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Research Article

Determinants of CO_2 Emissions in Belt and Road Initiative Countries: Evidence from Panel models

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Abstract

This study investigates the determinants of CO_2 emissions in 146 Belt and Road Initiative (BRI) countries over the period 1990–2023 using a comprehensive panel data framework. The analysis examines the effects of economic growth, population, fossil fuel energy consumption, renewable energy consumption, and foreign direct investment (FDI) on environmental degradation. To ensure robustness and address issues of unobserved heterogeneity, endogeneity, and dynamic persistence, the study employs pooled OLS, fixed effects, first-difference, and System GMM estimators. The empirical results show that population growth, fossil fuel energy consumption, and FDI consistently increase CO_2 emissions across all model specifications. In contrast, renewable energy consumption significantly reduces emissions, highlighting its role in promoting environmental sustainability. The relationship between GDP and CO_2 emissions is found to be non-linear, supporting the Environmental Kuznets Curve (EKC) hypothesis, where the impact of economic growth on emissions varies across development stages. The findings suggest that environmental degradation in BRI countries is primarily driven by demographic pressure, carbon-intensive energy use, and foreign investment patterns, while renewable energy adoption plays a mitigating role. Policy implications emphasize the need to accelerate the transition toward clean energy, improve environmental regulation of FDI, and promote sustainable development strategies in rapidly growing economies.

Keywords: CO_2 emissions, Belt and Road Initiative, EKC, renewable energy, FDI, panel data, System GMM

1. Introduction

Climate change has become one of the most pressing global challenges of the 21st century, driven largely by the continuous increase in greenhouse gas emissions, particularly carbon dioxide (CO_2). Despite global efforts under frameworks such as the Paris Agreement, CO_2 emissions continue to rise, especially in developing and emerging economies where economic growth, industrial expansion, and energy demand remain strongly dependent on fossil fuels [1, 2]. Recent evidence suggests that while some advanced economies are beginning to decouple economic growth from emissions, many developing regions are still experiencing a strong positive link between economic activity and environmental degradation [3]. In this context, the Belt and Road Initiative (BRI), which includes a large group of developing and emerging economies across Asia, Africa, and Europe, has attracted growing academic attention. The large-scale infrastructure investments and increased trade and financial integration under the BRI have significantly influenced energy consumption patterns, industrial activity, and environmental outcomes across participating countries. While the initiative promotes economic development and connectivity, concerns have been raised regarding its potential environmental consequences, particularly through increased fossil fuel use and pollution-intensive industrial relocation [4-6].

Previous studies have identified several key determinants of CO_2 emissions, including economic growth, population dynamics, energy consumption patterns, and foreign direct investment (FDI). The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation initially increases with income but eventually declines after a certain level of economic development is reached. However, empirical findings remain mixed, particularly in developing and heterogeneous panels such as

BRI countries [7-9]. Moreover, the role of renewable energy in reducing emissions and the environmental impact of FDI remain debated, with some studies supporting the "pollution haven" hypothesis while others highlight technology transfer and efficiency gains [10, 11].

Given these inconsistencies, this study examines the determinants of CO_2 emissions in 146 BRI countries over the period 1990–2023 using a comprehensive panel data approach. By employing pooled OLS, fixed effects, first-difference, and System GMM estimators, the study provides robust evidence while addressing issues of heterogeneity, endogeneity, and dynamic persistence. The study also tests the validity of the EKC hypothesis and evaluates the roles of renewable energy and FDI in shaping environmental outcomes. The findings contribute to the existing literature by providing updated and robust evidence on the environmental implications of economic growth, energy structure, population dynamics, and globalization in BRI economies. They also offer important policy insights for achieving sustainable development through cleaner energy transition and environmentally responsible investment strategies.

2. Literature Review

The relationship between economic growth and environmental degradation has been widely examined in the empirical literature, with particular attention given to CO_2 emissions as a key indicator of environmental quality. A central framework in this literature is the Environmental Kuznets Curve (EKC) hypothesis, which suggests an inverted U-shaped relationship between income and environmental degradation. According to this hypothesis, pollution initially increases during early stages of economic development but eventually declines as income rises and economies shift toward cleaner technologies and stricter environmental regulations [12, 13]. Recent studies, however, provide mixed evidence on the validity of the EKC, particularly in developing and emerging economies where structural dependence on fossil fuels remains high [14, 8].

