought on by population growth, especially in nations with inadequate energy infrastructure or sustainable urban planning. This result corroborates the works of Chaurasia (2020), Dong et al. (2018), and Adusah-Poku (2016).

4.3. The Moderating Effect of Infrastructure on the Trade, Renewable Energy and Environmental Quality Relationship

The results in Table 5 examine the moderating role of infrastructure in the relationship between trade openness and environmental quality.

Findings reveal that, for the full sample, trade openness results in higher CO_2 emissions. The infrastructure coefficient is negative and significant not only for the full sample but also for developed countries. This implies that advanced infrastructure, through energy efficiency, cleaner technologies, and improved environmental management, leads to less CO_2 emissions. On the contrary, this coefficient is positive but insignificant in developing

Table 3: Correlation matrix

Variables	CO_2	REN	TRADE	GDPG	GDPGSQ	INFRA	POPG
CO_2	1.0000						
REN	−0.4216*	1.0000					
	0.0000						
TRADE	0.2438*	−0.3153*	1.0000				
	0.0000	0.0000					
GDPG	−0.0209	0.0626*	0.0565*	1.0000			
	0.1336	0.0000	0.0001				
GDPGSQ	0.0190	−0.0348*	0.0289*	0.2139*	1.0000		
	0.1702	0.0144	0.0389	0.0000			
INFRA	0.3287*	−0.3250*	0.3043*	−0.1395*	−0.0221	1.0000	
	0.0000	0.0000	0.0000	0.0000	0.1291		
POPG	0.0300*	0.2633*	−0.0633*	0.2123*	−0.0046	−0.2358*	1.0000
	0.0304	0.0000	0.0000	0.0000	0.7380	0.0000	

Table 4: Results of the separate effect of trade and renewable energy on environmental quality

Variables	Full sample		Developed countries		Developing countries	
	Coef.	z	Coef.	Z	Coef.	z
CO_2 (−1)	1.028	8.19***	0.893	4.78***	1.011	8.94***
TRADE	0.007	2.22**	−0.001	−1.44	0.001	2.36**
REN	−0.012	−11.4***	−0.033	−3.74***	−0.004	−3.07***
GDPG	0.035	4.87***	0.039	9.53***	0.041	6.04***
GDPGSQ	−0.008	−8.36***	−0.005	−10.43***	0.031	−7.98***
POPG	0.182	3.12***	0.008	0.01	0.195	1.53
_cons	0.546	1.75	1.328	0.91	0.432	1.94*
AR (1)	−3.4988		−3.2907		−2.2834	
Prob	0.0005		0.0010		0.0224	
AR (2)	−0.7683		−1.1376		0.2064	
Prob	0.4423		0.2553		0.8365	
Sargan test	149.0658		34.7513		108.0409	
Prob	0.8724		0.5215		0.7314	
Obs	5,012		1,406		3,606	

Table 5: Results of the moderating effect of infrastructure on the trade and environmental quality relationship

Variables	Full sample		Developed countries		Developing countries	
	Coef.	z	Coef.	z	Coef.	z
CO_2 (−1)	1.013	13.02***	0.950	12.06***	1.013	5.73***
TRADE	0.005	−2.64**	−0.002	−1.85*	0.032	9.72***
INFRA	−0.002	−9.95***	−0.012	−2.37**	0.039	1.39
TRADE*INFRA	−0.024	−2.28**	0.003	0.58	−0.003	−7.62***
GDPG	0.035	6.13***	0.033	8.03***	0.040	1.02
GDPGSQ	−0.014	−5.6***	−0.023	−9.74***	−0.012	−8.99***
POPG	0.192	3.53****	0.017	2.75***	0.195	3.49***
_cons	0.170	1.39	0.525	1.61	0.184	1.01
AR (1)	−3.6323		−3.4607		−2.3802	
Prob	0.0003		0.0005		0.0173	
AR (2)	−0.6129		−0.9806		0.2614	
Prob	0.5399		0.3268		0.7938	
Sargan test	148.7786		34.2355		104.8829	
Prob	0.8645		0.5198		0.7286	
Obs	5,012		1,406		3,606	

countries, which may suggest that infrastructure development in these countries has not yet led to the environment's liberation, perhaps because of carbon-intensive infrastructure, less strict environmental regulation, or insufficient use of green technologies. Furthermore, the interaction term (TRADE*INFRA) is negative and significant for the full sample and developing countries. This means that improved infrastructure can alleviate the environment problems caused by trade through cleaner production and energy efficiency.

