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Article

The Impact of Fossil Fuel Consumption, Renewable Energies, and Economic Growth on Environment Change in Lithuania

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Abstract The world is approaching a critical juncture beyond which climate change may become irreversible, threatening the entitlement of current and future generations to a healthy and sustainable planet. Therefore, this study assesses the impact of fossil fuels, renewable energy, and economic growth on carbon dioxide (CO_2) emissions in Lithuania, using data from 1996 to 2020. The Autoregressive Distributed Lag (ARDL) bound test is employed to examine the long-term relationship between these variables. Additionally, the ARDL model is used to evaluate the individual effects of each variable on CO_2 emissions. Surprisingly, the findings reveal that fossil fuels reduce the harmful impact of carbon emissions in Lithuania, while investment in renewable energy mitigates and alleviates these emissions. However, economic growth is positively and significantly associated with an increase in carbon emissions, suggesting that emissions will rise as the economy expands. These results advocate for policies that promote sustainable economic growth, foster the adoption of environmentally friendly investments, and enhance resilience to mitigate CO_2 emissions and address climate change in Lithuania.

Keywords CO_2 emissions; renewable energy; fossil fuel; economic growth; ARDL model

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1. Introduction

Lithuania is a long-standing, robust nation in the Baltic region that has achieved remarkable economic growth in recent years. However, human survival faces a serious and immediate threat from the current level of global climate change. The historical rise in greenhouse gas emissions, primarily driven by the burning of fossil fuels (FF) and economic growth over the last century, is often identified as the key human-induced driver of climate change. The use of fossil fuels is the leading source of carbon emissions in Lithuania, with significant detrimental effects on the nation's economy, environment, and public health. When fossil fuels such as coal, oil, and natural gas are burned, greenhouse gasses like carbon dioxide (CO_2) are released into the atmosphere. In Lithuania, fossil fuels are primarily used in industrial operations, heating, transportation, and power generation. These activities exacerbate global climate change and significantly contribute to the country's carbon footprint [1].

The combustion of fossil fuels releases harmful pollutants such as CO_2, nitrogen oxides, sulfur dioxide, and particulate matter into the environment, leading to air pollution and associated health risks. Urban and industrial areas in Lithuania face particularly severe air quality issues. Emissions from fossil fuel combustion contribute to smog formation, respiratory disorders, cardiovascular diseases, and even premature death, especially among vulnerable groups like children, the elderly, and individuals with pre-existing medical conditions. Addressing these health risks by reducing pollutants is vital for improving public health and the overall quality of life in Lithuanian society. Fossil fuel combustion also harms biodiversity and the environment [2]. In Lithuania, climate change is manifested in rising temperatures, shifting rainfall patterns, and extreme weather events, all of which pose risks to ecosystems, agriculture, and water resources. Coastal communities and forest ecosystems are particularly vulnerable to these changes, which may result in economic losses and environmental degradation [3]. Moreover, the economic costs associated with fossil fuel use are significant. These include increased healthcare expenses due to pollution and Lithuania's economic vulnerability stemming from its dependence on imported fossil fuels. Fluctuating energy prices, supply interruptions, and geopolitical risks further threaten the nation's energy security, underscoring the need for a transition to more sustainable and locally sourced energy solutions [4].

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Lithuania has taken robust measures to reduce its dependence on fossil fuels and embrace renewable energy sources[1]. By investing in renewable technologies such as wind power, solar panels, and biomass heating, Lithuania is reducing carbon emissions while fostering economic growth. Renewable energy sources like solar, hydroelectric power, wind, and biomass emit little or no greenhouse gasses during electricity generation [5]. Replacing fossil fuels in electricity production, heating, and transportation can significantly reduce Lithuania's carbon footprint and support global efforts to combat climate change [6]. Unlike fossil fuel combustion, renewable energy does not release pollutants like sulfur dioxide, nitrogen oxides, or particulate matter, thereby improving air quality and mitigating smog-related health risks, particularly in urban and industrial areas. Lithuania's heavy reliance on imported fossil fuels makes it susceptible to geopolitical risks and energy price fluctuations. Transitioning to renewable energy can enhance energy security by reducing dependence on imported fuels and diversifying the nation's energy sources [7]. Furthermore, investments in renewable energy infrastructure and technology can create job opportunities in sectors such as research, development, installation, and maintenance, driving economic growth and fostering innovation in the clean energy industry [8]. Renewable energy initiatives align with sustainable land use and environmental conservation practices [9]. For instance, siting wind and solar farms on degraded or brownfield land can mitigate land-use conflicts and minimize ecosystem disruption. Similarly, sustainable management of agricultural waste and forests can produce biomass energy, contributing to rural economic development and biodiversity conservation.

Europe faces a range of challenges, including the COVID-19 pandemic, the energy crisis, and the war in Ukraine, which have collectively impacted economic and environmental stability. In Lithuania, the COVID-19 pandemic disrupted economic stability through strict lockdowns, travel bans, and supply chain interruptions, negatively affecting businesses, industries, and employment [10]. Moreover, the war in Ukraine further exacerbated Europe's energy crisis by disrupting energy supplies, particularly natural gas, as many countries, including Lithuania, had been heavily reliant on Russian energy imports[2]. In Lithuania, residential energy consumption accounts for over 30% of total energy use [11], with increasing demand contributing significantly to carbon dioxide emissions. Addressing residential energy use and reducing emissions has become a primary goal of Lithuania's Energy Strategy. Policymakers are encouraged to adopt strategies that address climate change while promoting energy efficiency and sustainability in households.