Energy consumption has been identified as a major determinant of CO_2 emissions in both developed and developing countries. Empirical findings consistently show that fossil fuel energy consumption contributes significantly to environmental degradation due to its carbon-intensive nature. In contrast, renewable energy consumption is generally found to reduce emissions by replacing polluting energy sources and improving energy efficiency [15,16]. However, the magnitude of this effect varies across countries depending on energy infrastructure, technological capacity, and policy frameworks. Population growth is another key driver of CO_2 emissions. The IPAT framework (Impact = Population × Affluence × Technology) suggests that population size directly influences environmental pressure through increased energy demand, consumption, and urbanization [17]. Recent empirical studies confirm that population growth tends to increase CO_2 emissions, particularly in developing economies where rapid urban expansion and industrialization intensify resource use.

Foreign direct investment (FDI) has received significant attention in the environmental economics literature due to its ambiguous impact on emissions. The pollution haven hypothesis argues that multinational firms relocate pollution-intensive activities to countries with weaker environmental regulations, thereby increasing emissions in host countries [18]. Conversely, the pollution halo hypothesis suggests that FDI can reduce emissions by transferring cleaner technologies and improving production efficiency [19]. Empirical evidence remains mixed, with recent studies finding that the impact of FDI depends on institutional quality, industrial structure, and regulatory enforcement [7]. In the context of the Belt and Road Initiative (BRI), recent research has increasingly focused on its environmental implications. The large-scale infrastructure development and trade expansion associated with the BRI have raised concerns about increased fossil fuel consumption and carbon emissions in participating countries. Studies indicate that while the BRI promotes economic integration and growth, it may also intensify environmental pressure due to reliance on carbon-intensive industries, particularly in developing member countries [20]. At the same time, some studies highlight potential environmental benefits through green investment cooperation and renewable energy projects under the initiative.

Despite growing literature on these topics, there remains a gap in comprehensive cross-country analyses that jointly examine economic growth, energy structure, population dynamics, and FDI within a unified dynamic panel framework for BRI countries.

This study addresses this gap by employing multiple econometric techniques, including System GMM, to provide robust evidence on the determinants of CO_2 emissions over a long time period.

In recent years, the empirical consensus regarding the determinants of environmental degradation within the Belt and Road Initiative (BRI) has transitioned from identifying isolated economic variables to modeling complex, structurally coupled macroeconomic transmission channels. Recent research highlights a clear dichotomy between localized structural optimization and regional environmental pressures. For instance, investigations into urban carbon emission intensity (CEI) reveal that while the BRI actively facilitates industrial restructuring and the relocation of traditional energy-intensive production out of major economic centers, this redistribution structurally alters the energy intensity of transit nodes and host countries [21]. Furthermore, modern econometric evaluations indicate that macro-level determinants like regional integration and current account dynamics only result in net environmental mitigation when tightly coupled with targeted domestic green infrastructure policies; otherwise, expanding economic connectivity tends to nullify the environmental gains of localized renewable energy transitions [6].

3. Research Methodology

3.1. Analytical framework and model specification

This study uses a panel dataset of 146 Belt and Road Initiative (BRI) countries covering the period 1990–2023. The dataset is structured as a country-year panel, which allows the analysis to capture both cross-country heterogeneity and time variation in environmental and macroeconomic factors. The long time span enables the study to observe structural changes in energy consumption patterns, economic development, and environmental outcomes over time.

3.2. Variables

The dependent variable is carbon dioxide emissions (CO_2), used as a proxy for environmental degradation. The explanatory variables include economic growth (GDP), population (POP), fossil fuel energy consumption (FSFE), renewable energy consumption (RE), and foreign direct investment (FDI) [22]. GDP captures the scale of economic activity and development level, while population reflects demographic pressure on energy demand and environmental resources [23]. FSFE represents dependence on carbon-intensive energy sources, whereas RE captures the shift toward cleaner and more sustainable energy systems. FDI is included to examine the role of international capital flows in shaping environmental outcomes through scale, composition, and technique effects [24].

3.3. Empirical Models

This study specifies three main empirical models to examine the determinants of CO_2 emissions.

Model 1 (Baseline specification):

$$CO_2\_it = \beta_0 + \beta_1 GDP\_it + \beta_2 POP\_it + \beta_3 FSFE\_it + \beta_4 RE\_it + \beta_5 FDI\_it + \varepsilon\_it$$

This model estimates the direct effects of macroeconomic, demographic, and energy-related variables on CO_2 emissions without additional nonlinear or interaction terms.

Model 2 (EKC specification):

$$CO_2\_it = \beta_0 + \beta_1 GDP\_it + \beta_2 GDP^2\_it + \beta_3 POP\_it + \beta_4 FSFE\_it + \beta_5 RE\_it + \beta_6 FDI\_it + \varepsilon\_it$$

This model incorporates the squared term of GDP to test the Environmental Kuznets Curve (EKC) hypothesis, which suggests a nonlinear relationship between economic growth and environmental degradation.