In developed countries, the impact of infrastructure as a moderator is not statistically significant. Thus, the environmental effects of trade are not largely influenced by the quality of infrastructure, which may be explained by the fact that the systems are already advanced and cleaner. However, in developing countries, both trade and the interaction term are significant, with trade leading to increased emissions, and the negative interaction term showing that infrastructure upgrades can counterbalance the environmental degradation caused by trade. Consequently, these results suggest

Table 6: Results of the moderating effect of infrastructure on the renewable energy and environmental quality relationship

Variables	Full sample		Developed countries		Developing countries	
	Coef.	z	Coef.	z	Coef.	z
CO_2 (−1)	0.994	7.79***	0.903	6.45***	1.013	9.28***
REN	−0.017	−8.05***	−0.033	−3.24***	−0.005	−4.55***
INFRA	−0.001	−1.73	−0.002	−4.34***	0.003	1.57
REN*INFRA	−0.004	−6.27***	0.036	0.06	−0.012	−4.74***
GDPG	0.036	7.76***	0.040	7.62***	0.040	9.88***
GDPGSQ	−0.013	−8.09***	−0.033	−4.02***	−0.003	−5.82***
POPG	0.179	7.09***	−0.002	−0.13	−0.194	−1.53
_cons	0.685	1.35	1.14	1.31	0.348	1.61
AR (1)	−3.5793		−3.4037		−2.3229	
Prob	0.0003		0.0007		0.0202	
AR (2)	−0.67172		−1.0528		0.2819	
Prob	0.5018		0.2924		0.7780	
Sargan test	152.5789		36.5272		108.1696	
Prob	0.9145		0.5348		0.7372	
Obs	5,012		1,406		3,606	

that improving the quality of infrastructure can facilitate the capacity of trade openness to be an environmental ally, especially in developing economies.

Table 6 shows the effect of infrastructure as a moderator on the relationship between renewable energy and environmental quality.

It is evident from the results displayed in Table 6 that renewable energy is vital for the improvement of the environmental quality, as it has a negative and significant effect on CO_2 emissions. This result is confirmed for the whole sample and the two sub-samples. For developed countries, the negative coefficient of infrastructure is significant, implying that well-built infrastructure lowers CO_2 emissions by promoting the integration of renewable energy systems and improving energy efficiency. Advanced waste management, smart grids, and efficient transportation all reduce energy loss and environmental impact. For developing countries, the infrastructure coefficient is positive but still insignificant.

The interaction term (REN*INFRA) for the whole sample is negative and significant, stating that the release of CO_2 is due to the quality of infrastructure. Similarly, the interaction term is negative and significant in developing countries, indicating that a willingness to invest in renewable energy and better infrastructure results in lower CO_2 emissions. This implies that effective infrastructure improves the performance, uptake, and distribution of renewable energy technologies while also improving the quality of the environment. Overall, the findings suggest that infrastructure, provided it is of high quality and environmentally sustainable, has the potential to enhance the benefits of renewable energy on climate change.

5. CONCLUSION AND POLICY RECOMMENDATION

This study investigates the relationship between trade openness, renewable energy, and environmental quality in both developed and developing countries. Specifically, it focused on how infrastructure moderates this relationship. To address endogeneity, dynamic effects, and unobserved country-specific heterogeneity, we used the two-step System Generalized Method of Moments estimator on a dataset that covered 154 countries between 1990 and 2024. To account for heterogeneity, we divided the sample into 112 developing countries and 42 developed countries. Overall, the results support that infrastructure has varying effects across samples, renewable energy enhances environmental quality, and trade openness increases CO_2 emissions.

