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The Impact of Renewable and Non-Renewable Energy Consumption on Environmental Sustainability in Central Asian Countries

Ergash Ibadullaev [1], Yuldoshboy Sobirov [2], Nodira Namazova [3], Gulistan Musaeva [4], Oybek Xudayarov [5], Tukhtabek Rahkimov [6]*

[1] *Economics Department, Mamun University, Urgench 220100, Uzbekistan*

[2] *Department of Accounting, Mamun University, Urgench 220100, Uzbekistan*

[3] *Department of Social Sciences, Bukhara State Medical Institute, Bukhara 200126, Uzbekistan*

[4] *Department of Uzbek Language and Literature, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent 100000, Uzbekistan*

[5] *Department of Bank Account and Audit, Tashkent State University of Economics, Tashkent 100066, Uzbekistan*

[6] *Department of Economics, Urgench State University, Urgench 220100, Uzbekistan*

ABSTRACT

This study investigates the impact of non-renewable energy production, renewable energy production, and population size on per capita greenhouse gas emissions in Central Asian (CA) countries over the period 2000–2024, utilizing the Panel ARDL–PMG (Pooled Mean Group) estimation technique. The analysis provides both long-run and short-run country-specific insights into the determinants of emissions, offering a nuanced understanding of environmental dynamics in the region. The long-run results reveal that non-renewable energy production is positively and significantly associated with per capita greenhouse gas emissions, indicating that reliance on fossil fuels continues to drive environmental degradation. In contrast, renewable energy production is found to have a negative long-run effect, suggesting that investments in clean energy sources can effectively mitigate emissions over time. Population size also exhibits a negative long-run association with per capita emissions, reflecting potential demographic influences on energy consumption patterns. Short-run estimates demonstrate heterogeneous effects across countries: in two Central Asian nations, non-renewable energy production

*CORRESPONDING AUTHOR:

Ergash Ibadullaev, Economics Department, Mamun University, Urgench, 220100, Uzbekustan; Email: ergashibadullaev90@gmail.com

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substantially increases per capita emissions, whereas in the other two, it reduces emissions. Similarly, renewable energy production has a positive short-run impact in three countries, a negative impact in one, and an insignificant effect in another. These findings underscore the importance of recognizing country-specific dynamics and adopting tailored energy and environmental policies. The study contributes to regional policy discussions by highlighting the need for a balanced transition towards renewable energy while addressing the unique socio-economic contexts of each country.

Keywords: Renewable Energy; Non-Renewable Energy; Environmental Sustainability; CA; CO_2; Greenhouse Gas Emissions

1. Introduction

Central Asia-comprising Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan-stands at a critical juncture in its energy and environmental trajectory. Historically, the region has relied heavily on abundant fossil fuel reserves to support economic growth, energy security, and domestic consumption. Kazakhstan and Turkmenistan, endowed with vast oil and natural gas deposits, remain major exporters of hydrocarbons, while Uzbekistan continues to depend primarily on natural gas and coal for electricity generation. By contrast, Kyrgyzstan and Tajikistan possess substantial hydropower potential and rely extensively on river systems to meet domestic electricity needs, albeit with challenges related to seasonal variability, aging infrastructure, and limited diversification [1,2].

In recent years, rising concerns over climate change, environmental degradation, and sustainability have prompted Central Asian governments to reconsider their traditional energy pathways. The global shift toward low-carbon development, coupled with national priorities to enhance energy efficiency and diversify energy sources, has intensified interest in renewable energy alternatives. Renewable energy offers multiple potential benefits for the region, including reduced greenhouse gas emissions, enhanced energy security, and opportunities for green economic growth. However, transitioning from conventional fossil-fuel-based systems to renewable and low-carbon technologies presents complex challenges. These include infrastructural constraints, financial limitations, intermittency issues, regulatory shortcomings, and the need for substantial institutional reforms [3].

Against this backdrop, understanding the evolving relationship between energy consumption, renewable energy deployment, and environmental outcomes in Central Asia is both timely and policy-relevant. Despite increasing attention to global energy transitions, the Central Asian region remains underrepresented in empirical analyses, particularly those examining the differential effects of renewable and non-renewable energy sources on greenhouse gas emissions. Existing cross-country studies often overlook the unique geopolitical, economic, and environmental conditions that shape energy use in Central Asia. Moreover, recent years have witnessed significant policy reforms and investments in renewable energy infrastructure, underscoring the need for updated, region-specific assessments.

This study addresses these gaps by conducting a comprehensive empirical examination of how the composition of electricity production-renewable versus non-renewable-affects per-capita greenhouse gas emissions in the five Central Asian countries. The analysis integrates environmental science, economic theory, and policy assessment to provide a holistic understanding of the forces shaping the region's energy-environment nexus. Specifically, the study draws on an extended STIRPAT framework and employs an ARDL-PMG estimation strategy to capture both short-run adjustment dynamics and long-run elasticities of emissions with respect to renewable and non-renewable electricity production while controlling for population effects. This methodological approach offers a level of granularity and rigor that is largely absent from earlier regional studies.

