نشریه علمی-پژوهشی
مطالعات کشورها
شاپای الکترونیکی: ۹۱۹۳-۲۹۸۰
دانشگاه تهران - دانشکده مطالعات جهان

هزینه‌های فناوری، افزایش انرژی‌های تجدیدپذیر، نوآوری و انتشار دی‌اکسید کربن در آسیای مرکزی و جنوب قفقاز

امیرمحمد اسماعیلی کورانی[۱*]، اوتابک کاسیموف[۱]، میرزوهیدجون محمدعلی‌اف[۲]، قاضی‌خان موساخانوف[۳]

۱. گروه اقتصاد و کسب‌وکار بین‌الملل، دانشکدهٔ اقتصاد و مدیریت کسب‌وکار، دانشگاه سگد، سگد، مجارستان.
۲. گروه اقتصاد و املاک و مستغلات، دانشگاه معماری و مهندسی تاشکند، تاشکند، ازبکستان.
۳. گروه گردشگری و هتلداری، دانشگاه دولتی اقتصاد تاشکند، تاشکند، ازبکستان.

مشخصات مقاله

مقالهٔ پژوهشی
موضوع: اقتصاد
حوزهٔ موضوعی: آسیای مرکزی و جنوب قفقاز

تاریخ دریافت: ۱۴۰۵/۰۲/۲۲
تاریخ بازنگری: ۱۴۰۵/۰۳/۲۲
تاریخ پذیرش: ۱۴۰۵/۰۳/۳۰
تاریخ انتشار: ۱۴۰۵/۰۴/۲۳

چکیده

در این مقاله، رابطهٔ بین هزینه‌های فناوری، تولید انرژی‌های تجدیدپذیر، تحقیق و توسعه (R&D) و انتشار دی‌اکسید کربن (CO_2) در هشت کشور آسیای مرکزی و جنوب قفقاز طی دورهٔ ۲۰۰۰ تا ۲۰۲۴م بررسی شده است. این پژوهش بر پایهٔ ۲۰۰ مشاهده در قالب داده‌های پانلی متوازن انجام شد. برای تحلیل این داده‌ها، از الگوی خودبرازش با وقفه‌های توزیعی-میانگین گروهی تجمیع‌شده (ARDL-PMG) و حداقل مربعات معمولی کاملاً اصلاح‌شده (FMOLS) استفاده شد. در این تحلیل، شاخص ترکیبی برای هزینه‌های فناوری همراه با متغیرهای تولید برق تجدیدپذیر، هزینه‌های تحقیق و توسعه، درجهٔ‌بازبودن تجاری، تولیدناخالص داخلی (GDP) سرانه و شهرنشینی وارد مدل شد. شاخص ترکیبی برای هزینه‌های فناوری با بهره‌گیری از تحلیل مؤلفه‌های اصلی (PCA) و بر اساس هزینه‌های فناوری‌های خورشیدی و بادی ساخته شد. پیش از استنتاج نتایج، مجموعه‌ای از آزمون‌های تشخیصی جامع- شامل آزمون‌های ریشهٔ واحد پانلی و ارزیابی هم‌انباشتگی- همچنین آزمون‌های متعدد برای بررسی وابستگی مقطعی، خودهم‌بستگی سریالی و ناهمسانی واریانس، به‌منظور تأیید استواری و اعتبار مدل اجرا شد. نتایج نشان داد شاخص هزینه‌های فناوری اثر مثبت و معناداری دارد؛ بدین معنا که که کاهش هزینهٔ فناوری‌های تجدیدپذیربا کاهش انتشار آلاینده‌ها همراه است. همچنین، تولید برق از منابع تجدیدپذیر در بلندمدت بر انتشار دی‌اکسید کربن اثر منفی و در خور توجهی دارد. در نتیجه، همسو با فرضیهٔ جانشینی است. همچنین، افزایش هزینه‌های تحقیق و توسعه نیز به کاهش انتشار دی‌اکسید کربن کمک می‌کند. به‌طور کلی، یافته‌های پژوهش حاکی از آن است که افزایش بهره‌گیری از انرژی‌های تجدیدپذیر و تداوم کاهش هزینه‌های فناوری، ابزارهای سیاستی مؤثری برای کاهش انتشار آلاینده‌ها در این اقتصادهای در حال گذار است. ازاین‌رو، برای کاهش مؤثر انتشار دی‌اکسید کربن، اتخاذ سیاست‌هایی برای توسعهٔ انرژی‌های تجدیدپذیر، تنوع‌بخشی به تجارت و تقویت نوآوری فناورانه ضروری است.

واژگان کلیدی:
الگوی برازش‌با وقفه‌های توزیعی-میانگین گروهی تجمعی‌شده (ARDL-PMG)،
انتشار دی‌اکسید کربن،
انرژی‌های تجدیدپذیر،
آسیای مرکزی،
جنوب قفقاز،
حداقل مربعات معمولی کاملاً اصلاح‌شده (FMOLS)،
هزینه‌های فناوری.

ارجاع به این مقاله: اسماعیلی کورانی ام، کاسیموف ا، محمدعلی‌اف م، موساخانوف ق. (۱۴۰۶). «هزینه‌های فناوری، افزایش انرژی‌های تجدیدپذیر، نوآوری و انتشار دی‌اکسید کربن در آسیای مرکزی و جنوب قفقاز». *مطالعات کشورها*. ۵(۲): ۳۷۱- ۳۹۷. doi: https://doi.org/10.22059/jcountst.2026.414264.1529.

وبگاه: https://jcountst.ut.ac.ir/ | رایانامه: jcountst@ut.ac.ir
شاپای الکترونیکی: ۹۱۹۳- ۲۹۸۰ | ناشر: دانشگاه تهران

* نویسندهٔ‌مسئول: esmailiamirmohamad@gmail.com، https://orcid.org/0000-0001-8637-8052

Journal of
Countries Studies
EISSN: 2980-9193
The Faculty of World Studies University of Tehran

Technology costs, renewable energy development, innovation, and CO_2 emissions in Central Asia and the South Caucasus

Amir Mohammad Esmaeili Korani[1]*, Otabek Kasimov[1], Mirzohidjon Mukhammadaliyev[2], Qazikhan Musakhanov[3]

1. Department of International Economics and Business, Faculty of Economics and Business Administration, University of Szeged, Szeged, Hungary.
2. Department of Economics and Real Estate, Tashkent University of Architecture and Civil Engineering, Tashkent, Uzbekistan.
3. Department of Tourism and Hotel Business, Tashkent State University of Economics, Tashkent, Uzbekistan.

Article Info

Original Article

Main Object: Economics
Scope: Central Asia and the South Caucasus

Received: 12 May 2026
Revised: 12 June 2026
Accepted: 20 June 2026
Published online: 14 July 2026

Keywords:
ARDL-PMG,
Central Asia,
CO_2 emissions,
FMOLS,
renewable energy,
South Caucasus,
technology costs.

Abstract

This paper examines the relationship between technology costs, renewable energy generation, research and development (R&D), and CO_2 emissions in eight Central Asian and South Caucasus countries spanning 2000–2024 across 200 balanced panel observations. To analyze this panel data, the Autoregressive Distributed Lag-Pooled Mean Group (ARDL-PMG) and Fully Modified Ordinary Least Squares (FMOLS) models were employed incorporating a composite index for technology costs (constructed using Principal Component Analysis (PCA) for solar and wind technologies cost), renewable electricity generation, R&D expenditure, trade openness, Gross Domestic Product (GDP) per capita, and urbanization. Before drawing conclusions, comprehensive diagnostics were conducted, including panel unit root tests, cointegration assessments, and multiple evaluations for cross-sectional dependence, serial correlation, and heteroskedasticity to validate the robustness of the model. The technology cost index shows a significant and positive impact, suggesting that lower renewable technology costs are associated with reduced emissions. Renewable electricity generation demonstrates a substantial negative long-term impact on CO_2 emissions, thereby supporting the displacement hypothesis. Similarly, R&D expenditure reduces CO_2 emissions. Overall, this work demonstrates that increasing renewable energy deployment and continuing to see technology cost reductions are effective policy instruments for mitigating emissions in these transitional economies. To effectively reduce CO_2 emissions, policies promoting renewable energy expansion, trade diversification, and technological innovation are needed.

Cite this article: Esmaeili Korani AM, Kasimov O, Mukhammadaliyev M, Musakhanov Q. (2027). “Technology costs, renewable energy development, innovation, and CO_2 emissions in Central Asia and the South Caucasus”. *Countries Studies*. 5(2): 371-397. doi: https://doi.org/10.22059/jcountst.2026.414264.1529.