Table 1. Descriptive statistics.

variables	Mean	Std.Dev	Min	max
co2	0.3826513	1.619924	-3.826326	3.864029
gdp	3.791912	6.383486	-58.31823	153.4926
pop	3.852598	0.4947065	2.057963	4.60517
fsfe	4.04408	0.728717	0.4945336	4.60517
re	2.871173	1.605257	-2.302585	4.588024
fdi	0.9861596	1.325302	-6.684429	6.107207

Table 2. Correlations.

	lgco2	gdp	lgpop	lgfsfe	lgre	lgfdi
lgco2	1					
gdp	-0.0751	1				
lgpop	0.7753	-0.0859	1			
lgfsfe	0.8042	-0.0516	0.6221	1		
lgre	-0.707	-0.0395	-0.5448	-0.6467	1	
lgfdi	0.1647	0.1054	0.234	0.1024	-0.1013	1

3.4. Econometric Models

3.4.1. Pooled Ordinary Least Squares (OLS)

The pooled OLS model is employed as a baseline estimation technique. It assumes homogeneity across countries and ignores unobserved country-specific and time-specific heterogeneity. In this specification, CO_2 emissions are regressed on the explanatory variables using the full pooled sample, treating the panel data as a single cross-section. While pooled OLS provides an initial indication of the relationships among variables, it is prone to omitted variable bias because it does not account for unobserved heterogeneity across countries or over time. As a result, the estimated coefficients may be biased and inconsistent if country-specific effects are correlated with the regressors.

3.4.2. Fixed Effects (FE) Model

The Fixed Effects model addresses the limitations of pooled OLS by controlling for unobserved, time-invariant heterogeneity across countries. Such factors may include geographical characteristics, institutional quality, cultural differences, or persistent policy frameworks that influence CO_2 emissions. By allowing each country to have its own intercept, the FE estimator effectively removes bias arising from these unobserved characteristics. The model exploits within-country variation over time, making it particularly suitable for panel data settings where cross-country heterogeneity is substantial. However, the FE model does not address potential endogeneity arising from simultaneity, reverse causality, or dynamic persistence.

3.4.3. System Generalized Method of Moments (System GMM)

The System GMM estimator is used to address endogeneity concerns, including reverse causality, omitted variable bias, and dynamic persistence in CO_2 emissions. It is particularly appropriate for dynamic panel data models that include a lagged dependent variable as a regressor. System GMM combines equations in first differences and in levels, using lagged values of endogenous and predetermined variables as internal instruments. This approach improves efficiency and reduces bias relative to difference GMM,

especially when variables are persistent over time. The estimator is well-suited for large-N, moderate-T panels, such as the dataset of 149 Belt and Road Initiative (BRI) countries over the period 1990–2023, where both heterogeneity and endogeneity are likely to be present.

4. Results and discussions

Table 3 presents the regression results for the determinants of CO_2 emissions across four model specifications. The findings show that population (lgpop), fossil fuel energy consumption (lgfsfe), renewable energy (lgre), and foreign direct investment (lgfdi) are consistently significant across all models, while GDP (gdp) exhibits mixed and model-dependent effects. Population has a strong, positive, and highly significant impact on CO_2 emissions in all specifications, indicating that population growth is a major driver of emissions. Fossil fuel energy consumption is also positive and significant throughout, confirming its role in increasing environmental degradation. In contrast, renewable energy consistently shows a negative and significant effect, suggesting that higher renewable energy use helps reduce CO_2 emissions [22]. FDI is positive and significant in all models, with increasing magnitude in later specifications, supporting the possibility that foreign investment is associated with more emission-intensive activity. GDP is insignificant in early models but becomes significant with varying signs in later specifications, indicating a non-linear relationship with emissions and sensitivity to model specification. The lagged GDP term further suggests dynamic effects of economic activity on emissions [25,9]. Overall, Table 3 indicates that emissions are primarily driven by population growth, fossil fuel dependence, and FDI inflows, while renewable energy plays a mitigating role.