This study addresses a gap in the literature by examining the combined impact of fossil fuels and renewable energy on Lithuania's carbon emissions, in contrast to previous research that either generalizes energy-environment dynamics across regions or concentrates on larger economies. Although Martins et al. (2021) [12] and Zhang et al. (2024) [13] emphasize the global and regional effects of fossil fuels and renewable energy on emissions, they neglect the distinct dynamics inside smaller economies undergoing a transition to sustainability. This work contributes by demonstrating that, in Lithuania, fossil fuel usage under certain situations mitigates emissions, providing a novel insight into the complex energy-environment dynamic. The authors used the "Autoregressive Distributed Lag (ARDL) Bound Test" for co-integration analysis. The ARDL model is used to examine the short-term and long-term connections between the dependent and independent variables.

The current study is organized as follows. Section 2 contains a literature review. Section 3 provides a comprehensive discussion of the employed methodology. Section 4 presents the results and discussion, and Section 5 concludes with policy recommendations, limitations, and future research gaps.

2. Literature Review

2.1. Fossil Fuel & Carbon Emission

Ogundipe et al. (2020) [14] examined the relationship between fossil fuel consumption and environmental quality in Nigeria, a country heavily reliant on fossil fuel-based energy since the discovery of oil in 1956. Utilizing Johansen cointegration analysis on data spanning 1970–2017,

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[1] Infromation retrieved from https://economy-finance.ec.europa.eu/system/files/2023-05/LT_SWD_2023_615_en.pdf (accessed 17 December 2024).

[2] Infromation retrieved from https://library.fes.de/pdf-files/bueros/budapest/20409.pdf (accessed 17 December 2024).

the study finds that approximately 80% of CO_2 emissions in Nigeria result directly from fossil fuel combustion. Moreover, Botello et al. (2017) [15] highlighted the global implications of fossil fuel emissions, particularly in marine ecosystems. Fossil fuel exploration, spills, and emissions contribute significantly to CO_2 concentrations, accounting for 76% of emissions from fossil fuel burning and cement production globally. Furthermore, Martins et al. (2021) [12] investigated the intertemporal relationship between fossil fuel consumption and CO_2 emissions in G7 countries from 1965 to 2018. Using ARDL bounds testing, the study reveals a positive causality between fossil fuel use and emissions. Notably, short-term elasticities show that a 1% increase in the consumption of oil, coal, and natural gas leads to a 0.48%, 0.31%, and 0.17% increase in CO_2 emissions, respectively. In the long run, these effects persist, albeit at slightly reduced magnitudes. Similarly, Hou et al. (2023) [16] explored the role of fossil fuels in OPEC countries, where fossil energy constitutes 80% of the energy mix and contributes to 35% of global CO_2 emissions. The study confirms that fossil fuel consumption positively influences emissions in both the short and long term, reinforcing the critical role of developed economies in driving global emissions. In emerging economies like Pakistan, Ali et al. (2024) [17] demonstrated the complex interplay between energy prices, green finance, and CO_2 emissions. The study employs RALS-EG cointegration and ARDL methods to evaluate the long-term relationship between variables. The findings suggest that oil prices reduce emissions, whereas rising gas prices and economic growth contribute to higher emissions over the long term. Similarly, Aali et al. (2024) [18] focused on the role of fossil fuel and renewable energy consumption in Pakistan's carbon emissions. Utilizing the Environmental Kuznets Curve (EKC) theory, the study finds that GDP growth initially drives emissions upward but technological innovation and renewable energy consumption eventually mitigate environmental degradation. The study by Zhang et al. (2024) [13] investigated the effects of non-renewable energy production and usage on CO_2 emissions in China. Using QARDL estimation, the findings reveal a significant positive relationship between fossil fuel energy consumption, energy production (from oil, coal, and nuclear), and emissions. This aligns with Cao et al. (2023) [19], who examined China's fossil fuel CO_2 emissions between 2000 and 2019. The results show an average annual growth rate of 6.29%, with future predictions indicating continued emission increases through 2030.

