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RESEARCH ARTICLE

THE IMPACT OF GEOPOLITICAL RISK, TRADE OPENNESS, AND ENERGY CONSUMPTION ON CARBON EMISSIONS: THE CASE OF TURKEY

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Abstract

This paper examines the key determinants of carbon emissions in Turkey using data from the period 1995–2023. The primary objective is to reveal the impacts of the geopolitical risk index, trade openness, energy consumption, and income levels on emissions. To jointly assess the short – and long-run relationships, the Autoregressive Distributed Lag (ARDL) approach is employed. The findings indicate that electricity consumption increases emissions in both the short and long run, while income contributes to emission growth, particularly in the long run. The trade Openness exhibits a complex relationship, showing both mitigating and aggravating effects in different periods. Geopolitical risk has a limited direct impact on emissions and does not play as pronounced a role as energy and trade channels. The results emphasize the importance of reducing the carbon intensity of energy production and consumption, implementing energy efficiency policies, and adopting low-carbon strategies in foreign trade to mitigate emissions. Furthermore, the design of energy security policies should take into account the potential influence of geopolitical uncertainties.

Keywords: Geopolitical Risk, Energy Consumption, Carbon Emissions, Trade Openness, ARDL Model
Jel Codes: F52, Q41, Q54, F18, C22

1. Introduction

The adverse consequences of climate change one of the most pressing environmental issues driven by global warming have been intensifying each day and often result in devastating outcomes. Since the Industrial Revolution, the detrimental effects of rising global temperatures have led numerous scholars to investigate the causes and propose mitigation strategies (IPCC 2023; Stern 2007). In this context, reducing greenhouse gas emissions, which contribute significantly to global warming, has become a central goal in environmental research and policymaking. Among all greenhouse gases, carbon dioxide (CO_2) stands out as the most harmful in terms of its impact on climate change, accounting for approximately 75% of total emissions. In particular, CO_2 resulting from fossil fuel consumption remains in the atmosphere for more than a century. Fossil

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fuels, which are major sources of CO_2, are widely used in production processes and are especially prevalent in emerging economies such as Turkey, where economic growth objectives continue to drive emissions upward.

As a result of efforts spearheaded by the United Nations, the foundations of the Framework Convention on Climate Change were laid in 1991. Since then, a series of international agreements have been established to curb environmental degradation and reduce carbon emissions. However, many of these agreements have lacked binding enforcement mechanisms, thereby limiting their effectiveness in mitigating emissions. The most recent initiative, the European Green Deal (European Commission 2019), introduced more stringent measures aimed at emission reduction. Within this framework, the Carbon Border Adjustment Mechanism (CBAM) has been developed to impose regulatory instruments such as carbon tariffs on embedded emissions in international trade (European Commission 2021). The economic growth goals of countries, alongside increasing fossil fuel use, tend to move in tandem with rising emission levels. This paper presents Figure 1, which illustrates the trends in carbon emissions and gross domestic product (GDP) growth for Turkey over the 1990–2023 period, based on data obtained from the World Bank and compiled by the author.

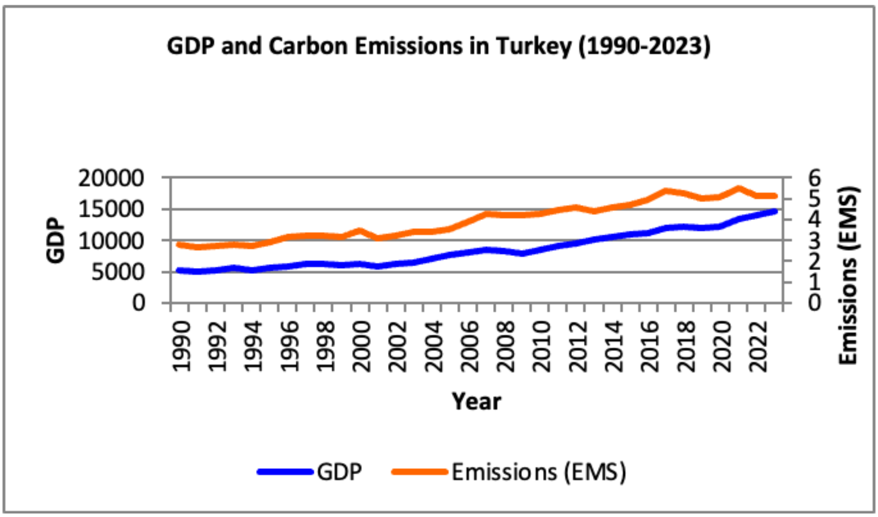

Figure 1. Economic Growth and Carbon Emissions in Turkey (1990–2023)
Source: Author's own elaboration based on data obtained from the World Bank

Figure 1 clearly shows that per capita GDP and per capita carbon emissions in Turkey moved in tandem over the 1990–2023 period. In the post - 2000 years, when economic growth accelerated, carbon emissions also rose markedly. Especially after 2010, the increase in GDP parallels the increase in emissions. This pattern indicates that environmental pressures intensify during periods of heightened economic activity and reveals that Turkey's economy largely rests on a fossil – fuel – based structure of production and consumption. The rise in fossil-fuel-related emissions is also indirectly associated with international trade. In Turkey, the trade openness is driven to a considerable extent by energy demand, with coal, oil, and natural gas dominating imports. Fossil-fuel imports contribute both to the current-account Openness and to higher carbon emissions (Özokcu and Özdemir 2017).