Website: https://jcountst.ut.ac.ir/ | Email: jcountst@ut.ac.ir |
EISSN: 2980-9193
Publisher: University of Tehran

* Corresponding author: esmailiamirmohamad@gmail.com, https://orcid.org/0000-0001-8637-8052

1. Introduction

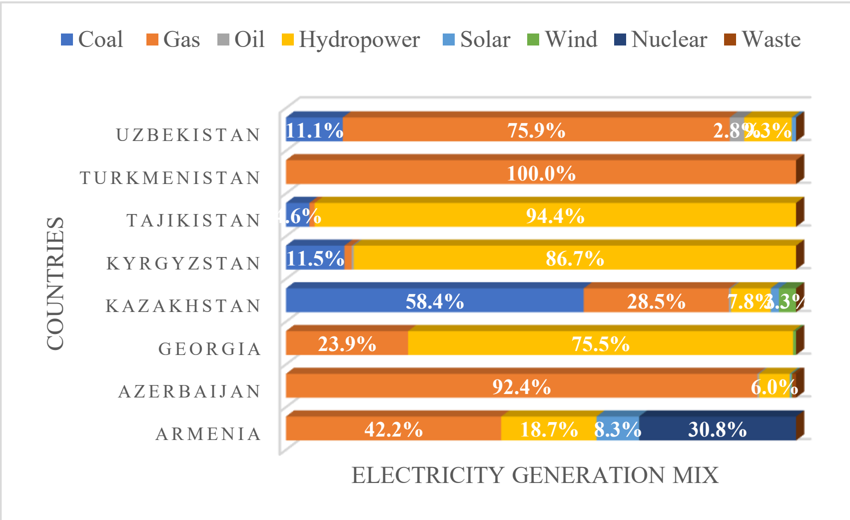
The accelerating climate crisis has intensified the need for a transition toward sustainable energy systems. This challenge is particularly significant in developing and transition economies, where current patterns of economic growth and energy consumption may result in the long-term lock-in of carbon-intensive infrastructure. The South Caucasus and Central Asia (comprising Georgia, Azerbaijan, Armenia, Uzbekistan, Kazakhstan, Tajikistan, Kyrgyzstan, and Turkmenistan) constitute an important, yet underexplored, area for examining the relationship between energy use and the environment in post-Soviet transitional economies. These nations face a unique combination of challenges: significant dependence on fossil fuels, outdated Soviet-era energy infrastructures, rapid urbanization, and increasing connections to global commodity markets. Simultaneously, they have significant, predominantly unexploited, green energy potential; for example, Kyrgyzstan, Tajikistan, Armenia, and Georgia in hydropower, and Kazakhstan, Uzbekistan, Turkmenistan, and Azerbaijan in solar and wind resources (Skalamera, 2025). The scholarly research on renewable energy and carbon emissions has substantially grown in recent years. Research repeatedly indicates that the increased utilization of renewable energy sources is inversely related to emissions in numerous regions worldwide (Apergis & Payne, 2010a; 2010b; 2010c; Ben Jebli et al., 2016; Balsalobre-Lorente et al., 2018; Sha et al., 2025).

The research's geographical scope is uneven. Central Asia and the South Caucasus are notably less studied, despite their geopolitical importance and vulnerability to environmental changes. Most current analysis concentrates on industrialized nations (OECD: Organization for Economic Co-operation and Development members), major developing economies (like China and Brazil), and African countries, often excluding these post-Soviet states from systematic panel studies. On the other side, the cost of renewable energy technology as a standalone factor influencing emissions has been given limited attention in panel econometric studies. This is a critical omission, given that steep cost reductions over the last ten years have fundamentally changed the financial feasibility of clean energy investments. This may suggest a lack of detailed focus on current market realities. Moreover, advanced panel cointegration methods have been sparingly applied to transitional economies. These economies are characterized by very different institutional growth patterns and varied natural resource bases; this is likely to impact the interpretation of findings if not accounted for.

Central Asia and the South Caucasus countries were selected due to the following region-specific factors. After the fall of the Soviet Union in 1991, these countries pursued distinct developmental trajectories. However, they retained similar institutional legacies, such as centralized energy infrastructure and state involvement in energy sector

(Mikhalev & Rakhimov, 2023; Shadrina, 2022). The energy landscapes in this region are varied (Figure 1). Hydropower is the main source of electricity in Tajikistan at 94%, Kyrgyzstan at 87%, and Georgia at 75%. Conversely, fossil fuels are still deeply rooted in other countries. For instance, Kazakhstan and Uzbekistan rely on them for 87% of their power, mostly through coal and gas. Turkmenistan runs almost entirely on natural gas at 100%, and Azerbaijan is at 92% (IEA, 2023). This wide range of setups allows for examining heterogeneous energy system conditions.

Economic profiles of the region are also different. There are hydrocarbon exporters like Kazakhstan and Azerbaijan that bring in massive revenue, contrasted with agricultural economies like Tajikistan or Kyrgyzstan that often face energy shortages (Mehta et al., 2021). The energy sector faces another issue, due to rapid urbanization. In Tajikistan, urbanization is 28%, whereas in Armenia and Georgia, it is over 63% and 60%, respectively (World Bank, 2023a). Cities have problems with increasing capacity and outdated infrastructure (Sabyrbekov & Overland, 2025). The level of trade openness also differs from county to county. Some markets are quite closed, such Turkmenistan with a trade-to-GDP ratio of 34%. Others, like Kyrgyzstan (132%) and Armenia (120%), are very open to global trade (World Bank, 2023b). This variation in trade openness underscores economic integration challenges and opportunities in the region.



Source: Authors' compilation

Figure 1. Comparative distribution of electricity generation by source across Central Asian and South Caucasian

Despite significant renewable potential for solar and wind, estimated at 25,800 TWh a year (Laldjebaev et al., 2021), actual use is still pretty modest outside hydropower. Policy interest seems to be growing lately.

This shift is likely due to the Paris Agreement, energy security during geopolitical shifts, technology costs reduction and vulnerability towards climate change (IEA, 2020; Vakulchuk & Overland, 2021; IRENA, 2023). However, empirical evidence quantifying the impacts of renewable deployment and technology cost dynamics on emissions in this specific regional context remains scarce (Vakulchuk et al., 2023; Sulaimanova et al., 2023).

This research aims to fill several gaps in the literature by providing the comprehensive empirical assessments of the determinants of CO_2 emissions across the combined South Caucasus and Central Asian region. While previous studies have typically focused on individual countries or selected sub-regions, no study has jointly examined the role of renewable technology costs, renewable energy generation, and innovation in explaining environmental outcomes across these eight transition economies.

A second contribution is the development of a novel renewable technology cost index constructed from international solar photovoltaic (PV) and wind turbine costs, transportation costs, and Principal Component Analysis (PCA). While renewable energy includes hydropower, biomass, geothermal, wind, and solar, this study focuses on solar PV and onshore wind. This is because hydropower is a mature and unevenly distributed technology across the eight countries, while biomass and geothermal play only a minor role in the region. In contrast, wind and solar account for most recent renewable capacity expansion and have experienced the strongest cost declines, making them the most relevant for analyzing current energy transition dynamics. This approach enables a more comprehensive measurement of renewable technology affordability and allows an empirical evaluation of how renewable technology costs influence CO_2 emissions in the region.

Finally, the study contributes methodologically by utilizing Autoregressive Distributed Lag-Pooled Mean Group (ARDL-PMG) framework and Fully Modified Ordinary Least Squares (FMOLS) approaches to investigate both short-run and long-run relationships from 2000 to 2024. This provides new evidence on the long-term environmental effects of renewable technology costs, renewable energy expansion, and research and development (R&D) in the South Caucasus and Central Asia.

The rest of the paper follows a standard path. Section 2 presents theoretical and empirical scholarly works. Section 3 defines the data sources, the construction of variables, and the econometric methodology. Section 4 provides the estimation outcomes, and Section 5 concludes with a summary of the findings and offers recommendations. Section 6 discusses the limitations of the study and outlines directions for future research.

2. Literature review and theoretical framework

This study develops an integrated theoretical framework to explain how renewable technology costs, renewable energy generation, research and development, trade openness, economic growth, and urbanization influence CO_2 emissions in Central Asia and the South Caucasus. The present framework combines several complementary theoretical perspectives to justify the selection of explanatory variables and to clarify the mechanisms through which they affect environmental quality. Specifically, Diffusion of Innovation Theory, the displacement hypothesis, Endogenous Growth Theory, Trade-Environment Theory, the Environmental Kuznets Curve (EKC), and Ecological Modernization Theory are integrated to establish a coherent conceptual basis for the empirical model.

2.1. Integrated theoretical framework and empirical evidence

Technology costs are a key driver of global energy transition. While several researches have examined the environmental impacts of renewable energy deployment, relatively few works have examined the impact of renewable technology affordability on environmental outcomes. According to Diffusion of Innovation Theory, the adoption of new technologies is greatly influenced by their relative advantage and economic feasibility (Rogers, 2003). Decreasing investment barriers for companies and governments accelerates adoption and diffusion of renewable technologies as they get more affordable. In Rogers' framework, perceived relative advantage is strongly influenced by cost, so falling renewable technology costs are expected to increase adoption probabilities, thereby accelerating the diffusion of renewables, decreasing dependence on fossil fuel–based energy, and ultimately enhancing environmental quality.

There is growing evidence that the economics of low-carbon transitions have changed fundamentally since the costs of renewable technologies are falling. Nemet (2006) suggested that productivity gains in manufacturing and the benefits of accumulated expertise contributed to decreases in the cost of photovoltaics. Kavlak et al. (2018) also found technological improvement and the size of manufacturing to be the two main drivers of cost reductions in solar photovoltaics. Renewables are becoming more and more competitive with traditional fossil fuels as the cost of utility-scale solar photovoltaics has fallen substantially over the last decade (IRENA, 2023). According to Way et al. (2022), ongoing deployment of low-carbon technologies is anticipated to lead to more reductions in costs, generating a self-reinforcing cycle of adoption and innovation. Consequently, it is anticipated that decreasing renewable technology costs will facilitate renewable investment and aid in reducing CO_2 emissions.