2.2. Renewable Energy Consumption & Carbon Emission

Azam et al. (2022) [20] conducted a comprehensive analysis of the top five emitting countries, using data from 1960 to 2017. Their study revealed a bi-directional relationship between renewable energy consumption (REC) and economic growth (EG). This finding suggests that an increase in renewable energy usage can stimulate economic growth, while economic growth also fosters the adoption of renewable energy technologies. In another study, Javed et al. (2024) [21] focused on the role of green growth, energy efficiency, and green technology innovation in improving environmental performance among the world's top manufacturing nations. By utilizing the CS-ARDL model, their research highlighted that green growth and energy efficiency positively influence environmental sustainability, while trade openness and economic expansion contribute to environmental degradation. Similarly, Shafiq et al. (2021) [22] focused on a group of European and American countries from 1971 to 2014. Their study demonstrated a strong long-term relationship between energy use and carbon emissions, highlighting the crucial role of renewable energy in mitigating carbon output. In the context of OPEC member countries, Matori (2024) [23] identified a significant breakpoint in the relationship between per capita CO_2 emissions and renewable energy consumption over the period from 1990 to 2019. Their study emphasized the importance of renewable energy in mitigating CO_2 emissions in oil-dependent economies, especially as these countries face challenges in balancing energy consumption with environmental sustainability. While Azam et al. (2022) [20] also explored renewable energy consumption in G7 nations, they found that these developed countries have achieved a relatively stronger decoupling of energy use from carbon emissions. This observation reinforces the notion that developed economies, with access to cleaner technologies and robust environmental policies, can significantly reduce carbon emissions through renewable energy adoption. Various other studies have focused on the impact of residential energy usage on carbon emissions. Research by Salari & Javid (2017) [24] and Spandagos & Ng (2018) [25] delved into factors such as energy-efficient building technologies and the influence of climate variation on energy consumption patterns. These studies underscore the importance of incorporating energy efficiency measures alongside renewable energy to further curb carbon emissions in the residential sector. Moreover, Javed et al. (2023) [26] explored the symmetric and asymmetric effects of green technology innovation, economic policy uncertainty, and Foreign Direct Investment (FDI) on carbon emissions in Italy. Their research, employing linear and non-linear ARDL models, demonstrated that green technology innovation and economic policy uncertainty mitigate environmental degradation in the long run, while FDI exacerbates environmental issues.

2.3. Economic Growth & Carbon Emission

Schröder & Storm (2020) [27] provided a sobering perspective on decoupling, emphasizing that while there is weak evidence of emissions and growth decoupling at higher income levels, global carbon emissions generally increase monotonically with rising per capita GDP. Their findings, derived from fixed-effects regressions on OECD data (https://www.oecd.org/en/data.html), suggest that economic growth remains intrinsically tied to carbon emissions, particularly in the absence of transformative climate policies. In contrast, studies like those by Li et al. (2020) [28] and Yang et al. (2021) [29] examined the role of eco-innovation and renewable energy in mitigating emissions, particularly in high-growth economies. Li et al. (2020) [28] demonstrated that eco-innovation significantly reduces CO_2 emissions across quantiles, supporting the EKC hypothesis in China. Economic growth initially increases emissions, but its squared term indicates a reversal at higher income levels, validating the existence of an inverted U-shaped trajectory. Yang et al. (2021) [29] focusing on economies along the Silk Road Economic Belt, reinforced this trend by showing that renewable energy adoption and capital formation decrease emissions over both short and long horizons. Similar trends emerge in the South Asian context, where Khan et al. (2022) [30] confirmed a bidirectional causal relationship between economic growth and CO_2 emissions. Using an extended EKC framework, they observe that economic growth and globalization exacerbate environmental degradation, particularly in countries like Bangladesh, which rely heavily on non-renewable energy. Osobajo et al. (2020) [31] echoed these findings, demonstrating that energy consumption and economic growth significantly drive emissions in 70 countries over a 20-year period. Ali et al. (2024) [17] extended this conversation by investigating the effects of green finance and energy prices on carbon emissions in Pakistan. Their findings reveal that while green finance and human capital reduce emissions, economic growth exerts dual effects, decreasing emissions in the short run but contributing to long-term increases. In a similar vein, Raihan et al. (2022) [32] highlighted Malaysia's challenge in meeting its Paris Agreement commitments, as economic growth is found to significantly exacerbate emissions. However, renewable energy use and technological innovation emerge as effective mitigators, reducing carbon emissions and offering a potential route to a low-carbon economy. Table 1 presents a summary of the other related literature.

Table 1. Summary of the Literature.

Author(s)	**Methodology**	**Dependent Variable**	**Independent Variables**	**Outcomes**
Ali et al. (2024) [17]	RALS-EG Cointegration, ARDL	CO_2 Emissions	Energy prices (oil and gas), green finance, economic growth	Oil prices reduce emissions, but gas prices and economic growth increase emissions in Pakistan. Demonstrates complex dynamics between variables.
Hou et al. (2023) [16]	Panel Data Analysis	CO_2 Emissions	Fossil fuel consumption, energy mix	Fossil energy makes up 80% of OPEC's energy mix, contributing 35% of global emissions. Fossil fuel consumption positively influences emissions in both the short and long term.
Javed et al. (2023) [26]	Linear and Non-linear ARDL Models	CO_2 Emissions	Green technology innovation, economic policy uncertainty, FDI	Green innovation and policy uncertainty mitigate emissions; FDI exacerbates environmental issues in Italy.
Javed et al. (2024) [21]	CS-ARDL Model	Environmental Performance	Green growth, energy efficiency, trade openness, economic expansion	Green growth and energy efficiency improve environmental sustainability, but trade openness and economic growth worsen it in top manufacturing nations.
Martins et al. (2021) [12]	ARDL Bounds Testing	CO_2 Emissions	Oil, coal, and natural gas consumption	A 1% increase in oil, coal, and gas consumption raises CO_2 emissions by 0.48%, 0.31%, and 0.17%, respectively. Effects persist long-term but at reduced magnitudes.