As a primary energy source, fossil fuels are widely used in industrial production and substantially increase CO2 emissions. The sectors prioritized under the Carbon Border Adjustment Mechanism (cement, iron and steel, aluminum, fertilizer, and electricity) are among the most emission intensive precisely because of their high fossil-fuel use. Reducing fossil-fuel consumption and switching to renewable energy sources lowers carbon emissions (Mukhtarov et al. 2024).

A substantial body of research examines the determinants of carbon emissions. In recent years, particular attention has turned to the relationship between Geopolitical Risk Index (GPR) and emissions. (Caldara and Iacoviello 2022) define GPR to include ethnic conflicts, religious disputes, economic dependencies, political unrest, and other events that threaten national sovereignty, while Hu et al. (2023) also emphasize military interventions, armed threats, interventions by major powers, and terrorism developments that threaten national military security.

For Turkey, its prominent role in international trade and recurrent border related disputes place it among countries with relatively high geopolitical risk. The GPR index for Turkey constructed by (Caldara and Iacoviello 2022) is presented in Figure 2.

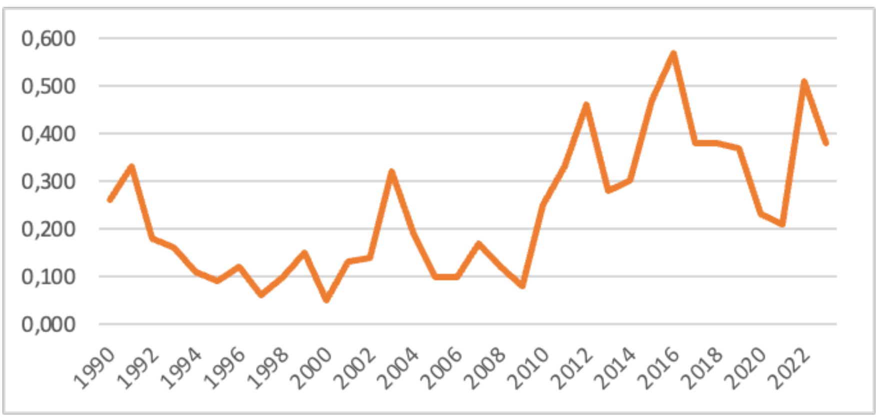

Figure 2. Geopolitical Risk Index for Turkey (1990–2023)
Source: Created by the author based on Caldara and Iacoviello (2022).

As illustrated in Figure 2, the Turkey Geopolitical Risk index for 1990–2023 exhibits pronounced fluctuations over time. After relatively high readings in the early 1990s, the GPR trended downward until the early 2000s, a pattern that can be linked to the relative stability of the post–Cold War period. Around 2003, the index displays a sharp spike, plausibly associated with the U.S. invasion of Iraq and heightened concerns over Turkey's border security. The post-2011 period is characterized by a marked rise in geopolitical risk; the Syrian civil war, terrorist attacks within

Turkey, the 2016 coup attempt, and cross-border military operations collectively drove the index sharply higher. The peak in 2016 likely reflects a moment when perceived internal and external threats reached a maximum. After 2018, the index shows a relative decline, though geopolitical uncertainties remain elevated. These swings make the GPR a critical indicator for understanding the implications of geopolitical conditions for Turkey's economy and security policies.

Given Turkey's strategic and geographic position, examining the relationship between GPR and carbon emissions is particularly salient. The literature evaluates the GPR–emissions nexus along two channels. First, higher GPR may dampen economic activity, reducing energy use and thereby lowering emissions. Second, rising GPR may discourage investment in technology and renewable energy, which negatively affects environmental outcomes by increasing emissions (Anser et al. 2021a).

The steadily rising volume of carbon emissions worldwide has become one of the major obstacles to achieving sustainable development goals. In this context, the increase in emissions accelerates climate change and compels a reshaping of environmental policies. Balancing economic growth targets with environmental sustainability has become even more complex for developing countries. For energy import dependent economies with persistent trade openness, such as Turkey, sustaining economic development without harming the environment is a priority for policymakers.