Furthermore, the study extends the temporal coverage up to 2024, capturing the most recent developments in the region's energy landscape, including new renewable energy projects, structural shifts in fuel mix, technological modernization, and evolving policy commitments in line with international agreements such as the Paris Agreement. The granularity of the dataset-particularly the disaggregation of electricity production into renewable and non-renewable sources-enables the identification of transitional dynamics often obscured in aggregate analyses. For instance, in some contexts, an expansion of renewable energy may temporarily coincide with higher emissions due to integration challenges, biomass combustion, or hydropower-related methane releases, while improvements in fossil fuel technology may reduce emissions intensity in the short run.

Taken together, these elements constitute the study's original contribution to the literature. First, it offers one of the most recent and regionally focused empirical analyses of the energy-emissions relationship in Central Asia, a region whose unique characteristics are insufficiently examined in prior research. Second, by incorporating updated data through 2024, the study captures contemporary structural shifts that significantly influence environmental outcomes. Third, the use of an extended STIRPAT model combined with ARDL-PMG estimation enhances the precision of both short-run and long-run elasticity estimates. Finally, the disaggregation of electricity production into renewable and non-renewable components provides novel insights into how differing energy sources shape emissions trajectories in transitional energy systems.

By generating context-specific and methodologically robust evidence, this study aims to inform policymakers, scholars, and regional stakeholders seeking to balance economic development with environmental stewardship. The insights generated here contribute to ongoing efforts to promote sustainable energy transitions in Central Asia and offer a foundation for more targeted, evidence-based policy interventions.

2. Literature Review

Renewable Energy-Environmental Sustainability

Renewable energy sources-derived from the sun, wind, water, biomass, and geothermal heat-emit minimal greenhouse gases and pollutants, making them central to environmental protection and sustainable development. Their role in reducing ecological pressure has long attracted scholarly attention, with numerous studies exploring the link between renewable energy deployment and environmental sustainability. Jaiswal et al. [4] emphasize that improving social, economic, and environmental well-being increasingly depends on the expansion of clean and sustainable energy systems. Their work outlines how renewable energy enhances productivity, supports economic progress, strengthens energy security and access, and mitigates climate-related threats to ecosystems and human health. In a related contribution, Kuziboev et al. [5] investigate how renewable energy and several governance-related variables shape environmental quality in developing Asian economies from 1996 to 2020 using GMM and quantile regression. Their findings reveal that renewable energy consistently exerts a strong negative effect on CO_2 emissions across all quantiles, whereas tax revenue and women's governance show varying impacts. The urgency of addressing environmental sustainability has intensified worldwide, as lowering CO_2 emissions remains essential for curbing global warming and sustaining long-term economic growth. Kuziboev et al. [6] further examine this issue by applying the two-step FOD-GMM approach to assess how renewable energy and human capital contribute to environmental improvement in Europe and Central Asia. Their results underscore the significant role that both renewable energy and human capital play in reducing emissions in these regions. They also find that economic growth has a neutral influence on carbon emissions, government efficiency increases emissions, and renewable energy continues to demonstrate a substantial emissions-reducing effect. Other scholars have explored additional determinants of environmental degradation. Majeed and Luni [7], using panel data from 166 countries (1990–2017) and employing Pooled OLS, RE, FE, and 2SLS estimators, show that water withdrawal worsens environmental quality, while renewable energy helps mitigate ecological damage. Similarly, Magazzino et al. [8] analyze the nexus among GDP, CO_2 emissions, and renewable energy consumption, identifying three empirical clusters and concluding that expanding renewable energy use can lower emissions without hindering economic growth. Their results highlight the crucial role of energy efficiency and renewable energy adoption for achieving growth with lower environmental costs. Alavijeh et al. [9] focus on the impact of institutional quality, technological innovation, GDP, and renewable energy on emissions in 14 EU member states using annual data (2000–2019) and the MMQR methodology. Their empirical results show that renewable energy significantly reduces emissions across all quantiles (0.1–0.9). While GDP increases emissions, improvements in institutional quality and technological innovation enhance environmental conditions across the lower and middle quantiles.

Growing awareness among scientists and policymakers has spurred the development of strategies such as greater energy efficiency and the transition toward sustainable energy systems. Alola et al.[10], analyzing India's energy profile from 1965 to 2018 with the Dynamioc-ARDL simulation method, demonstrate that both renewable energy consumption and efficiency in non-renewable energy use contribute positively to environmental sustainability by improving the load capacity factor.