Several policy implications arise from the study's findings. The findings emphasize the significance of coordinated strategies that incorporate infrastructure development, trade policies, and the promotion of renewable energy for the full sample. To maximize the environmental benefits of trade openness and renewable energy, policymakers should give priority to investments in energy and digital infrastructure. This will improve energy efficiency and facilitate the adoption of clean technologies. To ensure that trade expansion and energy transitions further improve environmental quality, policies for developed nations, where sophisticated infrastructure and regulatory frameworks already exist, should focus on ongoing innovation, modernizing current energy and transportation systems, and enforcing stricter environmental standards. Developed nations can also take the lead in promoting global technology transfer and the exchange of best practices. For developing countries, the results point to the necessity of focused investments in capacity-building and foundational infrastructure. Enhancing energy efficiency, increasing access to renewable energy technologies, and fortifying institutional frameworks to control trade-related environmental effects should all be goals of policy. Developing countries can also use "*leapfrogging*" tactics, which avoid more polluting conventional methods, by making direct investments in green infrastructure and sustainable energy systems. All things considered, these distinct policy suggestions highlight the need for context-specific interventions that are adapted to each nation's level of development and infrastructure to implement successful environmental and economic strategies.

This study has certain limitations despite the insights it provided. First, the analysis is based on aggregate data, which may not take into consideration sectoral or regional differences in the ways that trade openness, renewable energy, and infrastructure affect environmental quality. Second, the study primarily substitutes CO_2 emissions for environmental quality, potentially overlooking significant factors like air pollution, biodiversity loss, and resource depletion. Even though the sample covers a large number of countries over a long period of time, the observed relationships may also be affected by structural changes in global trade, energy systems, and climate policies over time.

Future research could get around these limitations by looking into more environmental quality indicators and incorporating more disaggregated data at the sectoral or regional levels. Future studies could also examine threshold effects, non-linear relationships, and the ways that institutional quality affects the relationship between trade and renewable energy policies in different development contexts.

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Appendix 1: List of countries

Developing countries		Developed countries	
Afghanistan	Gabon	Oman	Australia
Albania	Gambia, The	Pakistan	Austria
Algeria	Georgia	Panama	Belgium
Angola	Ghana	Paraguay	Canada
Argentina	Guatemala	Peru	Croatia
Armenia	Haiti	Philippines	Cyprus
Azerbaijan	Honduras	Qatar	Czechia
Bahamas, The	India	Romania	Denmark
Bahrain	Indonesia	Russian Federation	Estonia
Bangladesh	Iran, Islamic Rep.	Rwanda	Finland
Belarus	Jamaica	Saudi Arabia	France
Belize	Jordan	Senegal	Germany
Benin	Kazakhstan	Seychelles	Greece
Bhutan	Kenya	Solomon Islands	Hong Kong SAR, China
Bolivia	Kiribati	South Africa	Hungary
Bosnia and Herzegovina	Kuwait	Sri Lanka	Iceland
Botswana	Kyrgyz Republic	Sudan	Ireland
Brazil	Lao PDR	Syrian Arab Republic	Italy
Brunei Darussalam	Lebanon	Tajikistan	Japan
Bulgaria	Lesotho	Tanzania	Korea, Rep.
Burkina Faso	Libya	Thailand	Latvia
Burundi	Madagascar	Togo	Lithuania
Cabo Verde	Malaysia	Tonga	Luxembourg
Cambodia	Maldives	Tunisia	Macao SAR, China
Cameroon	Mali	Turkiye	Malta
Chad	Mauritania	Uganda	Netherlands
Chile	Mauritius	Ukraine	New Zealand
China	Mexico	Uruguay	Norway
Colombia	Moldova	Uzbekistan	Poland
Comoros	Mongolia	Vanuatu	Portugal
Congo, Dem. Rep.	Morocco	Venezuela, RB	Singapore
Congo, Rep.	Mozambique	Viet Nam	Slovak Republic
Costa Rica	Namibia	Yemen, Rep.	Slovenia
Dominica	Nepal	Zambia	Spain
Dominican Republic	Nicaragua	Zimbabwe	Sweden
Ecuador	Niger		Switzerland
Egypt, Arab Rep.	Nigeria		United Arab Emirates
El Salvador	North Macedonia		United Kingdom
Fiji			United States