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CAN SERBIA RECONCILE ECONOMIC GROWTH WITH SUSTAINABILITY IN A POLICY SPACE SHAPED BY CONTRASTING REGIONAL NORMS?

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Abstract. Our research investigates the dynamic relationship between economic growth and environmental sustainability in Serbia, a country situated at the intersection of Western environmental standards and Eastern development models. Specifically, it examines whether economic growth, as measured by GDP per capita, conflicts with environmental sustainability. It also considers the roles of renewable energy consumption (RENC), urbanization (URB) and trade openness (TO) as mediating variables. The analysis is based on annual time series data for Serbia from 1995 onward. A Vector Error Correction Model (VECM) framework is employed to assess both short-run and long-run relationships among the variables. Our research addresses the underexplored question of how countries like Serbia can reconcile growth with sustainability in a policy space shaped by contrasting regional norms. The results indicate a short-run trade-off between GDP and environmental sustainability, as lagged CO_2 emissions and RENC negatively affect GDP growth. However, in the long run, growth is positively associated with TO and URB, while RENC is strongly driven by URB. CO_2 emissions appear to evolve relatively independently of TO and URB. The adjustment coefficients confirm that GDP, CO_2 and RENC significantly respond to deviations from long-run equilibrium, with URB playing a central role in stabilizing the system.

Keywords: CO_2 emissions, renewables integration, GDP, trade openness, VECM, Error Correction Term (ECT).

JEL Classification: O44, C01, Q56.

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1. Introduction

In Serbia, the dynamics among CO_2 emissions, GDP growth, urbanization (URB), trade openness (TO) and renewable energy consumption (RENC) reflect the country's ongoing efforts to balance economic growth with environmental sustainability. Each factor contributes to and interacts with Serbia's environmental footprint and development goals, especially within the broader context of European Union (EU) environmental standards and global climate commitments (M. Jovanović et al., 2023). Serbia's economic growth has historically been accompanied by high levels of CO_2 emissions, largely due to the country's reliance on coal-fired power plants for energy generation. The Serbian energy sector, dominated by lignite coal, is a significant source of emissions, especially given Serbia's aging infrastructure and limited investment in energy efficiency (Klimenta et al., 2022). As GDP grows, the energy demand increases, leading to higher emissions unless offset by structural changes or clean energy investments. Despite this challenge, Serbia has been working on aligning its energy policies with EU standards and has pledged to reduce greenhouse gas emissions as part of the Paris Agreement commitments. Serbia's long-term strategy involves reducing its carbon footprint through policies aimed at increasing renewable energy sources (RES) and enhancing energy efficiency (Guven et al., 2020).

Urbanization has accelerated in Serbia, with the urban population steadily increasing as people migrate from rural areas to cities in search of better employment and living standards. Urbanization tends to drive energy demand and increases the per capita CO_2 emissions, especially when urban growth is not matched by sustainable infrastructure. This urban shift contributes to higher energy needs for residential, industrial and transportation purposes in urban areas. However, urbanization may also offer opportunities for more efficient energy use, as cities support concentrated infrastructure for RES, public transportation and smart energy management systems (Manojlović et al., 2023). Serbian cities, including Belgrade, have started to explore options for sustainable urban planning, though this shift requires considerable investment and policy support to achieve significant reductions in emissions (Ciric & Mandic, 2021; Vranjanac et al., 2018).

TO facilitates access to international markets, advanced technologies and investment in cleaner production practices, which help reduce the environmental intensity of economic growth. Serbia's trade relationships, particularly with the EU, encourage the adoption of higher environmental standards in goods and services. Nevertheless, TO may also lead to increased emissions if Serbia becomes a production hub for industries that have high energy demands and pollution levels (Sofijanic et al., 2021). The challenge for Serbia is to ensure that trade-driven growth aligns with sustainability goals (Stojanović et al., 2021), potentially through policies that favor cleaner industries and stricter environmental standards for traded goods.