The environmental consequences of non-renewable energy remain a persistent concern. As noted by Ansari[11], the extraction, processing, and disposal of non-renewable energy sources generate substantial environmental damage. Noor et al.[12] assess the effects of renewable and non-renewable energy on sustainable development in South Asia (1995–2019) using a panel ARDL framework. Their results indicate that both renewable and non-renewable energy exert significant positive long-run effects on sustainable development, with various diagnostic tests confirming the stability and reliability of the ARDL estimations.

The interaction between energy use, technological change, and environmental sustainability is explored by Imran et al.[13], who study QUAD economies (the US, Japan, Australia, and India) from 1991 to 2021. Their findings reveal that renewable energy production and technological innovation promote environmental sustainability, whereas fossil fuel consumption and economic growth weaken it. They also highlight that the combustion of conventional fuels releases high levels of greenhouse gases and other pollutants, generating substantial external costs-estimated at 4.0 to 9.5 cents per kilowatt-hour for coal-fired plants, exceeding costs associated with gas and renewable energy sources[14].

Finally, Saqib[15] examines 63 emerging and advanced economies (1990–2020) to evaluate how non-renewable energy, green energy, financial development, and economic growth contribute to carbon footprints. Their findings confirm long-run cointegration among all variables and indicate that green energy use decreases environmental risks, while non-renewable energy consumption enlarges the carbon footprint over time.

Empirical research on the energy-emissions nexus frequently relies on frameworks such as IPAT and STIRPAT to examine how population, economic growth, and energy structure drive CO_2 emissions[16,17]. While fossil-fuel-based electricity generation is commonly found to increase emissions, the mitigating effects of renewable energy vary substantially across studies, often due to different econometric approaches. For example, Polat, Yapraklı, and Çamkaya[18] use a cross-sectional augmented autoregressive distributed lag (CS-ARDL) model across OECD countries and demonstrate that both renewable and nuclear energy negatively affect CO_2 emissions in both the short and long run.

One major challenge in literature is methodological heterogeneity. Some studies employ static panel data approaches (e.g., fixed or random effects), while others use dynamic models (for example, ARDL, CS-ARDL) to account for long-run relationships and cross-sectional dependencies[17–19]. These differences often yield inconsistent estimates of energy-structure elasticities, especially concerning the effect of renewables on emissions. Moreover, relatively few studies incorporate the most recent data reflecting shifts in energy policy and investment since 2022, limiting the applicability of their conclusions in rapidly changing contexts.

Although global research is abundant, Central Asia remains underrepresented in empirical work that disaggregates energy sources. According to a systematic literature review by Vakulchuk, Overland, and Sabyrbekov[19], research on decarbonization in Central Asia is sparse, with a noticeable shift from a focus on fossil fuels to clean energy only emerging around 2019–2020. Despite growing scholarly interest, there remains a dearth of studies that specifically assess the environmental impact of renewable versus non-renewable electricity generation in the region.

Policy and institutional analyses complement this gap. For instance, the European Bank for Reconstruction and Development (EBRD) reports that in 2023 it invested over €1.2 billion in Central Asia, nearly 60% of which supported green projects, including major renewable energy plants in Uzbekistan and Kazakhstan. These investments underscore the region's growth but still underleveraged green infrastructure.

Furthermore, the OECD has documented Uzbekistan's financial commitment to the green transition. In 2023, Uzbekistan issued thematic bonds (green and sustainability bonds) to harness private capital for renewable energy and energy efficiency projects. Simultaneously, major infrastructure challenges persist, fossil fuels (notably natural gas) continue to dominate Uzbekistan's energy mix, and structural barriers in capital markets hinder the large-scale deployment of green technologies.

Recent reports highlight both progress and risk in Central Asia's energy transition. The *EBRD's Transition Report 2023–24* notes that Kazakhstan's share of renewable energy (especially solar and wind) in its electricity mix is growing, supported by partnerships (e.g., with the EU) to develop green hydrogen capacity. At the same time, coal and gas remain central to the region's energy paradigm.

Risk analyses also bring attention to key constraints. A PricewaterhouseCoopers (PwC) study suggests that although Kazakhstan and Uzbekistan have set ambitious green targets, their transition paths are impeded by aging infrastructure, grid reliability issues, and regulatory bottlenecks. Moreover, green finance is nascent: while green bonds are emerging, institutional frameworks and market depth remain insufficient for rapid decarbonization.

In sum, the literature indicates that:

- There is strong theoretical and empirical support for the influence of energy structure on CO_2 emissions, yet methodological differences hinder consistent conclusions.
- Central Asia is understudied, particularly in studies that disaggregate renewable versus non-renewable power generation in econometric models.
- Recent policy momentum - including green finance initiatives and international investments - has not yet been fully captured in academic research.
- Structural and institutional risks (e.g., grid infrastructure, regulation, and financing) pose significant barriers to energy transition despite growing investments.

The Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model has become a widely adopted analytical framework for examining the anthropogenic drivers of environmental pressure, particularly carbon dioxide emissions [19–21]. As an extension of the classical IPAT identity, the STIRPAT approach allows for stochastic estimation, hypothesis testing, and flexibility in capturing non-proportional effects of socioeconomic variables on environmental outcomes. Prior empirical studies using the STIRPAT framework have largely focused on aggregate energy consumption or total electricity production, often treating energy structure as a single composite variable and concentrating on developed or large emerging economies. Moreover, much of the existing literature relies on datasets ending before recent structural shifts in energy policy, investment in renewables, and decarbonization strategies. Against this backdrop, the present study advances the literature by applying a STIRPAT-based econometric model to Central Asian countries, explicitly disaggregating electricity production into renewable and non-renewable sources and employing data up to 2024. This approach enables a more nuanced assessment of how different energy generation pathways influence carbon emissions in the context of evolving energy transitions and policy reforms, thereby providing updated and region-specific insights into the environmental impacts of economic and technological change.

3. Theoretical Framework

Understanding the determinants of environmental sustainability, particularly in the context of energy consumption, requires a robust theoretical foundation. This study adopts the extended STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework, an econometric reformulation of the classical IPAT identity, which allows for empirical estimation of the relative contributions of population, technology, and energy structure to environmental impact [20–22].

The IPAT identity formalizes environmental impact (I) as a multiplicative function of population (P), affluence (A), and technology (T):

$$I = P \times A \times T$$

The Kaya identity, a closely related formulation, further decomposes CO_2 emissions into population, GDP per capita, energy intensity, and carbon intensity [23–27]. Within this framework, population reflects the scale of human activity, while the technology component captures the efficiency and carbon intensity of energy consumption. In this study, the structure of electricity production-renewable versus non-renewable-serves as a proxy for technological intensity and its environmental implications.

The STIRPAT model extends the deterministic IPAT formulation by introducing stochastic error terms and allowing coefficients to differ from unity, facilitating empirical estimation of elasticities [19–21]. The general STIRPAT model is expressed as:

$$I_i = a \cdot P_i^b \cdot A_i^c \cdot T_i^d \cdot e_i \quad (1)$$

where a is a constant, b, c, d represent the elasticities of population, affluence, and technology, and $e_i$denotes the stochastic error term. Log-linearization is commonly applied to allow interpretation of coefficients as elasticities:

$$\ln I_i = \ln a + b \ln P_i + c \ln A_i + d \ln T_i + \epsilon_i \quad (2)$$

Energy Structure and Sectoral Considerations.

Several studies have demonstrated the importance of disaggregating energy consumption by source within the STIRPAT framework. Fossil fuel-based electricity generation (coal, oil, and natural gas) is carbon-intensive and positively associated with CO_2 emissions, whereas renewable energy sources (solar, wind, hydropower, biomass) tend to reduce emissions [21,23]. Empirical applications confirm that incorporating energy type as part of the technological factor enhances the explanatory power of STIRPAT models and allows for sector-specific policy implications [24].

Based on the extended STIRPAT framework, the current study specifies the following model to examine the determinants of per-capita greenhouse gas emissions in Central Asian countries:

$$\ln CO_{2it} = \alpha + \beta_1 \ln P_{it} + \beta_2 \ln R_{it} + \beta_3 \ln N_{it} + \varepsilon_{it}$$

where:

CO_{2it} represents per-capita greenhouse gas emissions (CO_2 equivalents) for the country i at the time t;

P_{it} denotes total population;

R_{it} denotes electricity production from renewable sources;

N_{it} denotes electricity production from non-renewable sources;

ϵ_{it} is the error term.

The theoretical expectations are as follows: $\beta_1$is positive, reflecting that a larger population increases environmental impact; $\beta_2$is negative, reflecting the emission-reducing effect of renewable electricity; and $\beta_3$is positive, reflecting the emission-increasing effect of non-renewable electricity. This specification is theoretically consistent with the STIRPAT framework and aligns with empirical findings from previous studies [17–20] .

4. Materials and Methods

4.1. Data Description

This study investigates how per capita greenhouse gas emissions in Central Asian countries are influenced by electricity generation from renewable and non-renewable sources, along with population size. To conduct this analysis, annual panel data for the years 2000–2024 were compiled. The dependent variable is per capita greenhouse gas emissions, while the explanatory variables include electricity production from renewable sources, electricity production from non-renewable sources, and population levels. Data for all variables were collected from two publicly accessible databases: Our World in Data and the World Bank Open Data repository (https://ourworldindata.org/; https://data.worldbank.org/). A detailed description of each variable employed in the analysis is presented in **Table 1**.

Table 1. Definition of variables.