Table 1. (*Continued*)

Ogundipe et al. (2020) [14]	Johansen Cointegration Analysis	CO_2 Emissions	Fossil fuel consumption	80% of Nigeria's CO_2 emissions result from fossil fuel combustion. Highlights Nigeria's dependence on fossil fuels since oil discovery in 1956.
Osobajo et al. (2020) [31]	Pooled OLS, Cointegration	CO_2 Emissions	Economic growth, energy consumption	Energy consumption and economic growth significantly drive emissions in 70 countries.
Raihan et al. (2022) [32]	DOLS Model	CO_2 Emissions	Renewable energy, economic growth, technological innovation	Economic growth exacerbates emissions, but renewable energy and technological innovations mitigate them. Highlights Malaysia's challenges in meeting Paris Agreement commitments.
Schröder and Storm (2020) [27]	Fixed-Effects Regression	CO_2 Emissions	Economic growth, GDP per capita	Weak evidence of growth-emissions decoupling. Carbon emissions increase with GDP growth unless transformative climate policies are adopted.
Zhang et al. (2024) [13]	QARDL Estimation	CO_2 Emissions	Fossil fuel energy consumption, energy production (oil, coal, nuclear)	A significant positive relationship between fossil fuel energy production/consumption and CO_2 emissions in China.
This study	ARDL Bound & ARDL Model	CO_2 Emissions	Fossil fuel, Renewable energy, and Economic growth	Fossil fuels reduce the harmful impact of carbon emissions in Lithuania, while investment in renewable energy mitigates and alleviates these emissions. However, economic growth is positively and significantly associated with an increase in carbon emissions.

Source: Author(s) compilation.

3. Methodology

3.1. Data

The present study seeks to examine the impact of FF, REC, and EG on carbon emissions using annual time series data from 1996 to 2020 for Lithuania. The explanatory variable is CO_2 emissions, calculated in metric tons per capita. The explanatory variables are fossil fuel (FF), REC, and economic growth. Table 2 concisely illustrates the study's variables, units of measurement, and sources.

Table 2. Variables Information.

Variables	Abbr.	Measurement	Source
Carbon Emissions	CO_2	metric tons per capita	World Bank
Renewable Energy	REC	% of total final energy consumption	
Economic Growth	EG	GDP growth (annual %)	
Fossil Fuel	FF	Oil rents (% of GDP)	

Source: Author's compilation. World Bank: https://databank.worldbank.org/source/world-development-indicators

Additionally, Figure 1 depicts the flowchart of the used approach. Initially, we examined the stationarity characteristics of the fundamental variables. In the subsequent stage, we analyzed the long-term cointegration among the variables. The link between the variables in both the long and short term is examined in the third stage. Ultimately, we conducted diagnostic tests to validate our estimated models.

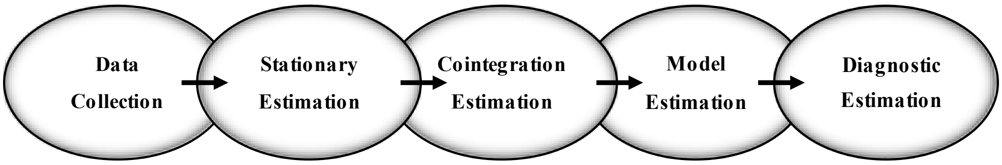

Figure 1. Methodological Flow.

Additionally, to investigate the relationship among study variables, the econometric model we constructed based on existing literature is shown below:

$$CO_{2it} = \alpha_0 + \alpha_1 FF_{it} + \alpha_2 REC_{it} + \alpha_3 EG_{it} + \mu_{it}, \quad (1)$$

where CO_{2it} represents CO_2 emissions, FF_{it} represents fossil fuel, REC_{it} represents renewable energy consumption, and EG_{it} represents economic growth. While α_0 is constant, α_1 to α_3 are the coefficients. μ_{it} represents the error term, and t is the time. Furthermore, Figure 2 presents a graphical depiction of variables.