RENC is also a growing focus in Serbia's energy strategy. The country has abundant RES, particularly in hydroelectric power, as well as potential for solar, wind and biomass energy (Derčan et al., 2012; B. Pavlović et al., 2021). Serbia's RES sector is still underdeveloped compared to its coal-based power generation, but recent years have seen a gradual increase in the share of RES in the energy mix (Žikić et al., 2022; Ali et al., 2022). The government has introduced policies and incentives to encourage investments in renewable energy, aiming to reduce dependency on fossil fuels and lower CO_2 emissions. EU funding and international partnerships have supported some of these efforts, but significant expansion of RES requires sustained investment, policy continuity and modernization of the national grid (Cvetković et al., 2022).

CO_2 emissions in Serbia remain high, largely due to the country's heavy reliance on coal. Approximately 70% of Serbia's electricity comes from coal-fired power plants, many of which are outdated and among the highest CO_2 emitters in Europe. This dependence on coal has contributed significantly to air pollution, especially during the winter months, placing several Serbian cities, including Belgrade, among Europe's most polluted (Stosic et al., 2021; Vulović et al., 2023). Despite international commitments to reduce greenhouse gas emissions, Serbia continues to support the coal industry through subsidies, emphasizing energy security and employment over environmental considerations.

Economic growth in Serbia has brought both prosperity and environmental pressures (Mihajlović, 2020; Obradovic et al., 2017). Industrialization and infrastructure projects have been central to Serbia's development strategy. However, many of these projects lack adequate environmental safeguards, leading to increased emissions and resource depletion (V. Jovanović et al., 2023). Foreign investments in mining, such as the controversial lithium mining project by Rio Tinto in the Jadar Valley, highlight this conflict. The project promises economic benefits and job creation but has faced widespread opposition due to environmental risks, including potential water pollution and irreversible landscape changes.

Rapid urbanization has strained public services and infrastructure, with public transportation systems underdeveloped and urban air quality frequently compromised by high vehicle emissions (Dzoljic et al., 2022; Gladović et al., 2023). While urbanization offers opportunities for efficient energy use, green urban planning in Serbia has been limited, and environmental concerns in urban areas remain largely unaddressed. Initiatives such as low-emission zones and expanded public transportation infrastructure have only recently gained traction and remain in their early stages.

Serbia's trade relationships with the EU have driven some industries to adopt higher environmental standards (Lukić et al., 2020), given the EU's strict regulations on traded goods. However, the environmental impact of trade is not uniformly positive. Serbia's close trade ties with non-EU countries, especially China (Jovičić et al., 2020) and Russia, have introduced environmentally damaging projects that would not meet EU standards (Soyaltin-Colella, 2023). Chinese-financed projects, including expansions of coal power plants and large construction projects with limited environmental oversight, have led to concerns about environmental degradation.

As mentioned, Serbia's RES sector shows potential but remains underdeveloped. Although hydropower accounts for about 30% of electricity generation, other RES, such as wind and solar energy, have seen slower growth (Ciric, 2019). Serbia's abundant RES are currently underutilized due to regulatory and infrastructure barriers. Small hydropower projects have sparked controversy, particularly in protected areas where they have disrupted local ecosystems, led to water shortages and sparked public opposition (Mišić & Obydenkova, 2022). Activists argue that these projects often proceed without proper environmental impact assessments, damaging natural habitats under the guise of "green energy". Meanwhile, investments in solar and wind energy face bureaucratic delays and require substantial improvements in Serbia's national grid infrastructure to achieve large-scale adoption (Dimić et al., 2018).

EU integration pressures have influenced Serbia's RES policies, with the EU providing financial support to encourage cleaner energy practices (Endrődi-Kovács & Tankovsky, 2022). However, Serbia's progress toward RES targets has been slower than anticipated, creating friction with the EU and raising questions about Serbia's commitment to sustainability. While Serbia has joined the EU Green Agenda for the Western Balkans, which promotes environmental protection and reduced pollution, many argue that implementation has been more symbolic than substantial (Markovic Khaze & Wang, 2021). Citizens are increasingly willing to challenge projects that they perceive as damaging to the environment (Ivanović et al., 2023), indicating that environmental concerns may become a stronger political force in Serbia.