Variable	Unit	Year	Logarithmic Forms	Sources
Per-capita greenhouse gas emissions in CO_2 equivalents	tonnes per person	2000–2024	$LOG(per_{capita_l}\_GHG)$	https://ourworldindata.org/grapher/per-capita-ghg-emissions
Electricity production by sources (renewable)	TWh	2000–2024	$LOG(elp\_REN)$	https://ourworldindata.org/grapher/electricity-prod-source-stacked
Electricity production by sources (non-renewable)	TWh	2000–2024	$LOG(elp\_non\_REN)$	https://ourworldindata.org/grapher/electricity-prod-source-stacked
Population total	person	2000–2024	$LOG(POPULATION)$	https://data.worldbank.org/indicator/SP.POP.TOTL?locations=1W

Because the variables used in the analysis are measured in different units, all factor values are transformed into their natural logarithms. This logarithmic conversion ensures comparability across variables and facilitates clearer interpretation of the econometric model results.

4.2. Cross-Sectional Dependence Test

Assessing cross-sectional dependence (CD) in the panel dataset is a crucial preliminary step, as it guides the selection of an appropriate unit root test [25]. For this purpose, the empirical analysis employs the CD testing procedure proposed in Pesaran and Smith [26]. The CD test is conducted using the following model specification, which reflects the framework introduced in Pesaran, Shin, and Smith [27]:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} Tp_{ij}{}^{2}\right) \quad (3)$$

In Equation (3), T denotes the time dimension of the panel, while N represents the cross-sectional dimension. The term $\boldsymbol{p^2_{ij}}$ refers to the sample estimate of the pairwise correlation of the residuals.

4.3. Panel Unit Root Test

To prevent spurious regression outcomes and to ensure the reliability of the empirical findings, the first step in the analysis involves examining the stationarity properties of the variables. Panel unit root testing has become widely adopted in empirical research because it generally offers greater statistical power than unit root tests applied to individual time series.

However, stationarity tests may yield biased results if cross-sectional dependence is ignored. Since first-generation panel unit root tests do not account for such dependence, this study employs the second-generation panel unit root tests introduced by Pesaran [28]. These include the cross-sectional Im, Pesaran, and Shin (CIPS) test and the cross-sectional Augmented Dickey–Fuller (CADF) test, both of which are designed to be robust in the presence of cross-sectional dependence. The CADF model is expressed in Equation (4).

$$\begin{aligned}\Delta y_{it} &= \alpha_i + \beta_i Y_{it-1} + \varphi \overline{y}_{t-1} \\ &\quad + \sum\nolimits_{j=0}^{q} \theta_{j+1}\Delta\overline{y}_{t-j} + \sum\nolimits_{k=1}^{q} \omega_k \Delta y_{it-k}\end{aligned} \quad (4)$$

In this context, y_{t-1} represents the average of the lagged levels across all N cross-sectional units at time t, while $y_t$denotes the first difference of the individual series within the model. After estimating the CADF regression for each cross-sectional unit, the CIPS (Cross-Sectionally Augmented IPS) statistic is computed by taking the average of the t-statistics corresponding to the coefficient β in the CADF regressions:

$$CIPS = N^{-1}\sum\nolimits_{t=1}^{N} CADF_t \quad (5)$$

Here, CADF$_i$ denotes the cross-sectionally augmented Dickey–Fuller statistic for the $\boldsymbol{i}^{\text{th}}$ cross-sectional unit. In the presence of cross-sectional dependence, this test provides more reliable and consistent results compared to first-generation panel unit root tests.

4.4. ARDL-PGM Approach

The ARDL approach, as developed by Pesaran et al. [27–30] is particularly suitable in this study because the dependent variable is integrated of order one, I(1). This framework allows the model to be expressed in an error correction form when the variables are either purely I(0), a combination of I(0) and I(1), or I(1). However, the ARDL methodology is not appropriate if any variable is integrated of order two, I(2). Moreover, by incorporating appropriate lag lengths for both endogenous and exogenous variables, the ARDL model mitigates endogeneity concerns and produces reliable and efficient parameter estimates. The ARDL (p,q) model employed in this study is specified as follows:

$$\begin{aligned}LOG(per\_capita\_GHG)_{it} &= \mu_i + \sum\nolimits_{j=1}^{p-1} \beta_{1_{ij}} LOG(per\_capita\_GHG)_{it-j} \\ &+ \sum\nolimits_{j=0}^{q-1} \beta_{2_{ij}} LOG(elp\_REN)_{it-j} + \sum\nolimits_{j=0}^{q-1} \beta_{3_{ij}} LOG(elp\_non\_REN)_{it-j} \\ &+ \sum\nolimits_{j=0}^{q-1} \beta_{4_{ij}} LOG(POPULATION)_{it-j} + \nu_{it}\end{aligned} \quad (6)$$