Table 3. Regression results for determinants of CO_2 Emissions

	(1)	(2)	(3)	(4)
VARIABLES	lgco2	lgco2	lgco2	lgco2
Gdp	0.000520	0.000576	0.000600**	-0.00332***
	(0.000679)	(0.000677)	(0.000236)	(0.000333)
Lgpop	1.076***	0.999***	1.186***	1.679***
	(0.0600)	(0.0635)	(0.0680)	(0.0503)
Lgfsfe	0.712***	0.702***	0.648***	1.050***
	(0.0288)	(0.0295)	(0.0143)	(0.0224)
Lgre	-0.156***	-0.149***	-0.0852***	-0.0592***
	(0.0123)	(0.0126)	(0.00568)	(0.0109)
Lgfdi	0.00757**	0.00828**	0.0134***	0.0231***
	(0.00385)	(0.00384)	(0.00137)	(0.00193)
L.gdp			0.00172***	-0.00506***
			(0.000168)	(0.000422)
Constant	-6.032***	-5.701***		-10.00***
	(0.252)	(0.258)		(0.187)
Observations	1,580	1,580	1,347	1,490
R-squared		0.511		
Number of id	101	101	100	101

Table 3 presents the results from the first-difference and System GMM estimations for CO_2 emissions. In Column (1), GDP has a positive but statistically insignificant effect, while its squared term is negative and highly significant, indicating a non-linear relationship between economic growth and emissions. In Column (2), GDP becomes negative and highly significant, while the

squared term remains significant, reinforcing the presence of a non-linear (Environmental Kuznets Curve-type) relationship across both estimators.

Population (lgpop) is positive and highly significant in both models, with a larger coefficient in the System GMM estimation, suggesting that population growth is a strong and persistent driver of CO_2 emissions. Fossil fuel energy consumption (lgfsfe) is also positive and highly significant in both specifications, confirming that greater reliance on fossil fuels consistently increases emissions, with a stronger effect under System GMM.

Renewable energy (lgre) is negative and highly significant in both models, indicating that increased use of renewable energy reduces CO_2 emissions. The effect remains robust across estimators, although the magnitude is slightly smaller in the System GMM model. Foreign direct investment (lgfdi) is positive and highly significant in both columns, suggesting that FDI contributes to higher emissions, supporting the pollution haven hypothesis.

Overall, the results across both estimators are consistent: population, fossil fuel consumption, and FDI increase CO_2 emissions, while renewable energy reduces them. GDP shows a robust non-linear relationship with emissions, confirming the presence of an Environmental Kuznets Curve effect in the sample.

5. Conclusion

This study investigated the determinants of CO_2 emissions in 146 Belt and Road Initiative (BRI) countries over the period 1990–2023 using a panel data framework. The analysis employed pooled OLS, fixed effects, first-difference, and System GMM estimators to ensure robustness and address issues of unobserved heterogeneity, endogeneity, and dynamic persistence. The empirical findings consistently show that population, fossil fuel energy consumption, and foreign direct investment are key drivers of CO_2 emissions across all model specifications. Population has the strongest and most stable positive effect, highlighting the dominant role of demographic pressure on environmental degradation. Fossil fuel energy consumption also significantly increases emissions, confirming the critical influence of energy structure in shaping environmental outcomes. Similarly, FDI is positively associated with emissions, supporting the pollution haven hypothesis and suggesting that foreign investment may be concentrated in more pollution-intensive sectors within BRI economies. In contrast, renewable energy consumption consistently reduces CO_2 emissions across all estimators, demonstrating its effectiveness in mitigating environmental damage and supporting the transition toward cleaner energy systems. This result underscores the importance of accelerating renewable energy adoption in achieving environmental sustainability. The relationship between GDP and CO_2 emissions is found to be non-linear and consistent with the Environmental Kuznets Curve (EKC) hypothesis. The inclusion of GDP and its squared term across dynamic specifications confirms that the impact of economic growth on emissions changes across development stages, shifting from an increasing to a potentially decreasing effect at higher income levels. This finding is further strengthened by the System GMM results, which account for endogeneity and dynamic effects.

Overall, the results suggest that CO_2 emissions in BRI countries are primarily driven by population growth, fossil fuel dependence, and foreign investment patterns, while renewable energy plays a mitigating role. The evidence highlights the need for policy measures that promote cleaner energy transition, improve the environmental quality of FDI, and manage the environmental pressures associated with rapid demographic and economic growth. Despite these contributions, the study has some limitations. First, the analysis is constrained by data availability and may not fully capture country-specific institutional and technological differences that influence emissions. Second, although System GMM addresses endogeneity, the choice of instruments may still introduce potential bias if not perfectly exogenous. Third, the study does not explicitly account for sectoral-level emissions or differences in environmental regulation across countries, which may lead to aggregation bias.

Future research could extend this work by incorporating sector-specific data (such as industry, transport, and agriculture emissions) to provide a more detailed understanding of emission sources. Additionally, future studies may explore the role of institutional quality, environmental regulations, and green innovation in shaping emissions dynamics. Comparative studies between

BRI and non-BRI countries, or regional sub-sample analyses, could also provide deeper insights into heterogeneous effects across different economic groups..

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