In this paper, we are motivated to analyze the relationship between CO_2 emissions and RENC, GDP, TO and URB in Serbia as its journey toward sustainable development remains complex and contentious. Economic growth has lifted living standards and supported industrial expansion, yet has often come at an environmental cost. Serbia's reliance on coal, limited adoption of RES and controversial mining projects reflect the challenges of transitioning to a sustainable economy.

The contribution of this analysis lies in its comprehensive evaluation of the intricate relationships between CO_2 emissions and factors such as RENC, GDP growth, TO and URB in Serbia. Our specific contributions include:

(1) Offers the first in-depth VECM application to Serbia's green transition.

(2) Applies innovative filtering of non-stationary variables (URB via HP-cycle).
(3) Distinguishes short-run growth costs from long-run sustainability gains.
(4) Highlights the central role of urbanization in system equilibrium.
(5) Provides policy-relevant insights for hybrid growth-sustainability models.
(6) Adds to the comparative literature on environmental strategies in transitional economies.
(7) Addressing controversies. By examining contentious issues like coal reliance and mining projects, the analysis contributes to understanding the socio-political dimensions of environmental challenges in Serbia.

This paper is organized into several sections. The current section provides an overview of the general context, motivation, challenges, controversies and contributions. The next section reviews the existing literature in the field, highlighting the limited research available. Section 3 outlines the proposed methodology, followed by the presentation of results and discussions in Section 4. Finally, Section 5 offers an in-depth discussion and concludes the study.

2. Literature review

In this section, the most and relevant research papers on Serbia and its path development are investigated. Notably the number of such publications is scarce. Econometric methods, including ARDL and the Environmental Kuznets Curve (EKC), were employed to examine the long-term impact of several macroeconomic variables on Serbia's public debt (Mitrašević et al., 2022). Additional analyses explored systemic credit risk in Serbia's banking sector (Drljača-Kanazir, 2021), the relationship between inflation and economic growth using an ARDL bounds testing approach (Obradovic et al., 2017), and the link between unemployment and GDP in Serbia to assess the validity of Okun's law (Mihajlović, 2020).

The relationship between CO_2 emissions, GDP, electricity consumption and TO in Serbia was investigated (Mitić et al., 2024) to support sustainable development. Using data (1995–2019), an ARDL model was applied to assess the EKC, followed by a bootstrap logistic regression model to predict environmental quality. Further, the impact of foreign direct investments (FDI) and economic growth on environmental degradation in the Balkans (1998–2019) was analyzed (A. Pavlović et al., 2021; Tütüncü et al., 2025). Balkan countries were grouped into high-income countries and upper-middle-income countries to test two hypotheses. The Pollution Haven Hypothesis (PHH) was examined using Pearson correlation across all countries, high-income countries and upper-middle-income countries, while the EKC hypothesis was tested using polynomial linear regression.

The demographic and economic determinants of energy consumption in the 28 EU member states from 1960 to 2014 were examined, emphasizing the pressing challenge of managing growing global energy demand amid climate change and fossil fuel dependency (Petrovic et al., 2017). The findings revealed that population size has a strong positive impact on energy consumption, with a 1% population increase resulting in a 1.59% to 1.76% rise in energy consumption. Another research examined the greenhouse gas (GHG) emissions from lignite samples collected from major deposits in Poland, Slovenia, and Serbia, focusing on the environmental impact of abandoned lignite mines (Pytlak et al., 2021). With the anticipated reduction in lignite excavation due to changes in the energy market, the cessation of mining activities involves restoring natural water conditions and flooding the mines, which could become sources of GHG emissions.

The challenges faced by developing countries in balancing economic development with pollution reduction to achieve sustainable development was addressed, a topic that remains underexplored (Jednak et al., 2021). It examines the relationships between FDI, TO, final energy consumption (FEC), capital (K), income and pollution (carbon emissions) in Serbia (1995–2018). Using the ARDL model, the research investigated both long- and short-run dynamics, as well as causal relationships among these variables. The findings revealed that in the long run, FDI and TO positively impact GDP, while pollution has a negative effect.