As noted by Pesaran et al. [27,28], the above equation can be equivalently expressed in the following reformulated form:

$$\Delta LOG(per\_capita\_GHG)_{it} = \mu_i + \gamma_{1i} LOG(per\_capita\_GHG)_{it-1} + \gamma_{2i} LOG(elp\_REN)_{it-1} + \gamma_{3i} LOG(elp\_non\_REN)_{it-1} + \gamma_{4i} LOG(POPULATION)_{it-1} + \sum_{j=1}^{p-1} \delta_{1_{ij}} \Delta LOG(per\_capita\_GHG)_{it-j} + \sum_{j=1}^{q-1} \delta_{2_{ij}} \Delta LOG(elp\_REN)_{it-j} + \sum_{j=0}^{q-1} \delta_{3_{ij}} \Delta LOG(elp\_non\_REN)_{it-j} + \sum_{j=0}^{q-1} \delta_{4_{ij}} \Delta LOG(POPULATION)_{it-j} + \varepsilon_{it} \quad (7)$$

In this specification, the terms expressed in first differences capture the short-run dynamics, while the terms in levels represent the long-run relationships. Here, Δdenotes the first-difference operator, and $\varepsilon_{it}$is the error term. The optimal lag lengths $(j, q)$are determined using either the Schwarz Bayesian Criterion (SBC) or the Akaike Information Criterion (AIC). For panel ARDL estimation, Pesaran and Smith [26] and Pesaran et al. [25] introduced two approaches: the Mean Group (MG) estimator and the Pooled Mean Group (PMG) estimator. Both methods, which are based on maximum likelihood estimation, are considered highly reliable because they account for long-run equilibrium relationships while accommodating heterogeneity across different cross-sectional units.

5. Results and Discussion

Table 2 presents the findings of the cross-sectional dependence test. The results show that the null hypothesis is rejected, indicating the presence of cross-sectional dependence in all series at the 1% significance level.

Table 2. Results of cross-sectional dependence test.

Variables	Pesaran CD	Prob.
$LOG(per\_capita\_GHG)$	0.92	0.00
$LOG(elp\_REN)$	4.60	0.00
$LOG(elp\_non\_REN)$	3.74	0.00
$LOG(POPULATION)$	14.78	0.00

The results of the cross-sectional dependence test suggest that any shock or change in one variable may influence all cross-sectional units within the panel. Consequently, the analysis proceeds with second-generation panel unit root tests. In the subsequent step, panel unit root tests were performed for the three variables at both their levels and first differences, as summarized in **Table 3**.

As indicated by the results in **Table 3**, the variables *LOG(per_ capita_ GHG), LOG(elp_ REN), LOG(elp_ non_ REN)*, and *LOG(POPULATION)* are all stationary at first difference according to the CADF and CIPS unit root tests. This confirms that it is appropriate to use these first-differenced variables in the subsequent model estimations. Building on this, the long-run and short-run impacts of electricity production from renewable and non-renewable sources, as well as population, on environmental sustainability in Central Asian countries were assessed, with the results presented in **Table 4**.

Table 3. Panel unit root test outcomes.

Variables	Level	First Difference
	CADF	
$LOG(per\_capita\_GHG)$	16.14*	43.57***
$LOG(elp\_REN)$	17.62*	36.23***
$LOG(elp\_non\_REN)$	7.18	35.19***
$LOG(POPULATION)$	2.05	19.56**
	CIPS	
$LOG(per\_capita\_GHG)$	−0.73	−4.96***
$LOG(elp\_REN)$	−0.91	−4.15***
$LOG(elp\_non\_REN)$	0.54	−4.06***
$LOG(POPULATION)$	4.62	−1.44**

Note: ***significance of 1%; **significance of 5% and *significance of 10%.

Table 4. Estimation ARDL (PMG).

Dependent Variable: $DLOG(per_{capita\_}GHG)$				
Variable	**Coefficient**	**Std. Error**	***t*-Statistic**	**Prob.**
Long Run Equation				
$LOG(elp\_non\_REN)$	0.944486	0.227498	4.151627	0.0001***
$LOG(elp\_REN)$	−0.087944	0.051092	−1.721299	0.0890**
$LOG(POPULATION)$	−2.003577	0.324684	−6.170856	0.0000***
Short Run Equation				
ECT(-1)	−0.365107	0.151995	−2.402095	0.0186***
$DLOG(elp\_non\_REN)$	−0.154326	0.242697	−0.635880	0.5266
$DLOG(elp\_REN)$	0.210074	0.116852	1.797780	0.0759**
$DLOG(POPULATION)$	−2.020704	6.368310	−0.317306	0.7518
C	11.75590	4.886550	2.405768	0.0184***

Note: ***significance of 1%; **significance of 5% and *significance of 10%.