The second key element of the framework is the generation of renewable energy. The theoretical support for the link between renewable energy and environmental betterment is provided by the displacement hypothesis. According to this hypothesis, renewable electricity generation reduces emissions by substituting fossil fuel-based energy sources in the energy mix. The higher the amount of renewable energy, the lower the dependence on carbon intensive fuels and the less environmental harm. The empirical evidence tends to support the proposition.

Apergis and Payne (2010a) discovered that renewable energy helps to achieve environmental sustainability in OECD countries. Ben Jebli et al. (2016) found that renewable energy use reduces CO_2 emissions in the OECD economies. Similarly, Attiaoui et al. (2017) and Balsalobre-Lorente et al. (2018) observed a negative association between renewable energy consumption and emissions in African countries and European economies, respectively. Recent studies by Kinyar and Bothongo (2024), and Borsha et al. (2024) underscore the necessity of the expansion of renewable energy for attaining long-term emission reductions. The significant potential for renewable energy in Central Asia and the South Caucasus, as well as the region's persistent dependency on fossil fuels, is likely to lead to decreases in CO_2 emissions as renewable electricity generation gradually replaces traditional energy sources.

R&D is another major factor of environmental quality. According to Endogenous Growth Theory, technological progress emanates from investments in the creation of knowledge, rather than originating externally (Romer, 1990). R&D activities spur innovation, enhance productive efficiency and stimulate the development of green technologies that could eventually reduce the emissions intensity of output over time. Acemoglu et al. (2012) further extended this argument by demonstrating that, where the necessary incentives exist, directed technical development may be steered toward ecologically friendly ways of production. Most of the empirical research conducted so far confirm the positive influence of innovation on the environment. Popp (2002) showed that innovation is encouraged by environmental and energy-related incentives and this leads to technology innovations that increase energy efficiency. Carrión-Flores and Innes (2010) discovered that environmental innovation increases environmental performance. Fernández et al. (2018) revealed that R&D expenditures help to reduce CO_2 emissions in developed countries.

Dauda et al. (2021) also find that innovation can reduce emissions in the African environment, but the effect is conditioned by the institutional setting and the technology dissemination mechanism. The environmental benefits of R&D are generally expected to be realized in the long run as technical innovation usually takes time to develop into economically viable applications.

Trade openness exerts a more ambiguous influence on environmental quality. Trade–Environment Theory suggests that international trade affects emissions through competing channels. On the one hand, expanding trade may increase environmental degradation through the scale effect, whereby greater economic activity stimulates production, transportation, and energy consumption. On the other hand, trade openness can improve environmental quality by facilitating technology transfer, enhancing productive efficiency, and increasing access to cleaner production techniques.

The Pollution Haven Hypothesis further argues that pollution-intensive industries may relocate to countries with relatively weak environmental regulations, thereby increasing local emissions. Conversely, the Pollution Halo Hypothesis suggests that foreign competition and international integration promote cleaner production practices (Demena & Afesorgbor, 2020).

Accordingly, the empirical evidence shows different results. Bento and Moutinho (2016) demonstrated that international trade impacts positively upon carbon dioxide emissions in the long-run in Italy. Nam and Ryu (2024) showed that trade increases CO_2 emissions, but beyond a certain level, helps reduce them in transition economies. By contrast, Dogan and Turkekul (2016) and Dogan and Seker (2016) reported negative trade-emissions relationships in USA and in the top renewable energy countries, respectively. Given the transition characteristics of Central Asian and South Caucasian economies, the environmental consequences of trade openness remain an empirical question.

Economic growth has traditionally occupied a central position in environmental economics through the Environmental Kuznets Curve hypothesis. The EKC proposes that environmental degradation initially worsens during early stages of development but eventually declines once economies attain higher income levels (Grossman & Krueger, 1991; Stern, 2004). First, the scale effect increases emissions as production and energy consumption expand. Then, the technique effect raises environmental quality via cleaner technologies, stronger institutions and tighter environmental regulations. Despite substantial empirical inquiry, no consensus has arisen on the GDP-emissions relationship (see e.g., Kinyar & Bothongo, 2024; Borsha et al., 2024).

The last component of the framework is urbanization. Ecological Modernization Theory contends that the processes of modernization can eventually result in better environmental outcomes through technological innovation, institutional adaptation and a more efficient use of resources (Mol & Spaargaren, 2000). However, urbanization can also lead to higher emissions through more energy use, transport, industrial concentration and the expansion of infrastructure. Empirical evidence also points to varied impacts. Poumanyvong and Kaneko (2010) showed that the effects of urbanization differ by development phases. Martínez-Zarzoso and Maruotti (2011) found a relationship between urbanization and emissions similar to the inverted U shape.

The study by Song et al. (2024) found that the carbon emissions from urban areas for both livelihood and production purposes are high, indicating a strong correlation in China. On the other hand, Chovancová et al. (2024) found that the increase in the urbanization rate affects the decrease in CO_2 emissions in the EU countries.

2.2. Research hypotheses and conceptual framework

Based on the integrated theoretical framework, technology costs, renewable energy generation, R&D, trade openness, GDP per capita, and urbanization are expected to influence CO_2 emissions through distinct but interconnected channels in Central Asia and the South Caucasus. Lower renewable technology costs are anticipated to facilitate renewable deployment and reduce emissions. Renewable energy generation and R&D are expected to contribute negatively to CO_2 emissions through fossil-fuel displacement and technological progress, respectively. In contrast, the effects of trade openness, GDP per capita, and urbanization remain theoretically ambiguous because of the coexistence of competing mechanisms.

3. Methodology

3.1. Data and variables

This study employs annual panel data from five Central Asian countries (Uzbekistan, Kazakhstan, Tajikistan, Kyrgyzstan, and Turkmenistan) and three South Caucasian countries (Georgia, Azerbaijan, and Armenia). This panel data is strongly balanced and analyzes 200 observations, spanning the years 2000 to 2024.

Table 1. Variables description

Variable	Abbreviation	Description	Source
CO_2 emissions	CO_2	Carbon dioxide emissions (metric ton) from transport, electricity generation, and heating	Our World in Data (2025)
Wind turbine cost	WT	Total installed cost (USD/kW)	IRENA (2025)
Solar panel cost	SP	Total installed cost (USD/W)	IRENA (2025)
Renewable technology cost index	COST	A PCA-based index of renewable equipment costs	Authors' Calculation
Renewable energy generation	REG	%energy generated by renewable with near-zero emissions	Energy Institute (2025)
Research and development	R&D	Research and development expenditure (%of GDP)	World Bank (2025)
Trade openness	TO	Sum of exports and imports of goods and services (% of GDP)	World Bank (2025)
Economic growth	GDP	Gross domestic product per capita (constant 2015 USD)	World Bank (2025)
Urbanization	URB	Urban population (% of total population)	World Bank (2025)

Source: Authors' compilation.

The selection of this time frame captures the post-independence maturation period of these economies and encompasses significant developments in renewable energy deployment and climate policy. Table 1 includes a list of the variables and their abbreviation, description, and source employed in this investigation, while Table 2 displays the descriptive statistics of the dataset, encompassing the number of observations along with standard deviation, the mean, and the minimum/maximum values for each variable. To address missing observations while preserving panel balance and avoiding listwise deletion that would substantially reduce sample size, robust linear time-series interpolation techniques were employed within each country. This approach is commonly applied in empirical panel data research when missing values are minimal and are expected to change gradually over time. It also facilitates the preservation of the data's temporal structure while minimizing potential sample selection bias (Wooldridge, 2010).

Table 2. Descriptive statistics

Variable	N	Mean	Median	Maximum	Minimum	Std. Dev.
CO_2 emissions	200	4.549	3.319	16.301	0.393	4.169
Wind turbine cost	200	0.139	0.147	0.229	0.072	0.040
Solar panel cost	200	2.503	1.112	6.326	0.287	2.206
Renewable technology cost index	200	0.000	0.012	2.172	-2.421	1.393
Renewable energy generation	200	41.800	19.894	101.118	0.007	38.616
Research and development	200	0.183	0.181	0.360	0.058	0.064
Trade openness	200	82.705	78.681	175.351	29.192	27.131
Economic growth	200	3651.513	2956.998	11850.170	429.537	2742.858
Urbanization	200	49.171	52.289	64.666	26.501	11.432

Source: Authors' calculations.

3.1.1. Dependent variable

The dependent variable is CO_2 emissions, which are measured from energy combustion and industrial activities. This variable comes from the Our World in Data database. CO_2 emissions are the principal anthropogenic cause of global warming, making them the most policy-relevant environmental outcome variable (Lee & Zhao, 2023; Geweda et al., 2025; Esmaeili Korani et al., 2025).