Additionally, Sotiroski et al. (2023) examined the use of Data Envelopment Analysis (DEA) to evaluate the efficiency of countries in achieving sustainable development goals. It analyzed 26 EU member states and Serbia, an EU candidate, over the period 2010–2017 using a non-oriented DEA model with variable returns-to-scale. Moreover, Fejzić et al. (2024) examined decarbonization pathways for the Drina River Basin, shared by Bosnia and Herzegovina, Montenegro, and Serbia, whose power sectors remain heavily reliant on coal. Additionally, Topic-Bozic et al. (2024) employed life cycle assessment to compare the environmental impacts of heat pump heating in Slovenia and Serbia under current and 2030 electricity mix scenarios. Results show that Serbia's heat pumps emit 84.7% more CO_2 per unit of heat than Slovenia's due to a more carbon-intensive grid. Also, B. Pavlović and Trtica (2024) analyzed the impact of introducing an Emissions Trading System (ETS) in Serbia's lignite-based electricity sector. Results showed that while the ETS may slow GDP growth in the short term due to adjustment costs, by 2030 growth accelerates and surpasses baseline projections, indicating that carbon pricing can ultimately support cleaner and more sustainable economic growth. Notably, Popović et al. (2025) estimated the carbon footprint of inbound tourism in Serbia. Findings highlight the need for sustainable travel options and carbon reduction measures to support environmentally responsible development.

Table 1 presents a comparative analysis of several prior studies focused on Serbia and its CO_2 emissions.

Table 1. Brief comparative analysis of the previous studies (source: by authors)

Ref	Objective	Methods	Main Findings	Region	Year
Mitić et al. (2024)	Investigate the relationship between CO_2 emissions, GDP, electricity consumption and TO in Serbia.	ARDL model for EKC, bootstrap logistic regression for environmental quality prediction.	Long-term EKC confirmed (inverted U-shape); electricity consumption impacts CO_2 emissions in the short run. All variables significantly influence environmental quality.	Serbia	1995–2019
A. Pavlović et al. (2021)	Analyze the impact of FDI and economic growth on environmental degradation in the Balkans, testing the PHH and EKC.	Pearson correlation for PHH, polynomial and multivariate linear regression for EKC and overall impacts.	PHH confirmed for Serbia, Albania, Croatia, Romania and Bulgaria; EKC hypothesis rejected. Highlights policy gaps in managing FDI's environmental impacts.	Balkans (Serbia, Albania, Croatia, Romania, Bulgaria)	1998–2019

End of Table 1

Ref	Objective	Methods	Main Findings	Region	Year
Petrovic et al. (2017)	Examine the demographic and economic determinants of energy consumption in EU member states, focusing on the challenges of climate change and energy dependency.	Analysis of demographic and economic data using statistical modeling to assess impacts on energy consumption.	Population and economic development positively affect energy consumption. Aging populations also drive energy use changes. EKC observed with income thresholds for transition.	28 EU member states	1960–2014
Pytlak et al. (2021)	Assess GHG emissions from lignite samples in Poland, Slovenia and Serbia, focusing on environmental impacts of abandoned lignite mines.	Microcosm experiments to measure GHG emissions.	CO_2 is the main GHG emitted from lignite; methane emissions are minimal. CO_2 production linked to nitrate concentration and redox potential. Prioritize detrital lignite to reduce GHG emissions.	Poland, Slovenia, Serbia	
Jednak et al. (2021)	Explore the relationship between FDI, TO, final energy consumption, income, and pollution in Serbia to ensure sustainable development.	ARDL for long- and short-run dynamics; Granger causality to identify directional relationships among variables.	FDI and TO positively influence GDP, while pollution negatively affects it. Unidirectional causality found from FDI to GDP, carbon emissions, TO and FEC.	Serbia	1995–2018
Sotiroski et al. (2023)	Evaluate the efficiency of countries in achieving sustainable development goals using DEA.	Non-oriented DEA model with variable returns-to-scale using macroeconomic and ecological indicators.	Finland consistently efficient; high efficiency in Netherlands, Luxembourg, Germany and Sweden. Baltic countries and Serbia showed average or below-average efficiency.	26 EU member states and Serbia	2010–2017