Within this framework, three factors stand out among the determinants of environmental performance: renewable energy use, the level of geopolitical risk, and the foreign trade balance. Substituting renewable energy sources for fossil fuels is widely regarded as an effective instrument for reducing carbon emissions. At the same time, geopolitical risks can indirectly affect emission levels by influencing energy supply security, investment decisions, and environmental priorities. Moreover, trade openness may intensify environmental burdens through their pressures on production and consumption; import-dependent consumption patterns tend to raise carbon emissions.

In this context, the study aims to analyze, within an econometric framework, the impact of energy consumption, the geopolitical risk index, per capita GDP, and the trade Openness on per capita carbon emissions in Turkey, using data from the 1990–2023 period. In the literature, studies that examine these variables collectively are limited; therefore, this paper offers an original contribution in this regard. The study is organized into four sections: the first section presents the theoretical framework in the introduction; the second section provides a review of the relevant literature; the third section outlines the analysis and findings; and the fourth section discusses the conclusions and implications.

2. Literature

A substantial body of research examines the adverse consequences of climate change driven by the rise in carbon dioxide (CO_2) emissions, which amplify global warming and environmental damage. As carbon emissions widely regarded as the principal cause of environmental pollution and global warming continue to increase, identifying their determinants and clarifying the nature of these relationships has become increasingly important. In this vein, the number of empirical papers analyzing the link between the Geopolitical Risk index developed by (Caldara and Iacoviello 2022) and carbon emissions has recently grown. In line with the focus of this paper, prior work addressing the relationships between carbon emissions and three key variables geopolitical risk, the foreign trade openness, and renewable energy consumption is reviewed under separate subsections.

2.1 Geopolitical Risk and Carbon Emissions

Luo and Sun (2024) examine the relationship between GPR and CO_2 for 27 countries using annual data for 1990–2020. Applying ordinary least squares, fixed and random-effects models, and panel quantile regression, the paper finds that GPR increases CO_2 emissions, with stronger effects among high-emitting countries. Using monthly data for China over 2000–2020, (Wang et al. 2022) analyze the causal linkage between GPR and CO_2. While full-sample tests do not detect Granger causality, sub-sample analyses reveal time varying, bidirectional effects: in some periods GPR raises CO_2, in others it lowers it; likewise, CO_2 influences GPR in a manner that shifts over time. Focusing on the BRICS, (Anser et al. 2021b) conduct panel analyses for 1985–2015. After accounting for cross-sectional dependence and slope heterogeneity and establishing cointegration via the Westerlund test, the paper estimates long-run coefficients using the Augmented Mean Group estimator and reports that geopolitical risk significantly increases CO_2 emissions in the long run. Also, for BRICS, (Zhao et al. 2021) employ ARDL and Nonlinear Autoregressive Distributed Lag models for 1985–2019 to study asymmetric effects. Their results indicate that positive changes in geopolitical risk reduce emissions in Russia and South Africa, whereas negative changes reduce emissions in China, India, and South Africa. (Riti et al. 2022) investigate the impact of geopolitical risk on environmental degradation measured by CO_2 emissions and ecological footprint in BRICS over 1990–2019. Using panel cointegration tests, the Pooled Mean Group (PMG) estimator, and panel causality tests, the paper finds that, at the panel level, geopolitical risk exacerbates environmental degradation, while country-specific results vary. (Chu et al. 2023) analyze E7 countries over 1995–2018, using panel cointegration and PMG-ARDL methods to assess the effects of GPR and economic policy uncertainty (EPU) on CO_2 emissions and ecological footprint. The findings suggest that GPR and EPU worsen environmental outcomes in the long run; in the short run, some adverse and some favorable effects emerge, and the role of economic complexity differs across countries. (Uddin et al. 2023) study BRICS (1990–2018) using CS-ARDL, FMOLS, and DOLS to evaluate how GPR, governance indicators, technological innovation, energy consumption, and foreign direct investment affect

CO_2 emissions. They report that GPR, corruption, political instability, and energy consumption increase emissions, whereas government effectiveness, regulatory quality, rule of law, FDI, and innovation reduce them.

In another China focused paper, (Wang et al. 2022) apply a bootstrap Granger rolling-window causality approach to 1985–2020 data and find pervasive bidirectional causality across sub-samples. The authors argue that GPR affects CO_2 through channels such as trade disputes, military activity, and risks to energy supply, while CO_2 levels can shape international cooperation and geopolitical configurations, thereby feeding back into GPR. For South Africa, (Lawal et al. 2023) use quarterly data for 1985–2018 and quantile Granger causality to assess the effects of GPR and globalization on CO_2 emissions. The results indicate especially strong bidirectional causality between GPR and CO_2, and between globalization and CO_2.