3.1.2. Independent variables

Renewable Technology Cost Index (COST) is a composite indicator constructed via PCA from two components: (a) global solar photovoltaic module costs in constant USD/Watt, sourced from the International Energy Agency; and (b) global weighted average levelized cost of electricity for onshore wind projects in constant USD/kW, obtained from International Renewable Energy Agency database. After obtaining the global cost estimates, the final costs of solar panels and wind turbines for the countries and study period were calculated by incorporating transportation costs from China to the destination countries. The reason for choosing China as the main exporter of renewable energy technology was that China is the global renewables leader, maintaining the highest global manufacturing capacity (Norman et al., 2024; IEA, 2024). Given the scale of production, it makes sense that the cost in China is attractive to the global market. The countries studied also have the geographical advantage of being close to China, as if China covers 80% of the wind and utility-scale solar capacity currently under development in the region (Norman et al., 2024).

While renewable energy includes a wide range of technologies, such as hydropower, geothermal, biomass, wind, and solar, this study focuses specifically on solar photovoltaic (PV) and onshore wind energy. This does not imply that other renewable sources are unimportant; rather, it reflects both data comparability and the structure of renewable deployment in the region. Hydropower, although historically dominant in several countries, is a mature technology with relatively stable cost structures and limited recent cost variation compared to newer technologies. In addition, hydropower is not uniformly available across all eight countries in the sample, which limits its comparability in a cross-country empirical framework. Moreover, among the remaining renewable sources, wind and solar account for the dominant share of recent renewable capacity additions and generation growth, while biomass and geothermal remain relatively marginal in most of the countries considered. Wind and solar also exhibit the most pronounced technological progress and cost reductions over the study period. For these reasons, the analysis concentrates on wind and solar technologies as the primary drivers of recent renewable energy transition dynamics.

The PCA-derived first principal component explains 96.97% of the variance in these two cost measures (eigenvalue= 1.939), with factor loadings of 0.707 for both variables, indicating they contribute equally to the composite index (Table 3). The use of global costs rather than country-specific costs is justified by the internationally traded nature of solar panels and wind turbines, particularly given that the countries included in the sample are predominantly importers of renewable energy technologies. The composite index captures the temporal costs of renewable technologies, where diminished values signify enhanced affordability. Theoretically, this promotes adoption of new technologies in developing countries as well as it helps to mitigate CO_2 emissions (Osman et al., 2023; Davison, 2003).

Table 3. PCA results for the renewable technology cost index

Factor loadings	
Standardized solar PV cost	0.7071
Standardized wind turbine cost	0.7071
Component statistics	
Eigenvalue	1.9395
Variance explained (%)	96.97
Cumulative variance (%)	96.97

Source: Authors' calculations.

Renewable Electricity Generation (REG) is the amount of renewable electricity produced as a percentage of all electricity produced. This indicator quantifies the proportion of electricity generated from hydroelectric, wind, geothermal, solar, and biomass sources. Data are sourced from the Energy Institute database. The renewable share statistic is conceptually superior to absolute renewable generation as it accounts for both the extent of renewable deployment and its relative impact on the energy mix, effectively illustrating the displacement effect on fossil fuel generation. The literature predominantly indicates that renewable energy production significantly reduces emissions (Sha et al., 2025; Attiaoui et al., 2017; Ben Jebli et al., 2016).

Research and Development (R&D) is expenditure as a percentage of GDP, obtained from the World Bank database. It serves as a proxy for a country's innovation capacity and technological dynamism. Theory indicates that R&D should promote more sustainable manufacturing methods and developments in energy efficiency (Mensah et al., 2018; Fernández et al., 2018).

Trade Openness (TO) is aggregate of exports and imports expressed as a percentage of GDP, obtained from the World Bank database. This variable measures the extent of economic integration into international markets. Trade openness can affect emissions via many mechanisms, including technology transfer, introduction of best practices, and access to renewable technologies (Dauda et al., 2021; Zhang et al., 2017).

GDP per capita (GDP) in constant USD, sourced from the World Bank database, is a variable that controls for the scale effect of economic activity on emissions. Economic development theoretically produces unclear results (see e.g., Kinyar & Bothongo, 2024; Borsha et al., 2024).

Urbanization (URB) is the proportion of the urban population relative to the overall population, sourced from the World Bank database. Urbanization may exhibit a positive correlation with CO_2 emissions owing to heightened energy consumption, transportation requirements, and industrial activities (Song et al., 2024). However, at more advanced stages, it can reduce emissions through the promotion of efficiency enhancements, technology transfer, and more compact, optimal urban designs (Chovancová et al., 2024).

Table 4 reports the Variance Inflation Factor (VIF) statistics. The results indicate that all VIF values are well below the commonly accepted threshold of 10, with the highest value observed for urbanization (4.80). The mean VIF is 2.70, suggesting a low degree of multicollinearity among the regressors. Therefore, multicollinearity is not considered a serious concern, and the estimated coefficients can be interpreted with confidence.

Table 4. Variance inflation factor analysis

Variable	VIF	1/VIF
COST	1.77	0.566
REG	1.53	0.655
R&D	2.24	0.447
TO	1.23	0.814
GDP	4.66	0.215
URB	4.80	0.208
Mean VIF	2.70	

Source: Authors' calculations.

3.2. Model formulation

This study examines the impact of COST, REG, and R&D on CO_2 by employing the advanced econometric techniques of ARDL-PMG and FMOLS to analyze dynamic interactions among the central Asian and south Caucasus countries from 2000 to 2024. The basic model is written as Equation (1).

$$LnCO_{2it} = \beta_0 + \beta_1 COST_{it} + \beta_2 LnREG_{it} + \beta_3 LnR\&D_{it} + \beta_4 LnTO_{it} + \beta_5 LnGDP_{it} + \beta_6 LnURB_{it} + u_{it} \quad (1)$$

where i denotes the country, t is the time period, β_0 is the constant parameter, and β_x (x= 1, 2, 3, 4, 5, 6) represent the elasticity parameters to be estimated. Moreover, u measures the error term. Ln denotes the logarithmic transformation which is employed to reduce heteroskedasticity across countries of vastly different economic scales, allow coefficient interpretation as elasticities, and improve normality of residual distributions. The control variables are TO, GDP, and URB which are also used to prevent variable omission bias.

3.3. Empirical strategy

Before estimating the model, the time-series properties of the variables are examined. It is necessary to determine their order of integration. To do this, several panel unit root tests are used (Kasimov, 2025). These include the LLC, IPS, and Fisher-type tests. The LLC test (Levin et al., 2002) assumes a common autoregressive process across cross-sectional units. It provides a basic evaluation of stationarity under homogeneity. In contrast, the IPS test (Im et al., 2003) allows for heterogeneity in autoregressive coefficients. In addition, Fisher-type tests are also used to enhance the robustness check. The joint use of these tests reduces the likelihood that inference regarding stationarity is driven by restrictive assumptions about cross-sectional homogeneity (Maddala & Wu, 1999).

Once the integration properties are understood, long-run relationships are investigated. Using panel cointegration methods, the relationship between CO_2 emissions and the explanatory variables is assessed over time. The residual-based panel cointegration tests proposed by Pedroni (1999; 2004) are employed. In addition, the Kao (1999) test is conducted as a complementary check. Employing both Pedroni and Kao tests increases the reliability of the findings. Since the data show a mix of integration levels, the ARDL model is employed. For panel data, the ARDL model can be specified as Equation (2).

$$Y_{it} = a_0 + \sum_{j=1}^{p} \beta_j Y_{i,t-j} + \sum_{j=0}^{q} \gamma_j X_{i,t-j} + u_{it} \tag{2}$$

where Y denotes the dependent variable for unit i at time t; X is a vector of regressors; β *and* γ are coefficients for lagged dependent and independent variables, respectively. The ARDL framework is well suited to macro-energy panels as it accommodates regressors that are integrated of order zero or one, provided none are I(2); moreover, ARDL models perform well in panels with relatively small dimensions (Amir et al., 2024; Razmi et al., 2024). The associated Error Correction Model (ECM) written as Equation (3), also elaborates the estimation of the speed at which deviations from long-run equilibrium are corrected.

$$\Delta Y_{it} = a_0 + \theta ECT_{i,t-1} + \sum_{i=1}^{p-1} \beta_j \Delta Y_{i,t-j} + \sum_{j=0}^{q-1} \gamma_j \Delta X_{i,t-j} + u_{it} \tag{3}$$

where Δ is the change in the dependent and independent variables; θ is speed of adjustment which should be negative if there's convergence to long-run equilibrium; ECT is error correction term which is lagged residual from long-run relationship.

The panel ARDL model is calculated by applying the PMG estimator introduced by Pesaran et al. (1999). The PMG estimator permits short-run coefficients and adjustment speeds to differ across countries, capturing heterogeneity in national energy structures and policy responses, while restricting long-run coefficients to be homogeneous. Compared with fully homogeneous estimators or fully heterogeneous alternatives, PMG provides an efficient compromise when long-run convergence is theoretically plausible (Rahro et al., 2024; Kasimov, et al., 2026).

4. Results and discussions

4.1. Panel unit root tests

Table 5 presents the outcomes of a series of panel unit root tests conducted on all variables at both levels and first differences. The findings suggest mixed orders of integration across the series. At the levels, the majority of variables do not deny the null hypothesis of a unit root, although a select few series demonstrate stationarity under particular test configurations. However, after adjusting for first differences, all variables become stationary at conventional significance levels across the majority of tests. The results indicate that the variables are integrated of order zero and one, I(0) and I(1), with none being I(2). This combination of integration orders provides a valid basis for employing the panel ARDL framework, which allows for the simultaneous estimation of both short-run dynamics and long-run relationships between CO_2 emissions and the selected explanatory variables.