Prior Serbian research papers largely employ ARDL/EKC or related single-equation designs and answer narrow questions, public debt, banking risk, inflation–growth links, Okun's law, offering long-run elasticities or EKC shapes but limited system dynamics (Mitrašević et al., 2022; Mihajlović, 2020; Drljača-Kanazir, 2021; Obradovic et al., 2017). Environment-focused ARDL/EKC work confirms an inverted-U EKC and short-run causality concentrated on electricity use (Mitić et al., 2024), while regional analyses emphasize FDI/PHH patterns and mixed EKC support (A. Pavlović et al., 2021). Complementary strands (Petrovic et al., 2017;

Sotiroski et al., 2023) assess macro-demographic demand or efficiency frontiers, and micro-evidence on lignite emissions (Pytlak et al., 2021) highlights technology/fuel specifics rather than economy-wide adjustment. In contrast, our contribution uses a multivariate VECM to identify (i) multiple cointegrating relationships linking GDP with TO and URB, CO_2's relative independence from TO/URB and RENC's long-run coupling with urbanization; (ii) short-run trade-offs where lagged CO_2 and RENC dampen GDP growth; and (iii) error-correction dynamics showing GDP, CO_2 and RENC adjust to long-run disequilibria with URB acting as a stabilizer. This system perspective yields policy-relevant levers, in particular, urban-centric planning and trade-facilitated diffusion of clean technologies, rather than pure correlation or threshold narratives.

3. Methodology

The dataset contains annual data for Serbia from 1995 onward, with the following variables: URB represents urbanization, measured as the percentage of the population living in urban areas; GDP refers to GDP per capita, in USD and serves as a proxy for economic growth; RENC stands for renewable energy consumption, expressed as a percentage of total final energy consumption; CO_2 indicates CO_2 emissions per capita, which is a proxy for environmental sustainability; and TO denotes trade openness, measured as a percentage of GDP.

The suitability of a Vector Error Correction Model (VECM) depends on two main conditions. First, all variables included must be non-stationary in levels, meaning they are integrated of order one or I(1). Second, there must be cointegration between the variables, indicating the existence of a stable, long-run equilibrium relationship among them.

In the context of our research question "Does economic growth conflict with environmental sustainability?", the VECM assesses the long-run and short-run dynamics between GDP and CO_2 emissions, incorporating RENC, URB and TO as exogenous variables.

To confirm the appropriateness of VECM for this analysis, one must first perform the Augmented Dickey-Fuller (ADF) test on each variable to determine whether they are I(1). The ADF test equation can be written as:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \varepsilon_t, \quad (1)$$

where $\Delta y_t = y_t - y_{t-1}$ is the first difference of the series; α is a constant (drift term); βt is an optional time trend; γ is the coefficient used to test for a unit root; δ_i are coefficients of lagged difference terms (to control for serial correlation); ε_t is the white noise error term.

The null hypothesis (H_0) is: $\gamma = 0$ → the series has a unit root (non-stationary), whereas the alternative hypothesis (H_1) is: $\gamma < 0$ → the series is stationary.

Afterward, the Johansen cointegration test is necessary to assess the presence of cointegration among the variables.

If both conditions are met, VECM becomes an appropriate method to examine whether GDP and CO_2 emissions are cointegrated, to estimate the speed at which the system returns to equilibrium following a disturbance and to distinguish between short-run and long-run causal relationships. The methodological flow is depicted in Figure 1.

The VECM–is derived from the Vector Autoregression (VAR) model when variables are non-stationary but cointegrated.

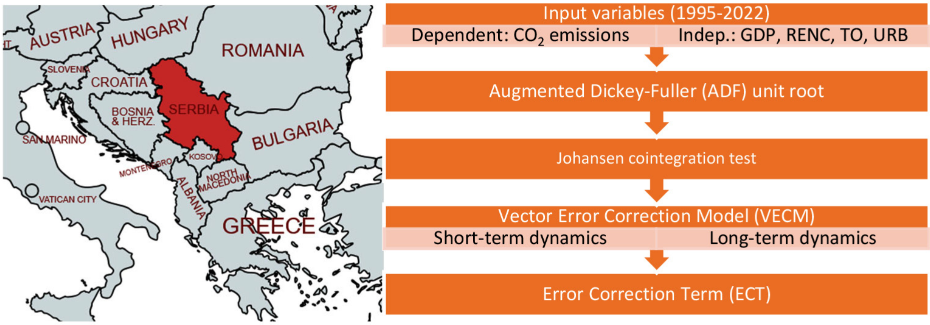

Figure 1. Methodology steps

It starts from the VAR(p) model in levels:

$$Y_t = A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + A_p Y_{t-p} + u_t, \tag{2}$$

where Y_t is a $k \times 1$ vector of non-stationary (I(1)) endogenous variables; A_i are $k \times k$ coefficient matrices; u_t is a vector of error terms.

It can be rewritten as a VECM equation:

$$\Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + u_t, \tag{3}$$

where $\Delta Y_t = Y_t - Y_{t-1}$ is the differenced series; $\Pi = \alpha\beta'$ is the long-run impact matrix; β contains the cointegrating vectors; α contains the adjustment coefficients (speed of adjustment); Γ_i are short-run dynamic coefficient matrices; u_t is a white noise error term; $\beta' Y_{t-1}$ is the Error Correction Term (ECT), measuring the deviation from long-run equilibrium. α indicates how strongly each variable responds to the disequilibrium.

Assuming one cointegrating relationship, the VECM system can be written as:

$$\Delta GDP_t = \alpha_1 \left(\beta_1 GDP_{t-1} + \beta_2 CO_{2t-1} + c\right) + \gamma_{11} \Delta GDP_{t-1} + \gamma_{12} \Delta CO_{2t-1} + u_{1t}; \tag{4}$$

$$\Delta CO_{2t} = \alpha_2 \left(\beta_1 GDP_{t-1} + \beta_2 CO_{2t-1} + c\right) + \gamma_{21} \Delta GDP_{t-1} + \gamma_{22} \Delta CO_{2t-1} + u_{2t}, \tag{5}$$

where $\beta_1 GDP_{t-1} + \beta_2 CO_{2t-1} + c$ is the long-run cointegration relationship; α_1 and α_2 reflect how GDP and CO_2 adjust toward long-run equilibrium.

4. Results and discussions

Figure 2 illustrates the relationships between CO_2 emissions and four key economic and environmental variables in Serbia: TO, URB, RENC and GDP. The first subplot shows a slight positive trend between CO_2 emissions and TO. This suggests that as Serbia becomes more open to international trade, CO_2 emissions tend to increase slightly. This relationship may reflect that increased trade may lead to higher industrial activity and energy demand, potentially increasing emissions. However, the trend is weak, indicating that other factors might also influence emissions, or that Serbia's trade-related activities may not be heavily carbon-intensive. The second subplot illustrates a very weak positive trend between CO_2

emissions and URB. This indicates that higher urbanization is slightly associated with an increase in CO_2 emissions, but the trend is almost flat, suggesting that urban population changes alone have a minimal direct impact on emissions. This means that Serbia's urban growth has not significantly increased emissions. The third subplot shows a clear negative relationship between CO_2 emissions and RENC. As the RENC increases, CO_2 emissions tend to decrease. This inverse relationship indicates that Serbia's efforts to increase RES in its energy mix contribute to lower emissions, highlighting the positive environmental impact of renewables. This trend supports the notion that expanding RES is an effective strategy for reducing Serbia's carbon footprint. The fourth subplot displays a weak positive relationship between CO_2 emissions and GDP. This suggests that as Serbia's economy grows, CO_2 emissions tend to increase slightly, though the correlation is not strong. This weak trend may reflect the early stages of the EKC hypothesis, where economic growth initially leads to higher emissions. However, the trend is not pronounced. Figure 3 displays the line-diagrams for the analyzed variables.