2.2 Geopolitical Risk and Energy Consumption

Adedoyin et al. (2020) analyze resource rich countries with high GPR over 1996–2017 using an ARDL model estimated via the Pooled Mean Group approach. Their results indicate that energy consumption and economic growth raise CO_2 emissions, economic policy uncertainty (EPU) is positively related to emissions in the long run, while geopolitical risk is associated with lower environmental impacts over the long horizon. The paper concludes that energy policies should incorporate risk factors such as EPU and GPR to support environmental sustainability. Hashmi et al. (2022) test the Environmental Kuznets Curve (EKC) for 17 advanced and emerging economies over 1997–2019 using a bootstrap ARDL framework that explicitly accounts for GPR. The findings confirm an inverted U relationship between environmental degradation and GDP per capita. They also show that GPR reduces emissions in the short run but increases them in the long run. For four Turkic republics Kazakhstan, Azerbaijan, Kyrgyzstan, and Uzbekistan Yesbolova et al. (2024) examine 2000–2020 panel data on renewable energy consumption, industrial production, and CO_2 emissions. The analysis shows that higher renewable energy consumption significantly lowers CO_2 emissions, whereas the effect of industrial production on CO_2 is statistically insignificant. Jiang and Khan (2023) study Belt and Road Initiative (BRI) countries for 1995–2019 using dynamic panel methods to assess the effects of renewable energy consumption and technological innovation on CO_2 emissions while controlling for economic growth, trade, foreign direct investment, urbanization, and industrialization. They find that technological innovation increases both renewable energy consumption and CO_2 emissions, whereas greater renewable energy consumption reduces CO_2. The EKC hypothesis is also supported. The results suggest promoting technological progress in energy systems alongside policies that incentivize renewables to improve environmental quality. Focusing on Turkey, Çoban (2015) employs annual data for 1990–2012 to investigate the impact of renewable energy consumption (REC) on per capita CO_2 emissions, using per capita GDP, per capita REC, and energy-sector per capita CO_2 as variables. Applying the ADF unit-root test, Johansen cointegration, Granger causality, and regression analysis, the paper reports a long-run cointegrating relationship and one-way causality from per capita REC to per capita CO_2. Regression results indicate that renewable energy consumption reduces CO_2, while per capita GDP increases it. In a sample of countries with high renewable energy use over 2000–2015, Huang et al. (2021) apply the generalized method of moments (GMM) and find that renewable energy consumption leads to a statistically significant decline in CO_2 emissions.

2.3 Trade Openness and Carbon Emissions

Bhayana and Nag (2024) examine how manufacturing sectors' participation in global value chains (GVCs) affects carbon emissions in 16 emerging market economies over 1995–2018. Using panel data and feasible generalized least squares (FGLS), they find that deeper GVC participation is positively associated with emissions, both on the domestic and export sides. Derindag et al. (2023) analyze 20 Indian industrial subsectors for 2006–2021 with a threshold-regression framework, using industrial carbon-emission intensity as the threshold variable to assess the roles of foreign direct investment (FDI) and foreign trade openness (FTO). The results reveal triple threshold effects: the impact of FDI on emissions is negative in low-intensity sectors, strongest in medium-intensity sectors, and moderate in high-intensity sectors. Trade openness suppresses CO_2 in low-intensity sectors but raises emissions in high-intensity sectors. Kang (2021) studies the relationship between the portion of CO_2 emissions embodied in international trade and economic growth for OECD and non-OECD countries during 2005–2015. Extending the Environmental Kuznets Curve (EKC) by incorporating a net-exports-based measure of emissions, the paper employs panel regressions, unit-root and cointegration tests, and Granger causality analysis. The EKC is validated, and bidirectional Granger causality between CO_2 emissions and economic growth is documented. For India over 1985–2019, Adebayo et al. (2023) use quantile-on-quantile (QQR) regression to evaluate how geopolitical risk, trade openness, and economic growth affect CO_2 emissions. The findings show that GPR increases emissions at middle quantiles but reduces them at lower and upper quantiles. Moreover, GPR, growth, and trade openness exert adverse effects on environmental quality, with heterogeneous impacts that vary across the emissions distribution. The paper recommends that policymakers account for quantile-specific effects of GPR and openness when designing environmental strategies.

2.4 Energy Consumption – Carbon Emissions – Trade Openness

Using panel data for 30 Chinese provinces over 2003–2019, Cheng et al. (2023) analyze the effect of GPR on carbon emissions. Panel regression results indicate that GPR, economic growth, international trade, and fossil-energy consumption raise emissions, whereas technological progress, industrial restructuring, and marketization curb them. With a panel of the 50 most globalized countries for 2000–2019, Mirziyoyeva and Salahodjaev (2023) examine the nexus among economic growth, renewable energy consumption, and CO_2 emissions using a two-step system GMM estimator. They find that renewable energy consumption reduces CO_2 emissions by roughly 0.26 percent, globalization supports environmental quality, and per capita GDP exhibits an inverted-U relationship with CO_2. Institutional indicators—such as the share of women in parliament—also have beneficial effects on emissions. For Azerbaijan over 1993–2019, Mukhtarov et al. (2023) apply DOLS to assess how per capita renewable energy consumption, per capita GDP, exports, and imports affect consumption-based CO_2 emissions. The evidence shows that renewable energy lowers CO_2, while per capita GDP and imports increase it; imports amplify emissions, whereas exports reduce them—patterns consistent with heterogeneous effects under greater trade openness.