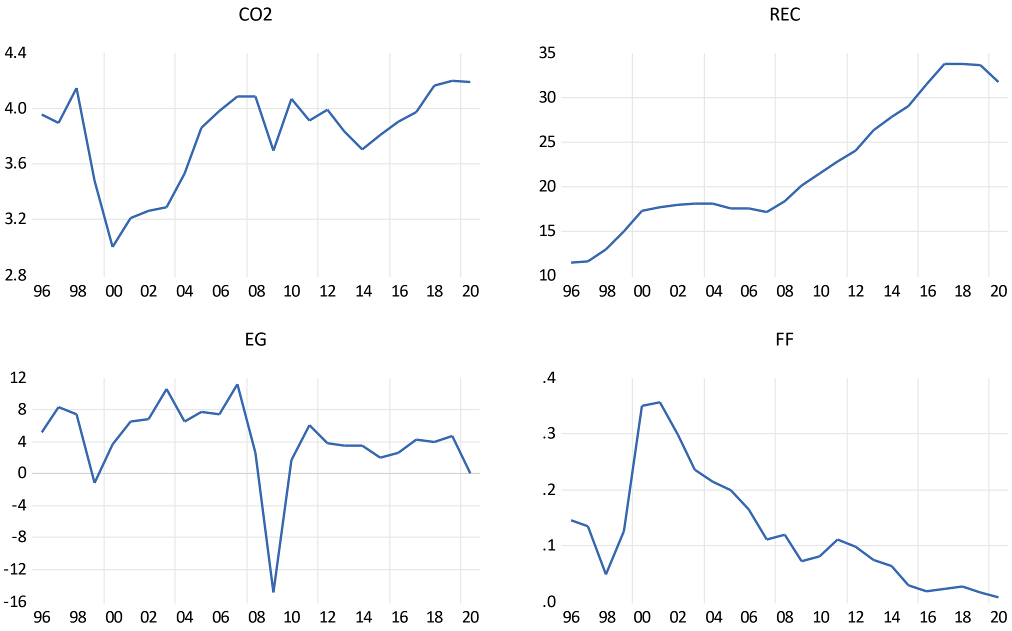

Figure 2. Trend of the Variables.

3.2. Estimation Techniques

3.2.1. Stability Cointegration

Identifying stationarity is essential when examining time series data. Stationarity is a property of a time series where its statistical characteristics stay consistent and unchanged throughout time [33]. A stationarity test is used to identify the integration sequence and select the suitable method. To this aim, the study used the "Augmented Dickey–Fuller (ADF)" unit root test. A cointegration study was then performed to find a long-term link between variables at various levels.

3.2.2. Autoregressive Distributed Lag and Bounds Test

Reliable policy consequences and precise projections need a suitable econometric methodology. Consequently, it is advised to use an econometrics model that makes use of the dataset's stationarity level depending on the consistency of the findings obtained from their examination. Previous research including that by Ali et al. (2024) [17], Martins et al. (2021) [12], and Sufyanullah et al. (2022) [34] has extensively employed the ARDL Bound Testing Model as presented by Pesaran et al. (2001) [35]. Furthermore, because of its capability to include customized lag length structure, the ARDL model offers more accurate estimates of both short- and long-term effects than other models such as OLS, VECM, or VAR.

The ARDL model has benefits over others because of its departure from traditional cointegration techniques. One important advantage of ARDL modeling is its flexibility to analyze relationships irrespective of whether the variables have stationary (I(0)), non-stationary (I(1)) order of integration, or a combination thereof. Essentially, it must efficiently depict the visual representation of all possible results. The dissimilar lag structures of the forecasted and forecasting variables were manipulated. This method was suitable for a small number of variables and a short time span. It ensured unbiased calculation of long-term memory and its coefficients. Additionally, it successfully addressed issues of "endogeneity, multicollinearity, heteroscedasticity, and autocorrelation" in the model. The ARDL model is defined in Equation (2).

$$\begin{aligned}\Delta CO_{2t} = \alpha_0 + \sum_{i=1}^{p} a_1 \Delta CO_{2_{t-i}} + \sum_{i=1}^{q} a_2 \Delta REC_{t-i} + \sum_{i=1}^{q} a_3 \, \Delta EG_{t-i} + \sum_{i=1}^{q} a_4 \Delta FF_{t-i} \\ + \delta_1 CO_{2t-1} + \delta_2 REC_{t-1} + \delta_3 EG_{t-1} + \delta_4 FF_{t-1} + \varepsilon_t,\end{aligned} \tag{2}$$

where the initial difference operator is Δ, the nation is indicated by i, and t shows the time. α_0 presents the intercept. The long-term influence is represented by the a_1–a_4 coefficients, whilst the short-term impacts are captured by the δ_1–δ_4 coefficients. Furthermore, q and p represent the ideal lag duration. Additionally, the difference between short-term level deviations and long-term equilibrium level variances is defined in this study as Error Correction Term (ECM). ε presents the stochastic error term. The following Equations (3)–(6) represent the ECM:

$$\Delta CO_{2_{it}} = \alpha_0 + \sum_{j=1}^{p} \alpha_1 \Delta CO_{2_{t-j}} + \sum_{j=1}^{q} \alpha_2 \Delta REC_{t-j} + \sum_{j=1}^{q} \alpha_3 \Delta EG_{t-j} \sum_{j=1}^{q} \alpha_4 \Delta FF_{t-j} + \gamma ECM_{t-1} + \varepsilon_{1t}, \tag{3}$$

$$\Delta REC_{it} = \alpha_0 + \sum_{j=1}^{p} \alpha_1 \Delta REC_{t-j} + \sum_{j=1}^{q} \alpha_2 \Delta CO_{2_{t-j}} + \sum_{j=1}^{q} \alpha_3 \Delta EG_{t-j} + \sum_{j=1}^{q} \alpha_4 \Delta FF_{t-j} + \gamma ECM_{t-1} + \varepsilon_{1t}, \tag{4}$$

$$\Delta EG_{it} = \alpha_0 + \sum_{j=1}^{p} \alpha_1 \Delta EG_{t-j} + \sum_{j=1}^{q} \alpha_2 \Delta CO_{2_{t-j}} + \sum_{j=1}^{q} \alpha_3 \Delta REC_{t-j} + \sum_{j=1}^{q} \alpha_4 \Delta FF_{t-j} + \gamma ECM_{t-1} + \varepsilon_{1t}, \tag{5}$$

$$\Delta FF_{it} = \alpha_0 + \sum_{j=1}^{p} \alpha_1 \Delta EG_{t-j} + \sum_{j=1}^{q} \alpha_2 \Delta CO_{2_{t-j}} + \sum_{j=1}^{q} \alpha_3 \Delta REC_{t-j} + \sum_{j=1}^{q} \alpha_4 \Delta EG_{t-j} + \gamma ECM_{t-1} + \varepsilon_{1t}, \tag{6}$$

where j shows the lagged value of the variables, and γ is the coefficient of error correction term that indicates the speed of adjustment.