4.2. Cointegration tests

Table 6 shows the outcomes of the panel cointegration tests conducted using the methodologies of Pedroni (1999; 2004) and Kao (1999). The reported statistics from both the Pedroni Phillips–Perron and Pedroni Augmented Dickey–Fuller tests are statistically significant at the 1% level, resulting in the rejection of the null hypothesis of no cointegration. Similarly, all Kao test statistics (Modified DF, DF, and ADF) are significant at conventional levels, confirming the presence of a stable long-run equilibrium correlation among the variables. Collectively, these findings offer robust evidence of panel cointegration. This result validates the use of cointegration-based estimators, such as the panel ARDL approach and FMOLS, for estimating long-term coefficients, and it endorses the examination of both short-term dynamics and long-term relationships.

4.3. Panel ARDL-PMG analysis

Following the AIC (Akaike, 1974), an ARDL (1,1,1,1,2,1,2) lag structure was selected for the panel PMG model. The results in Table 7 indicate that most explanatory variables exert statistically significant effects on CO_2 in the long run. The COST variable shows a positive, significant coefficient at the 1% level. Essentially, as renewable technology costs rise, CO_2 levels tend to follow.

Table 5. The unit root tests' results

	$LnCO_2$	COST	LnREG	LnR&D	LnTO	LnGDP	LnURB
Level 0							
Levin et al. (2002)	–1.514*	1.425	2.670	–1.336*	–4.226***	–2.890***	3.332
Im et al. (2003)	0.078	5.022	1.866	–1.492*	–2.834***	–0.053	2.599
ADF–Fisher Chi-square	14.930	0.605	20.419	21.964	30.819***	16.103	23.381
PP–Fisher Chi-square	8.510	0.916	9.139	30.059**	16.118	43.730***	13.303
Level 1							
Levin et al. (2002)	–6.781***	–0.039	–6.529***	–3.693***	–6.444***	–3.719***	–1.491*
Im et al. (2003)	–6.902***	–2.278**	–5.265***	–6.539***	–5.220***	–3.317***	–6.580***
ADF–Fisher Chi-square	76.577***	26.818**	58.866***	72.892***	55.193***	37.537***	266.647***
PP–Fisher Chi-square	121.401***	94.412***	90.548***	189.109***	72.953***	53.265***	58.521***

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.
Source: Authors' calculations.

Table 6. The cointegration tests' results

Test	Statistic	Prob.
Pedroni Phillips–Perron	–2.560	0.005***
Pedroni Augmented Dickey-Fuller	–2.911	0.001***
Kao Modified Dickey-Fuller	–2.492	0.006***
Kao Dickey-Fuller	–2.224	0.013**
Kao Augmented Dickey-Fuller	–2.503	0.006***

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.
Source: Authors' calculations.

Countries Studies, Vol 5, No 2, Summer 2027

Table 7. The results of the long-run ARDL-PMG model

Variable	Coefficient	Std. error	Statistic	Prob.
COST	0.058	0.012	4.610	0.000***
REG	-0.1392	0.0111	-12.60	0.000***
R&D	-0.0474	0.0179	-2.65	0.008***
TO	0.0555	0.0096	5.760	0.000***
GDP	-0.1142	0.0596	-1.92	0.055*
URB	0.7546	0.3416	2.21	0.027**

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.
Source: Authors' calculations.

This likely happens because expensive hardware and installation fees discourage a quick shift away from coal or gas. This result is particularly relevant for Central Asia and the South Caucasus, where high upfront investment costs and limited access to green finance can constrain the large-scale deployment of renewable energy technologies. This finding aligns with the concept of the need to reduce the cost of renewable technology (Osman et al., 2023; Davison, 2003). Renewable generation (REG) has a negative and highly significant coefficient. This suggests that producing more green energy successfully displaces fossil fuels (Sha et al., 2025; Dauda et al., 2021; Attiaoui et al., 2017; Ben Jebli et al., 2016; Bento & Moutinho, 2016). This finding reflects the region's substantial untapped renewable potential, especially in hydropower, solar, and wind. Employing these resources will be an effective strategy for reducing carbon dependence. Similarly, R&D has a negative and statistically significant impact on emissions. In other words, better energy efficiency and cleaner manufacturing techniques are driven by this technical knowledge and know-hows (Dauda et al., 2021; Mensah et al., 2018; Fernández et al., 2018; Carrión-Flores & Innes 2010). In contrast, Trade openness (TO) exhibits a positive and significant coefficient, suggesting that increased trade may raise CO_2. This may be explained by scale effects and higher production and transportation activities (Nam & Ryu, 2024; Bento & Moutinho, 2016). In the context of Central Asia and the South Caucasus, this may reflect export structures dominated by energy-intensive industries and primary commodities, which are naturally carbon-heavy. GDP shows a negative effect, though it is only significant at the 10% level. This provides limited evidence that higher income might lead to lower emissions (Haug & Ucal, 2019; Dogan & Turkekul, 2016). Finally, URB has a positive and significant effect on CO_2, indicating that urban expansion tends to increase energy demand, transportation use, and industrial activity (Sha et al., 2025; Song et al., 2024; Dauda et al., 2021). This outcome is consistent with rapid urban growth in major cities across the region, often accompanied by infrastructure expansion and increased fossil fuel consumption.

Table 8 presents the short-run mean group estimates. In the short run, changes in COST, R&D, and TO do not appear to reach statistical significance. This implies that their impact on CO_2 likely takes time to develop rather than immediate impact. This is plausible in the context of the region, as overhauling energy grids, updating technology, and shifting trade structures are gradual processes rather than overnight shifts. The coefficient for REG is negative, though it is only weakly significant at the 10% level. This suggests that while renewable energy starts to limit emissions early on, the immediate impact remains somewhat small (Borsha et al., 2024; Bento & Moutinho, 2016). This may reflect the comparatively little proportion of renewables in the current energy mix of several countries in Central Asia and the South Caucasus. GDP exhibits a positive and highly significant short-run effect, implying that short-term economic expansion is associated with higher CO_2 due to increased industrial output and energy consumption, which remains largely fossil fuel–based in the region. As Bento and Moutinho (2016) found about the short-run and long-run coefficients of output, it is clear that there is an inverted U-shaped linkage between emissions and output, since long-term economic development has a negative influence on CO_2 emissions. The short-run effect of URB is positive but statistically insignificant, suggesting that the environmental consequences of urbanization become more pronounced over time as urban infrastructure and energy demand continue to expand.

Table 8. The results of the short-run (mean group)

Variable	Coefficient	Std. error	Statistic	Prob.
D(COST)	-0.0818	0.0727	-1.12	0.261
D(REG)	-0.1526	0.0915	-1.67	0.095*
D(R&D)	-0.0167	0.0366	-0.46	0.648
D(TO)	0.0438	0.0690	0.63	0.526
D(GDP)	0.6411	0.2064	3.11	0.002***
D(URB)	43.4843	26.8858	1.62	0.106
COINTEQ	-0.5758	0.2077	-2.77	0.006***

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.
Source: Authors' calculations.

The negative error correction term is highly significant at the 1% level, affirming the presence of a stable long-run relationship among these variables. The magnitude of the coefficient (−0.576) suggests that around 58% of short-run deviations from the long-run equilibrium are corrected within one period, implying a relatively fast adjustment process toward long-run equilibrium in the South Caucasus and Central Asian region.

4.4. Diagnostic tests for model validation

To assess the robustness and reliability of the estimated panel ARDL-

Countries Studies, Vol 5, No 2, Summer 2027

PMG model, several diagnostic tests were conducted. The analysis began with an examination of cross-sectional dependence (Table 9).

Table 9. Diagnostic tests' results

Test	Statistic	P-value
CD	-0.195	0.846
Wooldridge	0.654	0.445
Modified Wald	5.010	0.756
Wald	341.156	0.000***

Note: *** represents the 1% significance level.
Source: Authors' calculations.

The Pesaran (2021) CD test evaluates the null hypothesis of cross-sectional independence among panel units. The results indicate that the null hypothesis cannot be rejected, suggesting the absence of cross-sectional dependence across countries. Next, serial correlation was examined using the Wooldridge test. Null hypothesis of Wooldridge (2010) test assumes no AR (1) serial correlation for first-order autocorrelation in panel data. The findings show that the null hypothesis cannot be rejected, confirming that the residuals are free from serial correlation and supporting the dynamic specification of the model. Third, groupwise heteroskedasticity was assessed using the Modified Wald test for panel data (Baltagi, 2008). The results indicate that the null hypothesis of homoskedasticity cannot be rejected, implying that the error variances are homogeneous across cross-sectional units. Finally, the Wald test (Wald, 1943) was applied to examine the joint significance of the explanatory variables. The results strongly rejected the idea that the coefficients are zero. This confirms that the chosen variables are jointly significant for explaining CO_2 emissions. Overall, these diagnostic results suggest that the panel ARDL-PMG model is well specified and suitable for reliable inference for the Central Asia and South Caucasus region.