For Turkey, papers directly linking GPR and emissions remain scarce. Using data for 1985–2019, Kızılkaya et al. (2024) implement Shin and Fourier-Shin cointegration tests and report that GPR and renewable energy consumption reduce CO_2 emissions in the long run, whereas economic growth and population increase them. In contrast, Aydın et al. (2024) employs the RALS-Fourier unit-root test, the Fourier-ADL cointegration model, and FMOLS to examine financial development, foreign direct investment (FDI), and GPR; their results indicate that GPR, financial development, and FDI each have positive and significant effects on emissions, suggesting that heightened geopolitical risk can raise energy demand and production pressure. Using ARDL cointegration for Turkey (1985–2019), Saadaoui, Doğan, and Omri (2023) find that GPR and renewable energy consumption exert negative and significant effects on CO_2 emissions, while economic growth and population increase emissions. Overall, the literature suggests that renewable energy consumption generally mitigates emissions, whereas the effects of GPR and greater trade openness are context-dependent, operating through channels such as energy demand, technology adoption, and the composition of trade. This study aims to contribute to the literature from a broad perspective by examining carbon emissions in relation to the geopolitical risk index, energy consumption, economic growth, and the trade Openness.

3. Methodology and Empirical Application

3.1 Method

In analyzing the relationships among economic variables, various econometric analysis techniques are employed. Particularly for examining short – and long-run associations, different cointegration methods such as those developed by Engle and Granger (1987), Johansen (1988), and Johansen and Juselius (1990) are frequently utilized. However, in this paper, considering the stationarity levels of the variables, the Autoregressive Distributed Lag bounds testing approach is preferred. Unlike traditional cointegration methods that require all variables to be integrated at the same order, the ARDL method does not impose such a restriction; in other words, the presence of cointegration can be investigated when the variables are either I(0) or I(1) (Sharifi-Renani, 2007, p. 3). Nevertheless, for the method to be applicable, the dependent variable must be integrated of order one (I(1)), while the independent variables may be either I(0) or I(1) (Pesaran et al., 2001, p. 290).

Another advantage of the ARDL technique is its suitability for small sample sizes and its ability to provide more consistent and reliable results compared to conventional cointegration techniques (Engle & Granger, 1987; Johansen, 1988, 1995) (Narayan & Smyth, 2005, p. 103). Narayan and Smyth (2005) also emphasize that this method offers more robust results under small sample conditions.

In this study, the stationarity properties of the series used were investigated through the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests. After determining the order of integration, the cointegration test was applied to identify both the short – and long-run relationships among the variables. Based on the empirical test results, both short-run and long-run coefficient interpretations were made. The model employed in the analysis is presented in Equation 1 below.

$$\mathrm{logems_t} = \beta_0 + \beta_1 \mathrm{logGPR_t} + \beta_2 \mathrm{logNXM_t} + \beta_3 \mathrm{logGDP_t} + \beta_4 \mathrm{logEC} + \varepsilon_t \quad (1)$$

Pesaran et al. (2001) proposed a method by which the long-run relationship expressed in Equation 1 can be estimated using the bounds testing approach. This method relies on estimating the long-run association among the variables through an unrestricted error correction model. An ARDL model is presented in Equation 2 below.

$$\Delta Y_t = \mu + \rho_Y Y_{t-1} + \rho_X Z_{t-1} + \sum_{i=1}^{p-1} a_i \Delta Y_{t-i} + \sum_{i=0}^{q-i} \beta_i \Delta Z_{t-1} + \varepsilon_t \quad (2)$$

3.2 Data Set

The paper examines the relationship between per capita CO_2 emissions and geopolitical risk, trade openness, per capita income, and per capita energy consumption in Turkey. In other words, it investigates the impact of geopolitical risk, trade openness, per capita income, and per capita energy consumption on per capita carbon emissions. In this context, per capita CO_2 emissions serve as the dependent variable, while geopolitical risk, trade openness, and per capita energy consumption are the independent variables, and per capita income is included in the model as a control variable. The equation for the constructed model is as follows:

Per Capita Carbon Emissions = f (Geopolitical Risk, Trade Openness, Gross Domestic Product, Energy Consumption)

The variables used in the model and their data sources are presented in Table 1.