3.2.3. Diagnostic Tests

The current work utilizes many diagnostic tests, such as the "Breusch–Pagan–Godfrey heteroscedasticity test, Breusch-Godfrey Serial Correlation LM Test, and Ramsey RESET test", to verify that the empirical analysis was completed correctly. In addition, the study employs "CUSUM and CUSUM-square" assessments to verify that the empirical analysis is thoroughly tested.

4. Results and Discussion

4.1. Preliminary Outcomes

Table 3 presents the descriptive statistics for every variable examined in this study. Each variable exhibits a positive average, with REC having the highest mean value of 21.8252. When comparing the minimum and maximum values of the variables, REC has the highest value and FF has the lowest value. When skewness scores are negative, it indicates that most variables have distributions that are skewed to the left and have lower values. Kurtosis values imply distributions that have a high degree of peakedness, particularly for EG.

Table 3. Descriptive Outcomes.

Variables	CO_2	EG	FF	REC
Mean	3.808440868	4.160937395	0.124901699	21.8252
Median	3.905926684	4.282596951	0.111123246	18.34
Maximum	4.200151961	11.10748014	0.356954383	33.78
Minimum	3.004941226	−14.83860837	0.008443611	11.47
Std. Dev.	0.333942693	4.947228305	0.10138587	7.129959747
Skewness	−0.936044846	−2.204561092	0.965922908	0.431012516
Kurtosis	2.844642852	9.876142507	3.056508403	1.937521552
Jarque-Bera	3.675891313	69.5017648	3.890855685	1.949945425
Probability	0.159144027	8.09E−16	0.142926	0.377202646
Sum	95.2110217	104.0234349	3.122542482	545.63
Sum Sq. Dev.	2.676425328	587.4016297	0.24669827	1220.071824
Observations	25	25	25	25

Source: Authors compilation.

In addition, the outcomes of ADF stationary tests are displayed in Table 4. Outcomes suggest that the indicators show stationarity for the level and the first difference for the intercept. Nevertheless, the ADF unit root test indicates that all variables exhibit stationarity at the level for both the intercept and trend. After successfully completing the unit root tests, it is necessary to do the cointegration test to demonstrate the durational correlation of factors.

Table 4. Stationary Outcomes.

Variables	Intercept		Trend + Intercept	
	level	1st diff	level	1st diff
CO_2	0.09842*		0.0265**	
EG	0.0014***		0.00075***	
FF	0.2249	0.0013***	0.03890**	
REC	0.0957*		0.01581**	

* represents a 10% level of significance, ** represents a 5% level of significance, and *** represents a 1% level of significance.

The findings of the "ARDL bound test" are displayed in Table 5. The outcomes indicate that the computed F-statistic surpasses the critical values at significance levels of 1% as it is less than 1%. Consequently, the null hypothesis, which suggests the absence of a long-term connection, will be disproven, while the alternative hypothesis, indicating the presence of a long-term association, will be supported.

Table 5. ARDL bounds test.

Dependent Variable: CO_2				
F-statistic	7.3269			
Value	1%	5%	10%	P-value
I(0)	4.614	3.272	2.676	0.000
I(1)	5.966	4.306	3.586	0.001

4.2. Autoregressive Distributed Lag Estimations

The "ARDL estimation" findings, displayed in Table 6, demonstrate that all independent factors exert significant and statistically meaningful effects on CO_2 emissions in the long and short term. The observed data exhibit coherence and consistency, affirming the notion that each of these components has a vital impact on the overall levels of CO_2 emissions in both the short and long term. Moreover, the error correction form outcome is 0.321 and statistically significant at 1%.

The findings present a particularly intriguing outcome regarding fossil fuels. Contrary to the conventional expectation that increased fossil fuel consumption drives higher CO_2 emissions, the data indicate that a one-unit rise in FF consumption results in a decrease of 3.015 and 3.193 units of CO_2 emissions in the long and short term, respectively. These results deviate from previous studies by Ali et al. (2024) [17], Martins et al. (2021) [12], and Ogundipe et al. (2020) [14] which typically associate increased FF use with elevated carbon emissions. This surprising inverse relationship may be attributed to Lithuania's adoption of advanced energy technologies and improved energy efficiency measures. Over the past decade, Lithuania has significantly modernized its energy infrastructure, transitioning towards cleaner and more efficient fossil fuel technologies. For example, the country has invested heavily in combined heat and power plants and modernized its natural gas systems to reduce carbon intensity. Furthermore, the Russia-Ukraine war has had profound impacts on Lithuania's energy sector. Historically reliant on Russian fossil fuels, Lithuania responded to the crisis by accelerating its transition towards energy independence. The operationalization of the Klaipėda LNG terminal, along with a reduction in dependence on carbon-intensive coal and oil, may explain the unexpected decrease in CO_2 emissions.