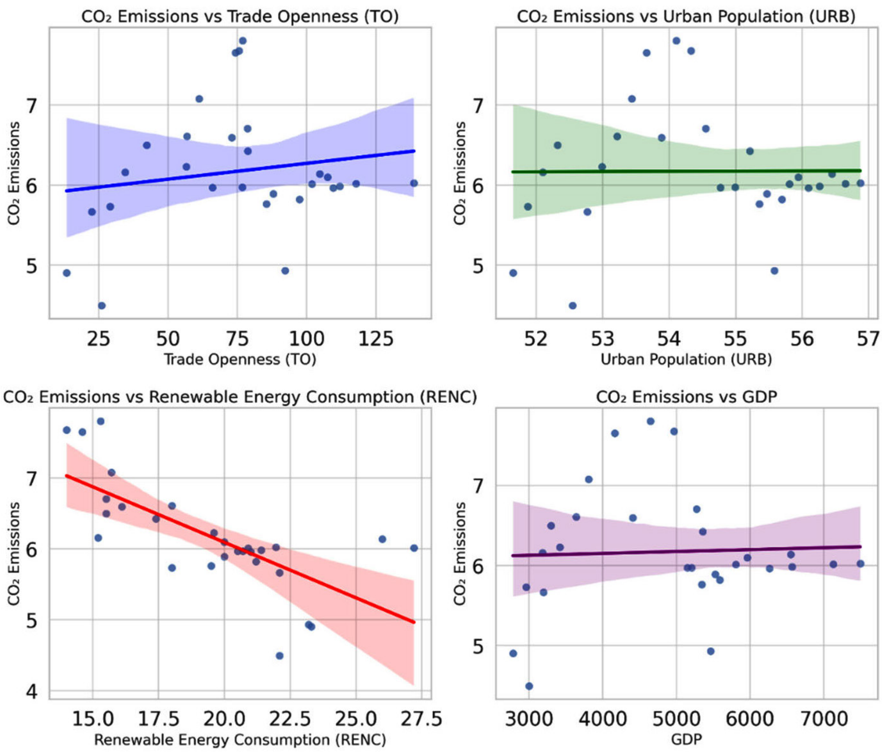

Figure 2. Relationships between CO_2 emissions and GDP, RENC, TO, URB

Figure 4 is insightful for presenting the distribution of variables. The CO_2 plot is relatively symmetric, suggesting a balanced spread of CO_2 emission values in the dataset. The distribution has a peak at the center, which may indicate a typical or common range for CO_2 emissions in the data, with fewer values at the extremes. The tails extend in both directions, implying there are lower and higher values, but the majority of data points cluster near the central peak. The GDP distribution is also symmetric, suggesting that most values of GDP fall within a certain central range, with fewer extremely high or low values. There is a clear peak, which indicates a concentration of observations around the average log-GDP values for the dataset. The tails are not very pronounced, which implies fewer variations at extreme ends. The URB distribution is quite narrow and does not display much variation, suggesting that urbanization levels are relatively stable in the dataset. The lack of extended tails implies a limited range of urbanization levels, possibly due to consistent urbanization across the dataset's countries or regions. The TO distribution is slightly skewed, with a more extended tail on one side. This skew suggests a wider range in trade openness levels. The peak at the center still shows a common or typical level of trade openness, with a minority of data points deviating into higher values. The RENC distribution is more varied, with multiple peaks, indicating that renewable energy consumption varies significantly across observations.