To examine the temporal stability of the estimated relationship, a sequential panel structural break test was conducted using the methodology implemented by Ditzen, Karavias, and Westerlund (2025), which extends the multiple structural break framework of Bai and Perron (1998) to panel-data settings. The findings indicate that the null hypothesis of parameter stability cannot be rejected, suggesting the absence of statistically significant common structural breaks over the sample period (Table 10). In other words, the relationship between CO_2 emissions and its determinants remained stable through time and did not experience any common time-related regime shifts across the panel countries. These results support the robustness of the estimated coefficients and imply that major events occurring during the study period did not induce a common structural change in the underlying model.

Table 10. Sequential panel structural break test results

Test	Statistics	1% critical value	5% critical value	10% critical value
F(1|0)	3.66	7.68	5.74	4.91
F(2|1)	3.33	8.42	6.47	5.70
F(3|2)	0.35	8.86	7.01	6.14
F(4|3)	0.29	9.34	7.42	6.45

Source: Authors' calculations.

4.5. Robustness check

To confirm the robustness of the long-run relationships estimated by the panel ARDL-PMG model, a FMOLS estimator was applied as a robustness check (Phillips & Hansen, 1990). FMOLS corrects for potential endogeneity and serial correlation in the regressors, providing consistent long-run coefficient estimates. Essentially, FMOLS complements the ARDL-PMG approach by providing an assessment of the long-run relationships without relying on short-run dynamics. The FMOLS results are presented in Table 11.

Table 11. The results of the FMOLS model

Variable	Coefficient	Std. error	Statistic	Prob.
COST	0.102	0.031	3.247	0.001***
REG	-0.205	0.039	-5.254	0.000***
R&D	-0.069	0.027	-2.508	0.013**
TO	0.194	0.027	7.134	0.000***
GDP	-0.031	0.061	-0.513	0.608
URB	-2.679	0.844	-3.172	0.001***

Note: ***, **, and * represent the 1%, 5%, and 10% significance levels, respectively.
Source: Authors' calculations.

For the most part, the variables remain statistically significant and to back up the main model's results. The COST coefficient is positive and quite significant. Similar to the main model's finding, it also suggests that when renewable technology costs increase CO_2 levels follows. REG remains negative and highly significant and supporting the effectiveness of environmental regulations in reducing emissions. R&D also shows a negative effect. This highlights how technological innovation helps lower carbon intensity over time.

On the other hand, TO is positive and significant, which again confirms that expanding trade tends to increase CO_2 levels. GDP also appearing negative but not statistically significant in FMOLS model. The FMOLS results for REG, COST, R&D, and TO are consistent with the ARDL-PMG results, except URB. URB shows a negative and significant effect in FMOLS, which differs from the positive impact observed in the ARDL model. This likely stems from how the two models work. FMOLS focuses strictly on long-run cointegration, in contrast, ARDL accounts for both short and long-runs dynamics. The negative impact aligns with studies by Chovancová et al. (2024). Table 12 presents the diagnostic test results for FMOLS.

Table 12. Diagnostic tests' results

Test	Statistic	P-value
CD	0.996	0.318
Residual stationarity	LLC: -5.394	0.000***
	ADF: 47.856	0.000***
	PP: 50.597	0.000***

Note: *** represents the 1% significance level.
Source: Authors' calculations.

The CD test confirms that the countries are cross-sectionally independent. Residual stationarity was also checked, and three different unit root tests indicate the residuals are stationary, I(0), which confirms a cointegrating relationship exists. There is no need for separate serial correlation or heteroskedasticity tests for FMOLS, because this model estimator is already modified to handle those issues, and the standard errors are naturally robust. Overall, FMOLS results for the main explanatory variables strongly support the original ARDL-PMG model results. Since the signs and significance levels of the main variables stay consistent, the relationship between CO_2 and its drivers in Central Asia and the South Caucasus appears to be quite steady across different estimation methods.

5. Conclusions and policy recommendations

CO_2 emissions were analyzed for eight former Soviet republics (including Georgia, Kazakhstan, Azerbaijan, Kyrgyzstan, Uzbekistan, Tajikistan, Armenia, and Turkmenistan) over the period 2000-2024 using strongly balanced annual panel data. A dynamic ARDL-PMG framework was employed to capture both short-run and long-run relationships. As a robustness check, the FMOLS model was used to verify the long-run cointegrating effects. The combination of these methods allows a comprehensive assessment of how renewable technology costs, renewable energy development, and innovation change the region's carbon footprint.

The long-run results from both ARDL and FMOLS show a strong degree of consistency for the main variables. COST exhibits a positive and highly significant long-run relationship with CO_2 emissions in both models. It indicates that higher renewable technology costs are associated with higher emissions. This suggests that expensive renewable technologies hinder their widespread adoption and delay the transition away from fossil fuels. The absence of a short-run effect reinforces the view that cost-related constraints operate mainly through long-term investment and infrastructure decisions.

REG displays a negative and statistically significant long-run impact on emissions in both ARDL and FMOLS. It confirms that higher renewable energy generation contributes to lower CO_2 emissions by substituting fossil fuel–based energy. Given the substantial untapped renewable potential in the region, particularly in hydropower, solar, and wind, this result highlights the structural importance of expanding renewable capacity. The short-run effect is weaker. It means that the emission-reducing benefits of REG strengthen over time as renewable shares in the energy mix increase. R&D also follows a similar path. It has a negative and significant long-term effect, though it is insignificant in the short term. It emphasizes the long-term importance of technological advancement and innovation in increasing energy efficiency and enabling cleaner manufacturing processes. The delayed impact reflects the time required for R&D investments to translate into commercially viable technologies and widespread adoption.

Among the control variables, TO is positively associated with emissions in the long run in both ARDL and FMOLS. It means that trade expansion increases CO_2 through scale effects, energy-intensive production, and transport-related emissions. URB is positive and significant in the ARDL long-run, but negative in FMOLS. That can be interpreted as urbanization-related emissions accumulate gradually over time and may be less evident in estimations that isolate only the pure long-run cointegrating relationship. This divergence likely arises from methodological differences, with ARDL capturing dynamic adjustment and structural change over time. In contrast, FMOLS reflects the average long-run association. GDP shows a positive and significant short-run effect in ARDL, reflecting the carbon-intensive nature of short-term economic expansion, while its long-run effect is weakly negative in ARDL and insignificantly negative in FMOLS. It indicates that economic growth alone does not ensure emission reductions without concurrent structural and technological advancements.

Overall, the findings highlight that CO_2 emissions in Central Asia and the South Caucasus are predominantly influenced by long-run structural variables rather than short-run dynamics. Sustained reductions in renewable technology costs, steady expansion of renewable energy output, and ongoing investment in R&D emerge as key solutions for obtaining long-term emission reductions. The findings highlight the importance of implementing long-term, region-specific strategies in energy and innovation for Central Asia and the South Caucasus. In order to reduce the ongoing emission-increasing impact of COST, governments need to decrease the effective cost of renewable technologies via targeted public support, concessional financing, and collaboration with leading industry businesses. The strong long-run emission-reducing role of REG highlights the need to accelerate renewable deployment by exploiting the region's substantial hydropower, solar, and wind potential and strengthening energy infrastructure. In parallel, sustained investment in R&D is essential to build domestic technological capabilities, support innovation, and ensure that the transition toward cleaner energy systems delivers sustainable reductions in CO_2 emissions.

6. Limitations and future research directions

Despite the robust econometric framework employed in this study, several limitations must be acknowledged. First, data availability poses a significant constraint, particularly regarding institutional quality indicators and public policy variables. For certain countries in the panel, most notably Turkmenistan, consistent and long-run time-series data on governance, regulatory capacity, and policy instruments are either incomplete, unreliable, or entirely unavailable, rendering their inclusion in a balanced panel estimation infeasible. Second, the length and complexity of the model specification itself imposed additional constraints. The Panel ARDL–PMG framework carries inherent econometric restrictions regarding the number of explanatory variables that can be simultaneously included without introducing estimation bias and degrees-of-freedom problems. Furthermore, software limitations in handling extended model specifications with a relatively small number of cross-sectional units reinforced the need for parsimony in variable selection. Accordingly, the model was designed to capture the most theoretically grounded and data-supported determinants, while remaining econometrically tractable.

Future research is strongly encouraged to adopt institutional and political economy perspectives, as governance quality, regulatory effectiveness, and public policy coherence are widely acknowledged as critical yet underexplored drivers of renewable energy transition. For studies facing similar data scarcity, the use of perceptional and composite indices, such as the World Bank Governance Indicators (WGI), the OECD Environmental Policy Stringency (EPS) index, or Transparency International's Corruption Perceptions Index, is recommended as a viable strategy to compensate for the absence of hard institutional data. Such approaches would substantially enrich the understanding of how non-economic factors shape long-run energy and emissions dynamics in data-scarce regional contexts.

Conflict of interest

The authors declared no conflicts of interest.

Ethical considerations

The authors have completely considered ethical issues, including informed consent, plagiarism, data fabrication, misconduct, and/or falsification, double publication and/or redundancy, submission, etc. This article was not authored by artificial intelligence.

Data availability

The dataset generated and analyzed during the current study is available from the corresponding author on reasonable request.