The role of renewable energy consumption in reducing CO_2 emissions is clearly demonstrated in both the short and long run. A one-unit increase in REC leads to a decrease of 0.0085 units in CO_2 emissions in the short term and 0.0537 units in the long term. This result emphasizes the immediate and gradual benefits of expanding renewable energy usage, with short-term reductions reflecting the rapid impact of REC adoption, while long-term effects highlight sustained environmental improvements. Lithuania's success in harnessing renewable energy can be attributed to its strong policy framework and investments in clean energy sources, including wind, solar, and biomass energy. The country's strategic emphasis on renewables aligns with broader European Union (EU) goals under the Green Deal to achieve carbon neutrality by 2050. The results also align with findings by Azam et al. (2022) [20], Raihan et al. (2022) [32], and Salari &

Javid (2017) [24], who concluded that increased reliance on renewable energy enhances environmental quality and contributes to economic sustainability. Given Lithuania's commitment to achieving its renewable energy targets, further investments in REC are likely to drive even more significant reductions in carbon emissions.

The relationship between economic growth and CO_2 emissions presents a more traditional outcome. The findings indicate that a one-unit increase in EG results in a rise of 0.0062 units in CO_2 emissions in the long term and 0.0186 units in the short term. This suggests that as Lithuania's economy expands, CO_2 emissions increase proportionately, posing challenges to environmental sustainability. The positive EG-CO_2 emissions relationship is consistent with prior research by Khan et al. (2022) [30] and Osobajo et al. (2020) [31], all of whom observed that economic expansion often leads to greater energy consumption and, consequently, higher carbon emissions. Lithuania's economic growth, driven by industrial output, transportation, and energy-intensive activities, underscores the need for balancing economic development with environmental preservation. Figure 3 illustrates the impact of each explanatory variable on CO_2 emissions.

Table 6. ARDL Estimations.

	Variables	**Coeff.**	**Std. Err.**	**t-statistic**	**P-value**
Long-run	FF(−1)	−3.0147**	1.13901	−2.6468	0.02014
	REC(−1)	−0.0085	0.00873	−0.9743	0.34771
	EG(−1)	0.00617	0.00968	0.63775	0.53471
Short-run	D(FF)	−3.1932***	0.70709	−4.516	0.00058
	D(REC)	−0.0537	0.04303	−1.2472	0.23434
	D(REC(−1))	−0.0804	0.05856	−1.3733	0.19287
	D(EG)	0.01857**	0.00732	2.5372	0.02479
	ECM(−1)	−0.320841***	0.078471	−4.088679	0.0015

* represents a 10% level of significance, ** represents a 5% level of significance, and *** represents a 1% level of significance.

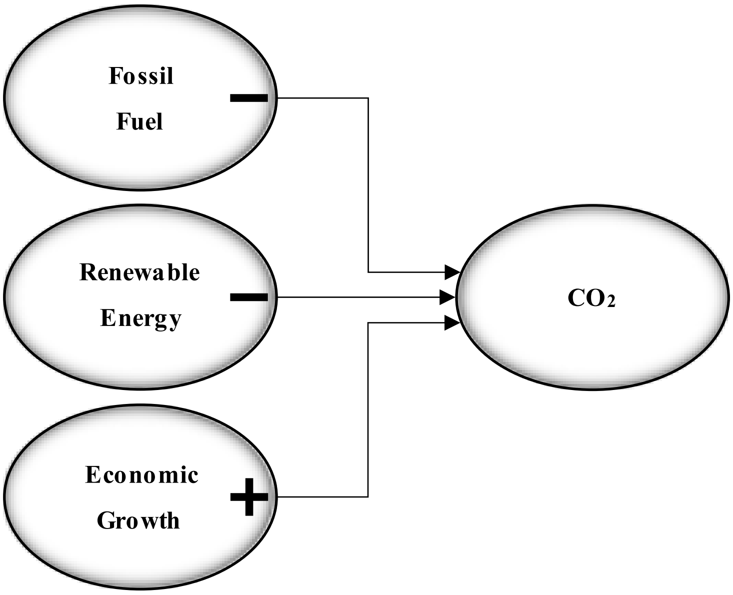

Figure 3. Overview of the impact of FF, REC, and EG on CO_2 Emissions.

4.3. Diagnostic Outcomes

Table 7 displays the diagnostic and stability tests conducted in this investigation. The experiments indicate that the model has structural stability. All probability values are above the 5% significance level. The distribution of the model follows a normal distribution with a mean of 0.85%. Furthermore, Figure 4 depicts the stability graph of the CUSUM and CUSUM of Squares, both of which fall under the 5% critical bound. This observation verifies the stability of the model employed in this work.

Table 7. Diagnostic Outcomes.