Table 1: Variables

Abbreviation	Description	Explanation
ems	CO_2 Emissions Per Capita	Tons
gpr	Geopolitical Risk Index	Historical GPR (Index: 1900:2019 = 100)
nxm	Trade Openness	Share of Net Trade in GDP (%)
gdp	Gross Domestic Product Per Capita	Constant 2015 US$
ec	Electric power consumption Per Capita	kWh

In this study, to investigate the determinants of carbon emissions, the geopolitical risk index, trade openness, per capita gross domestic product, and per capita energy consumption are used as independent variables, while per capita carbon emissions serve as the dependent variable. The limitation of the study period is due to the availability of the latest data for energy consumption in 2023. Accordingly, the variables cover the period 1990–2023, where (ems) denotes per capita carbon emissions, (gpr) represents the geopolitical risk index, (nxm) indicates the trade openness (measured as *net exports of goods and services (% of GDP)*, which reflects the balance of trade in relation to the size of the economy (negative values indicate a openness, while positive values indicate a surplus), (gdp) refers to per capita gross domestic product, and (ec) corresponds to energy consumption. Among the variables used in the analysis, the geopolitical risk index is obtained from the matteoiacoviello.com database, while per capita carbon emissions, trade openness, per capita energy consumption, and per capita gross domestic product are retrieved from the World Development Indicators (WDI) database of the World Bank.

Table 2: Descriptive Statistics of the Variables

Statistic	LEMS	LGDP	LGPR	LNXM	LEC
Mean	1.349	8.993	0.207	3.881	7.607
Median	1.397	8.979	0.182	3.887	7.702
Maximum	1.700	9.596	0.451	4.396	8.185
Minimum	0.984	8.537	0.0487	3.416	6.796
Std. Deviation	0.233	0.332	0.111	0.225	0.437
Skewness	-0.079	0.246	0.475	-0.203	-0.328
Kurtosis	1.599	1.717	2.135	3.183	1.830
Jarque-Bera	2.815	2.674	2.339	0.282	2.551
Probability	0.244	0.262	0.310	0.868	0.279

The descriptive statistics of the variables used in the study provide important insights into the distributions of the series. Table 2 summarizes these descriptive statistics. The mean and median values are close to each other, indicating a low influence of extreme observations. The standard deviations suggest relatively high fluctuations in the LEC variable. Skewness values are close to zero, indicating that the series are largely symmetric. The kurtosis values being less than 3 imply that the series are flatter than the normal distribution. Since the probability values of the Jarque–Bera test are above 0.05, it can be inferred that none of the series reject the null hypothesis of normality.

3.3 Empirical Findings

Table 3. Results of ADF and PP Unit Root Tests

		Variable	ADF	PP
Level	Intercept	DLEMS	-0.816(0)	-0.735(5)
		DLGPR	– 2.226(0)	-2.202(1)
		DLNXM	0.457(6)	-1.677(10)
		DLGDP	0.665(0)	1.970(8)
		DLEC	-2.696(2)***	-4.728(18)*
	Trend+Intercept	DLEMS	-2.963(0)	-2.963(0)
		DLGPR	-3.399(0)***	-3.236(5)***
		DLNXM	-3.194(2)	-2.736(7)
		DLGDP	-2.556(2)	-2.472(4)
		DLEC	-0.353(2)	0.125(11)
First Difference	Intercept	DLEMS	-6.435(0)*	-7.154(6)*
		DLGPR	-5.662(1)*	-7.840(11)*
		DLNXM	-5.387(1)*	-5.608(14)*
		DLGDP	-5.736(0)*	-6.501(7)*
		DLEC	-4.385(1)*	-4.335(4)*
	Trend+Intercept	DLEMS	-6.396(0)*	-8.039(8)*
		DLGPR	-5.620(1)*	-8.643(12)*
		DLNXM	-5.312(1)*	-5.435(14)*
		DLGDP	-4.324(5)**	-7.635(10)*
		DLEC	-5.518(1)*	-9.521(31)*

*, **, and *** indicate that the series are stationary at the 1%, 5%, and 10% significance levels, respectively. The values in parentheses denote that, in the ADF test, the lag length is determined according to the Akaike Information Criterion, while in the PP test, it is determined using the Bartlett Kernel Newey–West Bandwidth method.

The ADF and PP unit root test results indicate that the LEC variable is stationary at level, while all other variables are non-stationary at level but become stationary at the 1% significance level after first differencing. These findings reveal that the series exhibit a mixed order of integration at I (0) and I (1), thereby confirming the applicability of the ARDL approach.