The ARDL-PMG estimation results offer important insights into the factors influencing per capita greenhouse gas emissions in Central Asian countries. The long-run estimates indicate that electricity production from non-renewable sources has a strong and positive impact on emissions. A rise in fossil fuel-based electricity generation is associated with a corresponding increase in per capita GHG emissions. This finding reflects the structural characteristics of energy systems in the region, which remain heavily reliant on carbon-intensive sources such as coal and natural gas. Countries like Kazakhstan, Turkmenistan, and Uzbekistan continue to depend on legacy thermal power infrastructure, have limited adoption of advanced emission abatement technologies, and maintain energy-intensive industrial sectors, all of which contribute to elevated emissions levels [1].

In contrast, electricity production from renewable sources demonstrates a negative long-run effect on emissions. Although the magnitude of this effect is relatively modest, it corresponds with the gradual expansion of renewable energy capacity in the region, particularly in solar and wind sectors. Recent policy initiatives, including renewable energy auctions in Kazakhstan and Uzbekistan, are slowly shifting the energy mix toward cleaner sources [2]. The negative relationship suggests that scaling up renewable electricity contributes to long-term emissions reduction, despite the currently limited penetration of renewable technologies.

Population size exhibits a negative and significant long-run association with per capita emissions. This inverse relationship likely reflects the demographic and economic structure of the region. Population growth tends to lower per capita emissions because total emissions are largely driven by a small number of energy-intensive sectors, such as mining, metallurgy, and petrochemicals, rather than by household energy consumption [1,5]. Furthermore, ongoing urbanization and a relatively young population contribute to more energy-efficient consumption patterns, reducing emissions on a per capita basis.

The short-run dynamics provide additional nuance to these findings. The negative and significant error-correction term confirms the existence of a long-run equilibrium, indicating that deviations from the long-run path are gradually corrected over time. This adjustment speed aligns with expectations for economies in transition, where structural reforms and diversification in the energy sector occur progressively [2,3].

Short-run coefficients capture transitional effects. Changes in non-renewable electricity production are not significant in the short run, reflecting the rigidity of fossil-based energy systems. Renewable electricity production, however, exhibits a small positive short-term effect, which may be attributed to transitional factors such as reliance on fossil fuel-based backup generation for intermittent renewable sources, carbon-intensive construction of renewable infrastructure, and limited grid flexibility [1,4,5]. Over time, these transitional inefficiencies diminish, consistent with the negative long-run relationship observed for renewable energy.

Population dynamics do not show a significant short-run impact on emissions, suggesting that demographic effects primarily operate through structural and long-term mechanisms rather than annual fluctuations.

Additionally, this study examined the short-term effects of non-renewable and renewable electricity production, as well as population, on per capita greenhouse gas emissions for each Central Asian country, with the results summarized in **Table 5**.

Table 5. Individual country results.

Country	Estimation ARDL (PMG)			
	***ECT* (−1)**	***DLOG*(*elp_ non_ REN*)**	***DLOG*(*elp_ REN*)**	***DLOG*(*POPULATION*)**
Kazakhstan	−0.592*** (0.000)	0.556*** (0.025)	0.457** (0.000)	12.977 (0.477)
Kyrgyzstan	0.011*** (0.01)	0.017** (0.03)	−0.00 (0.97)	−1.305 (0.944)
Tajikistan	0.002*** (0.000)	0.038*** (0.000)	0.097*** (0.075)	0.707 (0.977)
Turkmenistan	−0.64*** (0.000)	−0.811*** (0.02)	0.523** (0.00)	−25.52 (0.89)
Uzbekistan	−0.605*** (0.000)	−0.572*** (0.000)	−0.027*** (0.00)	3.044 (0.47)

Note: ***significance of 1%; **significance of 5% and *significance of 10%.

The short-run analysis reveals heterogeneous effects of energy production on per capita greenhouse gas emissions across Central Asian countries. In two countries, non-renewable energy production has a positive impact on emissions per capita, whereas in another two, the effect is negative. Similarly, renewable energy production increases per capita emissions in three countries, decreases emissions in one, and shows no significant effect in another. Overall, the population appears to have minimal influence on per capita emissions in the short term.

Country-specific results illustrate these variations. In Kazakhstan, a rise in non-renewable energy production is associated with higher per capita emissions, and an increase in renewable energy production also leads to a modest increase in emissions. In Kyrgyzstan, higher non-renewable energy output corresponds to a slight increase in emissions per person. Tajikistan exhibits small positive short-term effects from both non-renewable and renewable energy production on per capita emissions. In Turkmenistan, increased non-renewable energy production is linked to a reduction in per capita emissions, while renewable energy production slightly raises emissions. For Uzbekistan, non-renewable energy production contributes to a decrease in per capita emissions, and renewable energy production has a negligible negative effect.