Diagnostic Tests	Statistics	Prob.	Decision
Breusch-Godfrey LM Test	0.7914955	0.82481	No serial correlation
Heteroskedasticity test	0.38267	0.7659	Homoskedastic
Histogram-Normality Test	0.313413	0.85491	Normally distributed
Ramsey Rest Test	2.395611	0.03379	Stable

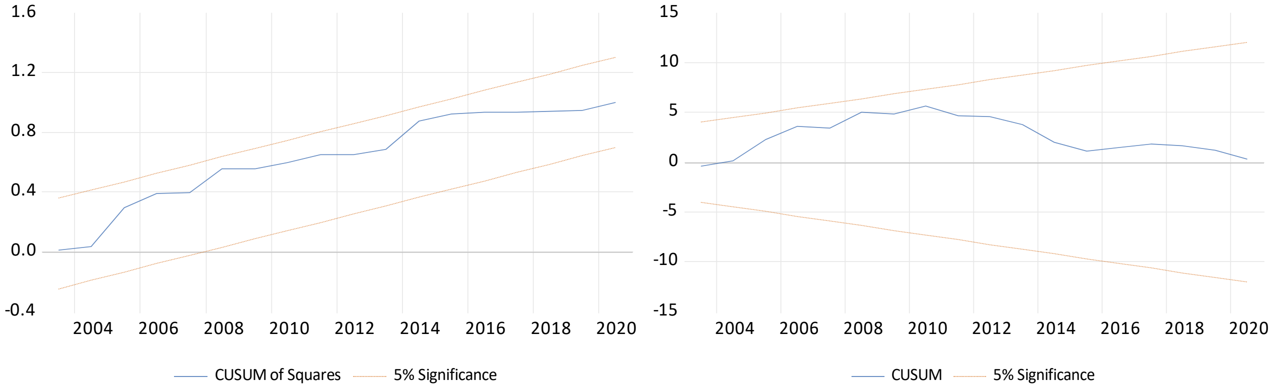

Figure 4. CUSUM of Square and CUSUM.

5. Conclusions

Understanding the factors that influence renewable energy consumption in Lithuania is crucial as it can contribute to the reduction of carbon emissions, enhancement of energy security, and promotion of sustainable development. This study investigated the impact of renewable energy consumption, fossil fuel usage, and economic growth on Lithuania's carbon emissions by utilizing data from 1996 to 2020. The ARDL Bounds test and ARDL technique were employed for analysis. The ARDL Bounds test confirmed the presence of a long-term link among the variables. The ARDL results indicated that each variable chosen for this study has an influence on the carbon emissions of Lithuania. The results indicated that both contemporary and conventional energy usage has an adverse effect on carbon emissions. Nevertheless, the ARDL analysis revealed that enhancing the economic performance of the nation leads to a rise in CO_2 emissions. Also, the report provides policy recommendations and advice for the Lithuanian government based on results.

5.1. Policy Recommendation

The paper suggests that there can be several policies that need to be put in place to promote sustainable development and reduce environmental degradation in Lithuania considering the impacts of economic growth, the use of renewable energy sources, and consumption of fossil fuel. Lithuania should prioritize funding for renewable energy development by establishing legislation that encourages the progress and utilization of clean energy sources such as biomass, solar, wind, and hydroelectric power. Policies that focus on investments in sustainable energy projects, tax incentives, and feed-in tariffs can further strengthen the renewable energy sector. Such programs not only reduce greenhouse gas emissions but also create employment opportunities and stimulate economic growth.

Furthermore, Lithuania must promote sustainable economic growth by prioritizing policies that encourage environmentally friendly development over growth strategies that neglect environmental damage. Financial assistance for eco-friendly firms, investments in green infrastructure, and support for circular economy practices can help reduce the environmental impact of economic expansion. By encouraging industries to adopt cleaner technologies and sustainable production methods, Lithuania can mitigate the adverse effects of economic growth on CO_2 emissions while maintaining competitiveness.

Finally, international cooperation is critical for addressing environmental challenges and enhancing Lithuania's ability to transition toward sustainability. Lithuania should actively engage with neighboring countries in the Baltic region to develop joint renewable energy initiatives that contribute to carbon emissions reduction and energy diversification. By participating in global agreements and sharing best practices, technologies, and resources, Lithuania can amplify its efforts to mitigate climate change and promote environmental protection on an international scale.

5.2. Limitations

This study thoroughly examines just the facets of fossil fuels, renewable energy, economic development, and carbon emissions. Another drawback is its exclusive emphasis on data from Lithuania between 1996– 2020. The work employed robust ARDL statistical approaches; hence, future researchers can use alternate procedures, such as the Method of Movement Quantile Regression (MMQR), to analyze panel data from Baltic economies and get a more profound comprehension of the results in a bigger picture. Furthermore, there exists a chance to examine other economic elements that might substantially influence the reduction of carbon dioxide emissions, including tourism, human capital, green financing, technical innovation, and stringent environmental regulations.

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Data Availability

We investigate the effects of REC, EG, and FF usage on reducing the consequences of CO_2 emissions in Lithuania. The analysis employs data that covers the historical period of the country from 1996 to 2020. All data was collected from the World Bank data set (https://databank.worldbank.org).

Author Contributions

Conceptualization: A.D.; Formal analysis: A.D.; Investigation: M.S.; Methodology: A.D.; Software: M.S.; Supervision: M.S., & H.O.; Visualization: A.D.; Writing – original draft: A.D.; Writing – review & editing: M.S.

Conflicts of Interest

The authors have no conflict of interest to declare.

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