Table 4: Results of ARDL Bounds Test and Diagnostic Tests

	F Statistic	Critical Value	
K	4	**Lower Bound**	**Upper Bound**
F-Statistic	17.378	2.52	3.56
Diagnostic Test			
	Test Statistic	**Probability Value**	
Breusch Pagan Godfrey	0.519	0.861	
Ramsey Reset	0.385	0.578	
Breusch Godfrey	0.519	0.861	
Jarque-Bera Normallik Testi	1.008	0.604	
R^2	0.996		
Adjusted R^2	0.987		

Note: *k refers to the number of independent variables. Critical values are taken from Table CI(iii) in Pesaran et al. (2001:300). The critical values correspond to the 1% significance level.

The ARDL bounds testing procedure yielded an F-statistic value of 17.37808, which is well above the upper bound critical value of 3.56 at the 1% significance level. This result indicates the presence of a long-run cointegration relationship between the dependent and independent variables in the model. According to the results of the ARDL (4,4,4,4,4) model, estimated with differenced series, the short-run effects on DLEMS reveal that the DLEC variable and some of its lags are statistically significant; this finding suggests that changes in energy consumption have a strong and positive impact on changes in emissions. Most of the coefficients of DLNXM are negative, and some are statistically significant, implying that changes in trade may reduce emission growth in the short term. The coefficients of DLGDP display mixed signs, with some positive and significant lags, indicating that increases in economic growth rates may contribute to higher emissions. The lag length structure was determined by setting the maximum lag to four, given the annual frequency of the data, and selecting the optimal specification based on the Akaike Information Criterion (AIC) and supporting diagnostic tests. Alternative lag orders were evaluated, but the ARDL (4,4,4,4,4) model provided the most consistent results across variables and satisfied the key econometric assumptions.

Diagnostic tests performed to evaluate the validity of the model produced satisfactory results. The Breusch–Pagan–Godfrey test ($p = 0.861447$) shows no evidence of heteroskedasticity in the model. The Ramsey RESET test ($p = 0.57876$) confirms the correct functional form specification. The Breusch–Godfrey LM test ($p = 0.8614$) indicates that the model is free from autocorrelation. Furthermore, the Jarque–Bera normality test ($p = 0.604096$) verifies that the residuals follow a normal distribution. The explanatory power of the model is remarkably high; with $R^2 = 0.996096$ and adjusted $R^2 = 0.987855$, a large proportion of the variation in the dependent variable is explained by the independent variables. Overall, these findings demonstrate that the estimated ARDL model is both statistically significant and econometrically reliable.

The long-run coefficient estimates, as presented in Table 5, reveal that the LGDP and LEC variables have positive effects at the 1% significance level, indicating that economic growth and energy consumption significantly increase carbon emissions in the long term. The LNXM variable is significant at the 10% level, and its positive coefficient suggests that the trade openness contributes to emission growth over the long run. In contrast, the LGPR variable is not statistically significant in the long term, while the constant term is estimated to be negative and significant; this implies the presence of a structural downward component in the emission level when other factors are held constant.

Table 5: Long and Short Run ARDL Estimation Results

LONG RUN TEST				
Variable	**Coefficent**	**Standard Error**	**t-statistic**	**Probability**
DLGDP	0.705	0.116	6.053	0.003
DLGPR	-0.061	0.072	-0.853	0.441
DLNXM	0.173	0.074	-2.338	0.079
DLEC	0.647	0.083	7.741	0.001
C	-0.021961	0.006068	-3.618882	0.0224
SHORT RUN TEST				
D(DLEMS(-1))	0.826	0.128	6.404	0.003
D(DLGDP)	0.671	0.125	5.360	0.005
D(DLGDP(-1))	-1.236	0.094	-13.104	0.000
D(DLGDP(-2))	-1.737	0.154	-11.266	0.000
D(DLGDP(-3))	-1.404	0.169	-8.296	0.001
D(DLGPR(-2))	0.131	0.039	3.360	0.028
D(DLNXM)	-0.308	0.040	-7.692	0.001
D(DLNXM(-1))	0.249	0.031	7.791	0.001
D(DLEC)	0.799	0.125	6.391	0.003
D(DLEC(-2))	1.162	0.179	6.474	0.002

The short-run estimation results, as presented in Table 5, indicate that economic growth (DLGDP) and energy consumption (DLEC) have positive and significant effects on emissions, although the lagged values of growth display negative and highly significant coefficients, suggesting that growth shocks undergo a corrective process over time that reduces emissions. The DLGPR variable is found to be positive and significant at the second lag, implying that geopolitical risk can increase emissions in certain periods. The trade deficit (DLNXM) exhibits both negative and positive coefficients in the short run, indicating a fluctuating impact pattern. This can be explained by the fact that widening trade deficits may initially reduce domestic emissions by outsourcing carbon-intensive production abroad through increased imports, whereas in subsequent periods the recovery of domestic demand and production tends to offset this effect, leading to higher emissions. This cyclical behavior highlights the dual role of trade deficits in shaping short-run emission dynamics. Although GPR is insignificant in the long run, this outcome may be attributed to the fact that Turkey's energy supply and emission trajectory are primarily shaped by long-term contracts and domestic demand, thereby offsetting the direct impact of geopolitical shocks. The CointEq(-1) coefficient is – 2.48, which is large in magnitude and statistically significant, indicating that the system returns rapidly to its long-run equilibrium.