References

Acemoglu D, Aghion P, Bursztyn L, Hemous D. (2012). "The environment and directed technical change". *American Economic Review*. 102(1): 131-166. https://doi.org/10.1257/aer.102.1.131.

Akaike H. (1974). "A new look at the statistical model identification". *IEEE Transactions on Automatic Control.* 19(6): 716-723. https://doi.org/10.1109/TAC.1974.1100705.

Amir M, Malik MS, Ali K. (2024). "Unlocking green growth: an ARDL estimation of pollution prevention practices for economic and environmental sustainability". *Environment, Development and Sustainability*. 26(8): 19983-20000. https://doi.org/10.1007/s10668-023-03449-w.

Apergis N, Payne JE. (2010a). "Renewable energy consumption and economic growth: Evidence from a panel of OECD countries". *Energy Policy*. 38(1): 656-660. https://doi.org/10.1016/j.enpol.2009.09.002.

Apergis N, Payne JE. (2010b). "Renewable energy consumption and growth in Eurasia". *Energy Economics*. 32(6): 1392-1397. https://doi.org/10.1016/j.eneco.2010.06.001.

Apergis N, Payne JE. (2010c). "The emissions, energy consumption, and growth nexus: Evidence from the Commonwealth of Independent States". *Energy Policy.* 38(1): 650-655. https://doi.org/10.1016/j.enpol.2009.08.029.

Attiaoui I, Toumi H, Ammouri B, Gargouri I. (2017). "Causality links among renewable energy consumption, CO2 emissions, and economic growth in Africa: Evidence from a panel ARDL-PMG approach". *Environmental Science and Pollution Research*. 24(14): 13036-13048. https://doi.org/10.1007/s11356-017-8850-7.

Bai J, Perron P. (1998). "Estimating and testing linear models with multiple structural changes". *Econometrica.* 47-78. https://doi.org/10.2307/2998540.

Balsalobre-Lorente D, Shahbaz M, Roubaud D, Farhani S. (2018). "How economic growth, renewable electricity and natural resources contribute to CO2 emissions?". *Energy Policy.* 113: 356-367. https://doi.org/10.1016/j.enpol.2017.10.050.

Baltagi BH. (2008). *Econometric Analysis of Panel Data.* 4th ed. Wiley. https://doi.org/10.1007/978-3-030-53953-5.

Ben Jebli MB, Youssef SB, Ozturk I. (2016). "Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries". *Ecological Indicators.* 60: 824-831. https://doi.org/10.1016/j.ecolind.2015.08.031.

Bento JPC, Moutinho V. (2016). "CO_2 emissions, non-renewable and renewable electricity production, economic growth, and international trade in Italy". *Renewable and Sustainable Energy Reviews.* 55: 142-155. https://doi.org/10.1016/j.rser.2015.10.151.

Borsha FH, Voumik LC, Rashid M, Das MK, Stępnicka N, Zimon G. (2024). "An empirical investigation of GDP, industrialization, population, renewable energy and CO_2 emission in Bangladesh: Bridging EKC-STIRPAT models". *International Journal of Energy Economics and Policy*. 14(3): 560-571. https://doi.org/10.32479/ijeep.15423.

Carrión-Flores CE, Innes R. (2010). "Environmental innovation and environmental performance". *Journal of Environmental Economics and Management.* 59(1): 27-42. https://doi.org/10.1016/j.jeem.2009.05.003.

Chovancová J, Petruška I, Cirella GT, Litavcová E. (2024). "Urbanization and CO_2

emissions: Panel data analysis of EU countries". In *City responses to disruptions in 2020: From lockdowns to aftermath* (pp. 123–175). Springer Nature: Singapore. https://doi.org/10.1007/978-981-99-7988-2_8.

Dauda L, Long X, Mensah CN, Salman M, Boamah KB, Ampon-Wireko S, Dogbe CSK. (2021). "Innovation, trade openness and CO_2 emissions in selected countries in Africa". *Journal of Cleaner Production*. 281, 125143. https://doi.org/10.1016/j.jclepro.2020.125143.

Davison J. (2003). "Costs of renewable energy and CO_2 capture and storage". In S. Gale (Ed.), *Greenhouse Gas Control Technologies—6th International Conference* (pp. 1125–1130). Pergamon. https://doi.org/10.1016/B978-008044276-1/50178-1.

Demena BA, Afesorgbor SK. (2020). "The effect of FDI on environmental emissions: Evidence from a meta-analysis". Energy Policy. 138, 111192. https://doi.org/10.1016/j.enpol.2019.111192.

Ditzen J, Karavias Y, Westerlund J. (2025). "Testing and estimating structural breaks in time series and panel data in Stata". *The Stata Journal*. 25(3): 526-560. https://doi.org/10.1177/1536867X251365449.

Dogan, E, Seker F. (2016). "The influence of real output, renewable and non-renewable energy, trade and financial development on carbon emissions in the top renewable energy countries". *Renewable and Sustainable Energy Reviews*. 60: 1074-1085. https://doi.org/10.1016/j.rser.2016.02.006.

Dogan E, Turkekul B. (2016). "CO_2 emissions, real output, energy consumption, trade, urbanization and financial development: Testing the EKC hypothesis for the USA". *Environmental Science and Pollution Research.* 23(2): 1203-1213. https://doi.org/10.1007/s11356-015-5323-8.

Energy Institute. (2025). *Statistical review of world energy 2025*. https://www.energyinst.org/statistical-review. (Retrieved February 9, 2026)

Esmaeili Korani A, Alam SMT, Rahro H, Bakhtiaran MJ. (2025). "Institutional quality, foreign direct investment, and renewable energy production: Evidence from Eastern European countries using a panel VAR model". *International Journal of Energy Economics and Policy*. 15(6): 334-345. https://doi.org/10.32479/ijeep.20680.

Fernández YF, López MF, Blanco BO. (2018). "Innovation for sustainability: The impact of R&D spending on CO2 emissions". *Journal of Cleaner Production*. 172: 3459-3467. https://doi.org/10.1016/j.jclepro.2017.11.001.

Geweda AE, Zayed ME, Khan MY, Alquaity AB. (2025). "Mitigating CO_2 emissions: A review on emerging technologies/ strategies for CO_2 capture". *Journal of the Energy Institute*. 118, 101911. https://doi.org/10.1016/j.joei.2024.101911.

Grossman GM, Krueger AB. (1991). "Environmental impacts of a North American free trade agreement (NBER Working Paper No. 3914)". *National Bureau of Economic Research*. https://doi.org/10.3386/w3914.

Haug AA, Ucal M. (2019). "The role of trade and FDI for CO_2 emissions in Turkey: Nonlinear relationships". *Energy Economics*. 81: 297-307. https://doi.org/10.1016/j.eneco.2019.04.006.

IEA. (2024). *Renewables 2024 Analysis and Forecast to 2030*. https://www.iea.org/reports/renewables-2024. (Retrieved February 9, 2026)

-------------. (2023). *Countries' Energy Profile*. https://www.iea.org/countries/uzbekistan/energy-mix. (Retrieved February 9, 2026)

--------------. (2020). *Evolution of Solar PV Module Cost by Data Source, 1970-2020*. https://www.iea.org/data-and-statistics/charts/evolution-of-solar-pv-module-cost-by-data-source-1970-2020. (Retrieved February 9, 2026)

Im KS, Pesaran MH, Shin Y. (2003). "Testing for unit roots in heterogeneous panels". *Journal of Econometrics*. 115(1): 53-74. https://doi.org/10.1016/S0304-4076(03)00092-7.

IRENA: International Renewable Energy Agency. (2025). *Renewable Power Generation Costs in 2024*.

https://www.irena.org/Publications/2025/Jun/Renewable-Power-Generation-Costs-in-2024. (Retrieved February 9, 2026)

--------------. (2023). *Renewable Power Generation Costs in 2022*. https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022. (Retrieved February 9, 2026)

Kao C. (1999). "Spurious regression and residual-based tests for cointegration in panel data". *Journal of Econometrics*. 90(1): 1-44. https://doi.org/10.1016/S0304-4076(98)00023-2.

Kasimov O. (2025). "Analysing the relationship between education and economic growth in Uzbekistan: A VAR model approach". *Hungarian Statistical Review*. 8(1): 31-47. https://doi.org/10.35618/hsr2025.01.en031.

Kasimov O, Esmaeili Korani A, Farkas B. (2026). "Impact of higher education on economic growth: evidence from Central Asia based on autoregressive distributed lag-pooled mean group estimation". *Asian Education and Development Studies*. 15(3): 1-13. https://doi.org/10.1108/AEDS-07-2025-0312.

Kavlak G, McNerney J, Trancik JE. (2018). "Evaluating the causes of cost reduction in photovoltaic modules". *Energy Policy*. 123: 700-710. https://doi.org/10.1016/j.enpol.2018.08.015.

Kinyar A, Bothongo K. (2024). "The impact of renewable energy, eco-innovation, and GDP growth on CO_2 emissions: Pathways to the UK's net zero target". *Journal of Environmental Management*. 368: 122226. https://doi.org/10.1016/j.jenvman.2024.122226.