These results highlight that the short-term relationship between energy production and greenhouse gas emissions is highly country-specific, reflecting differences in energy infrastructure, industrial composition, and the transitional dynamics of energy systems.

6. Policy Recommendations

Based on the econometric results and country-specific energy structures, the following evidence-based policy recommendations are proposed:

1. Accelerating Renewable Energy Deployment
    - Kazakhstan: Scale up utility-scale solar and wind projects through feed-in tariffs, competitive renewable energy auctions, and grid upgrades to facilitate integration [31].
    - Kyrgyzstan and Tajikistan: Leverage hydroelectric potential by modernizing existing dams and developing small-scale hydropower to expand clean energy capacity without increasing fossil fuel dependency.
    - Uzbekistan and Turkmenistan: Promote solar photovoltaic (PV) and concentrated solar power (CSP) projects in high-insolation regions, paired with energy storage solutions. Utilize green finance instruments, including sovereign green bonds and public-private partnerships, to mobilize investment [32].
2. Reduce Reliance on Non-Renewable Electricity
    - Implement carbon pricing mechanisms or gradually reduce subsidies for fossil-fuel-based electricity in countries like Turkmenistan and Kazakhstan to internalize environmental externalities.
    - Encourage energy efficiency measures across industrial and residential sectors to lower the carbon intensity of electricity consumption.
3. Strengthening Institutional and Regulatory Frameworks
    - Harmonize renewable energy regulations and grid codes to ensure reliable integration of intermittent sources.

- Develop long-term national energy strategies with clear renewable energy targets aligned with regional cooperation initiatives, such as cross-border power interconnections.

4. Tailor Policies to Country-Specific Conditions
   - Kazakhstan: Prioritize coal phase-out and rapid deployment of solar and wind.
   - Kyrgyzstan and Tajikistan: Optimize hydropower while mitigating ecological impacts on river systems.
   - Uzbekistan and Turkmenistan: Exploit solar potential and invest in energy storage and smart grid technologies.
5. Evidence-Based Monitoring and Evaluation
   - Establish robust monitoring and reporting frameworks to track the impact of renewable energy deployment on emissions, ensuring that policies are informed by empirical data.
   - Use econometric outputs, such as the estimated elasticities, to guide quantitative targets for renewable energy expansion and fossil fuel reduction.

In conclusion, effective decarbonization in Central Asia requires policies that are grounded in data, tailored to country-specific energy structures, and supported by robust institutional mechanisms. Renewable energy expansion, fossil fuel phase-out, and investment in infrastructure and regulatory reform are essential for achieving measurable reductions in GHG emissions.

7. Conclusions

This study examines the impact of renewable and non-renewable electricity production, along with population, on per-capita greenhouse gas emissions in Central Asian countries over the period 2002–2024. The analysis is conducted within an extended STIRPAT framework using the ARDL-PMG estimation approach. The findings highlight the critical role of the regional energy mix in shaping environmental outcomes.

Long-term results indicate that non-renewable electricity production significantly increases per-capita greenhouse gas emissions, reflecting the central role of fossil fuels in driving emissions in the region. Country-specific estimates reveal particularly strong effects in Kazakhstan and Turkmenistan, consistent with their heavy dependence on coal and natural gas for electricity generation.

In contrast, renewable electricity production demonstrates a modest but meaningful long-term reduction in emissions, suggesting that the expansion of renewable energy contributes to climate mitigation efforts. However, the overall scale of renewable deployment remains limited across most Central Asian countries. In the short term, the effects of renewable energy are weaker and, in some instances, even positive, indicating transitional challenges and integration constraints within existing energy systems.

Population exhibits a negative relationship with per-capita emissions, likely to reflect the scaling properties inherent in per-capita measures. The error-correction terms confirm that deviations from the long-run equilibrium are gradually corrected over time, with faster adjustment observed in countries such as Kazakhstan and Uzbekistan.

Overall, the results underscore that per-capita greenhouse gas emissions in Central Asia are largely driven by non-renewable electricity production. Although renewable energy adoption is increasing, it has not yet reached a sufficient level to offset the emissions impact of fossil fuel-based power generation.

This study also recognizes several limitations, including potential omitted variable bias, the absence of institutional factors, data quality concerns in certain countries, and a relatively short sample period for some renewable energy indicators.

Author Contributions

All authors contributed equally to the conception, design, data collection, analysis, and writing of this study. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

This study did not require ethical approval because it exclusively utilized publicly available secondary data and did not involve human participants, identifiable personal data, or animal subjects. All analyses were conducted in accordance with relevant guidelines and regulations for research using publicly accessible datasets.

Informed Consent Statement

Informed consent was not required for this study because it exclusively utilized publicly available secondary data and did not involve human participants or identifiable personal information.

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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