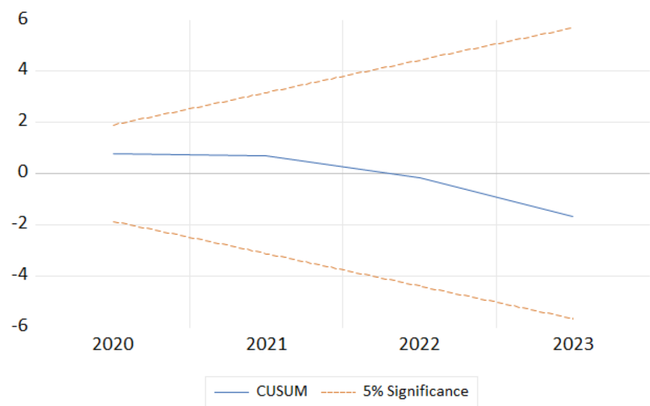

Figure 3: CUSUM Test

As shown in Figure 3, the CUSUM test graph is used to assess the stability of the model and the consistency of its parameters over time. An examination of the graph reveals that the cumulative residual series (blue line) remains within the critical bounds (dashed orange lines) representing the 5% significance level. This indicates that the model's parameters are stable over time and that the model does not contain any structural breaks. Therefore, it can be stated that the model is statistically consistent in terms of reliability and forecasting performance.

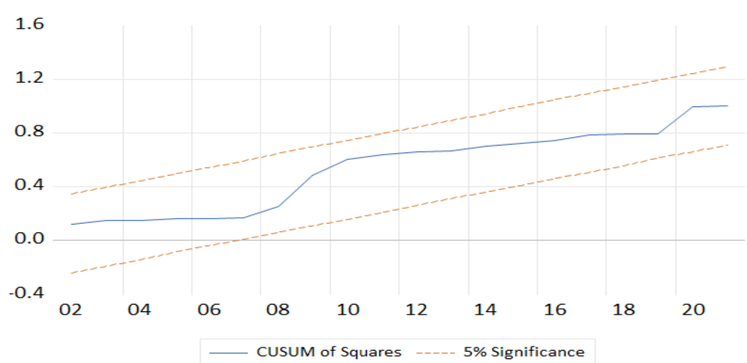

Figure 4: CUSUM of Squares Test

As shown in Figure 4, the CUSUM of Squares test graph is applied to detect potential structural breaks or changes in variance in the model parameters over time. An examination of the graph shows that the CUSUMSQ curve remains within the critical bounds representing the 5% significance level. This indicates that the model's parameters are stable over time and that there are no structural breaks or variance changes in the model. Consequently, the reliability and validity of the estimated ARDL model are diagnostically confirmed.

4. Conclusion and Implications

This study examines the relationship between carbon emissions and economic growth, geopolitical risk, trade openness, and energy consumption in Turkey over the period 1990–2023 using the ARDL approach, and identifies the existence of a long-run equilibrium relationship among the variables. The long-run estimates indicate that economic growth and energy consumption have a significant and positive impact on emissions, while the trade openness also contributes to emission increases in the long term, and geopolitical risk is not statistically significant in the long run. In the short run, the emission-increasing effects of growth and energy consumption are confirmed, while growth shocks tend to balance out over time, and the trade openness exhibits a fluctuating impact pattern. These findings are partly consistent and partly divergent from the existing literature: unlike Kızılkaya et al. (2024) and Saadaoui et al. (2023), the results do not reveal a mitigating long-run impact of geopolitical risk on emissions in Turkey, which may be explained by the dominant role of domestic demand and long-term energy contracts in shaping emission dynamics. Conversely, the evidence on the positive role of energy consumption is strongly in line with many previous studies (e.g., Mukhtarov et al., 2023; Hashmi et al., 2022; Adebayo et al., 2023), confirming that energy use remains the most critical driver of emissions. The findings underscore the critical importance of reducing the carbon intensity of electricity generation and consumption in emission mitigation; they support policy recommendations such as the gradual phase-out of coal-based electricity generation, expansion of renewable energy capacity, dissemination of energy efficiency standards, promotion of electrification and low-carbon fuels in transportation, increasing the share of rail and maritime transport in logistics, mandatory emission reporting for export-oriented sectors, phased implementation of a national ETS, and enhancement of energy source diversification to mitigate geopolitical risks.

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