Laldjebaev M, Isaev R, Saukhimov A. (2021). "Renewable energy in Central Asia: An overview of potentials, deployment, outlook, and barriers". *Energy Reports*. 7: 3125-3136. https://doi.org/10.1016/j.egyr.2021.05.014.

Lee CC, Zhao YN. (2023). "Heterogeneity analysis of factors influencing CO2 emissions: The role of human capital, urbanization, and FDI". *Renewable and Sustainable Energy Reviews.* 185, 113644. https://doi.org/10.1016/j.rser.2023.113644.

Levin A, Lin CF, Chu CSJ. (2002). "Unit root tests in panel data: Asymptotic and finite-sample properties". *Journal of Econometrics.* 108(1): 1-24. https://doi.org/10.1016/S0304-4076(01)00098-7.

Maddala GS, Wu S. (1999). "A comparative study of unit root tests with panel data and a new simple test". *Oxford Bulletin of Economics and Statistics*. 61(S1): 631-652. https://doi.org/10.1111/1468-0084.0610s1631.

Martínez-Zarzoso I, Maruotti A. (2011). "The impact of urbanization on CO2 emissions: Evidence from developing countries". *Ecological Economics*. 70(7): 1344-1353. https://doi.org/10.1016/j.ecolecon.2011.02.009.

Mehta K, Ehrenwirth M, Trinkl C, Zorner W, Greenough R. (2021). "The energy situation in Central Asia: A comprehensive energy review focusing on rural areas". *Energies*. 14(10): 2805. https://doi.org/10.3390/en14102805.

Mensah CN, Long X, Boamah KB, Bediako IA, Dauda L, Salman M. (2018). "The effect of innovation on CO_2 emissions of OECD countries from 1990 to 2014". *Environmental Science and Pollution Research.* 25(29): 29678–29698. https://doi.org/10.1007/s11356-018-2968-0.

Mikhalev AV, Rakhimov KK. (2023). "Central Asia and the Struggle for Soviet Legacy". *Russia in Global Affairs*. 21(2): 131-140. https://doi.org/10.31278/1810-6374-2023-21-2-131-140.

Mol AP, Spaargaren G. (2000). "Ecological modernisation theory in debate: A review". *Environmental Politics*. 9(1): 17-49. https://doi.org/10.1080/09644010008414511.

Nam HJ, Ryu D. (2024). "Impacts of trade and institutional quality on carbon emissions in transition economies". *Finance Research Letters*. 67, 105872. https://doi.org/10.1016/j.frl.2024.105872.

Nemet GF. (2006). "Beyond the learning curve: Factors influencing cost reductions in photovoltaics". *Energy Policy*. 34(17): 3218-3232. https://doi.org/10.1016/j.enpol.2005.06.020.

Norman J, Babajeva J, Sidorovskaya-Fretz N, Kozybay Z. (2024). "COP out: Azerbaijan, the Caucasus, and Central Asia building three times as much fossil as wind and utility-scale solar capacity". *Global Energy Monitor*. https://globalenergymonitor.org/report/cop-out-azerbaijan-the-caucasus-and-central-asia-building-three-times-as-much-fossil-as-wind-and-utility-scale-solar-capacity/.

Osman AI, Chen L, Yang M, Msigwa G, Farghali M, Fawzy S, Rooney W, Yap PS. (2023). "Cost, environmental impact, and resilience of renewable energy under a changing climate: A review". *Environmental Chemistry Letters*. 21(2): 741-764. https://doi.org/10.1007/s10311-022-01532-8.

Our World in Data. (2025). *CO_2 and Greenhouse Gas Emissions*. https://ourworldindata.org/co2-and-greenhouse-gas-emissions. (Retrieved February 9, 2026)

Pedroni P. (2004). "Panel cointegration: Asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis". *Econometric Theory*. 20(3): 597-625. https://doi.org/10.1017/S0266466604203073.

---------------. (1999). "Critical values for cointegration tests in heterogeneous panels with multiple regressors". *Oxford Bulletin of Economics and Statistics*. 61(S1): 653-670. https://doi.org/10.1111/1468-0084.0610s1653.

Pesaran MH. (2021). "General diagnostic tests for cross-sectional dependence in panels". *Empirical Economics*. 60(1): 13-50. https://doi.org/10.1007/s00181-020-01875-7.

Pesaran MH, Shin Y, Smith RP. (1999). "Pooled mean group estimation of dynamic heterogeneous panels". *Journal of the American Statistical Association*. 94(446): 621-634. https://doi.org/10.1080/01621459.1999.10474156.

Phillips PC, Hansen BE. (1990). "Statistical inference in instrumental variables regression with I(1) processes". *The Review of Economic Studies.* 57(1): 99-125. https://doi.org/10.2307/2297545.

Popp D. (2002). "Induced innovation and energy prices". *American Economic Review*. 92(1): 160-180. https://doi.org/10.1257/000282802760015658.

Poumanyvong P, Kaneko S. (2010). "Does urbanization lead to less energy use and lower CO2 emissions? A cross-country analysis". *Ecological Economics*. 70(2): 434-444. https://doi.org/10.1016/j.ecolecon.2010.09.029.

Rahro A, Esmaeili Korani A, Raiss Shaghaghi S. (2024). "Corruption and renewable energy consumption in 42 developed countries: A pooled mean group analysis". *Hungarian Statistical Review.* 7(2): 28-40. https://doi.org/10.35618/hsr2024.02.en028.

Razmi SF, Ghodratnama M, Razmi MJ, Korani AE. (2024). "Investigating factors affecting renewable and nonrenewable electricity generation in Iran". *International Journal of Energy Economics and Policy*. 14(5): 109-117. https://doi.org/10.32479/ijeep.16538.

Rogers EM. (2003). *Diffusion of Innovations.* 5th ed. Free Press. https://books.google.com/books?id=4wW5AAAAIAAJ.

Romer PM. (1990). "Endogenous technological change". *Journal of political Economy.* 98(5, Part 2), S71-S102. https://doi.org/10.1086/261725.

Sabyrbekov R, Overland I. (2025). "Urban climate resilience in transition economies: The case of Central Asia". *Environmental Research Letters.* 20(7): 074057. https://doi.org/10.1088/1748-9326/addfee.

Sha N, Ghardallou W, Murshed M, Makhmudov S. (2025). "The role of internet services in carbon productivity enhancement and environmentally-sustainable economic growth". *Journal of Environmental Management.* 395, 127734. https://doi.org/10.1016/j.jenvman.2025.127734.

Shadrina E. (2022). "A double paradox of plenty: renewable energy deployment in Central Asia". *Eurasian Geography and Economics*. 63(1): 1-26.

https://doi.org/10.1080/15387216.2020.1823868.
Skalamera M. (2025). “The varying levels of contrasting adaptation in Central Asia’s climate change politics”. *Central Asian Survey*. 44(1): 85-104. https://doi.org/10.1080/02634937.2024.2373086.
Song S, Tan H, Zhang Y, Ma Y. (2024). “A multiscale analysis of the relationship between urbanization and CO_2 emissions using geo-weighted regression model”. *Discover Sustainability*. 5(1): 113. https://doi.org/10.1007/s43621-024-00298-z.
Stern DI. (2004). “The rise and fall of the Environmental Kuznets Curve”. *World Development.* 32(8): 1419-1439. https://doi.org/10.1016/j.worlddev.2004.03.004.
Sulaimanova B, Overland I, Sabyrbekov R, Vakulchuk R. (2023). “Energy transition in Central Asia: A systematic literature review”. In *Climate change in Central Asia* (pp. 69-82). Springer. https://doi.org/10.1007/978-3-031-29831-8_6.
Vakulchuk R, Overland I. (2021). “Central Asia is a missing link in analyses of critical materials for the global clean energy transition”. *One Earth*. 4(12): 1678-1692. https://doi.org/10.1016/j.oneear.2021.11.012.
Vakulchuk R, Daloz AS, Overland I, Sagbakken HF, Standal K. (2023). “A void in Central Asia research: climate change”. *Central Asian Survey*. 42(1): 1-20. https://doi.org/10.1080/02634937.2022.2059447.
Wald A. (1943). “Tests of statistical hypotheses concerning several parameters when the number of observations is large”. *Transactions of the American Mathematical Society.* 54(3): 426-482. https://doi.org/10.2307/1990256.
Way R, Ives MC, Mealy P, Farmer JD. (2022). “Empirically grounded technology forecasts and the energy transition”. *Joule*. 6(9): 2057-2082. https://doi.org/10.1016/j.joule.2022.08.009.
Wooldridge JM. (2010). *Econometric Analysis of Cross Section and Panel Data*. MIT Press.
World Bank. (2025). “World development indicators”. https://databank.worldbank.org/source/world-development-indicators. (Retrieved February 9, 2026)
--------------. (2023a). “Countries’ urban population (% of total population)”. https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?locations=UZ. (Retrieved February 9, 2026)
---------------. (2023b). “Countries’ trade openness (% of GDP)”. https://data.worldbank.org/indicator/NE.TRD.GNFS.ZS?locations=UZ. (Retrieved February 9, 2026)
Zhang S, Liu X, Bae J. (2017). “Does trade openness affect CO_2 emissions: Evidence from ten newly industrialized countries?”. *Environmental Science and Pollution Research.* 24(21): 17640-17648. https://doi.org/10.1007/s11356-017-9392-8.