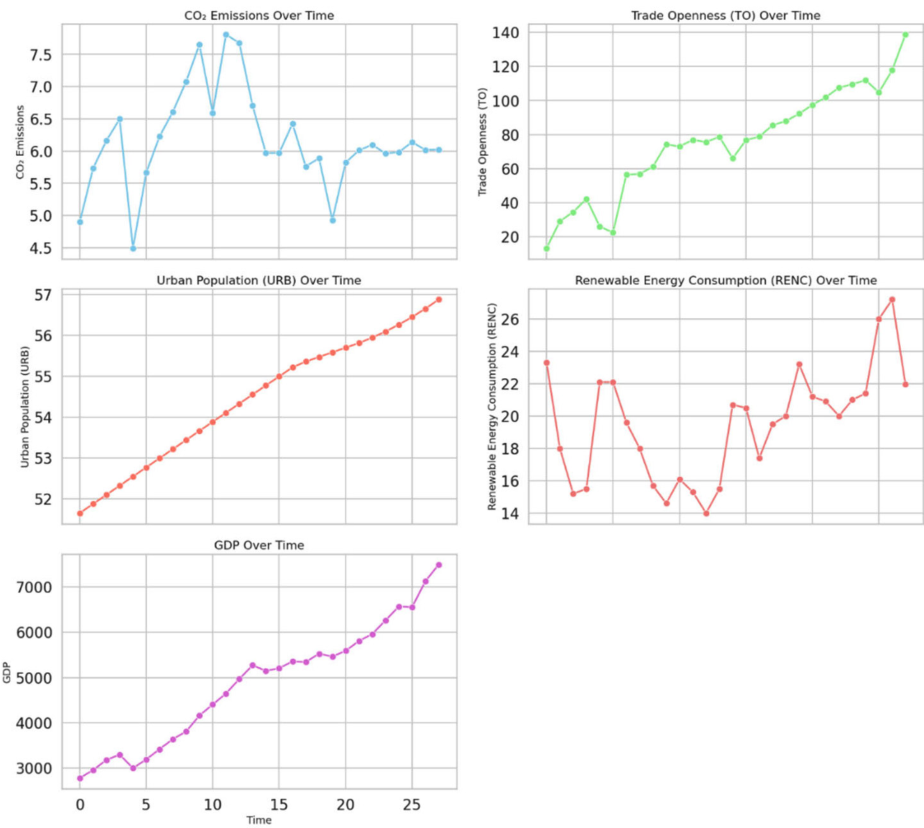

Figure 3. Line-trend diagrams of the analyzed variables for Serbia

Table 2 reports descriptive statistics for variables after their logarithmic transformation.

CO_2 emissions have a mean of 1.8125 and a median of 1.7952, indicating that the average log-transformed CO_2 emissions are relatively consistent with the central value (as in Table 2). The small standard deviation (0.1246) suggests low variability in emissions across the period.

The skewness (–0.2039) shows a slight left skew, while the kurtosis (3.6537) indicates a shape slightly more peaked than a normal distribution. The Jarque-Bera test result confirms that CO_2 emissions follow a normal distribution.

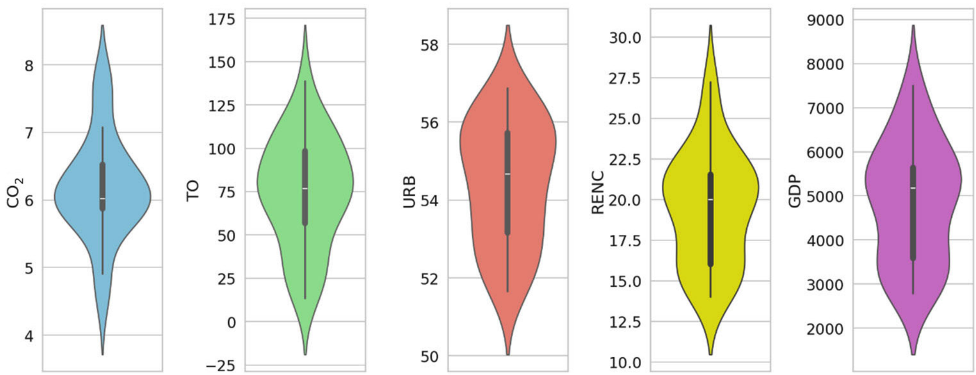

Figure 4. Violin plots of CO_2, GDP, URB, TO, RENC

Table 2. Summary statistics (source: by authors)

	CO_2	GDP	URB	TO	RENC
Mean	1.812	8.449	3.996	4.194	2.955
Median	1.795	8.551	4.001	4.341	2.995
Maximum	2.054	8.921	4.040	4.931	3.303
Minimum	1.503	7.930	3.944	2.594	2.639
Std. Dev.	0.124	0.291	0.029	0.562	0.178
Skewness	–0.203	–0.309	–0.273	–1.233	–0.102
Kurtosis	3.653	1.879	1.830	3.880	2.117
Jarque-Bera	0.692	1.911	1.945	8.001	0.958
Probability	0.707	0.384	0.378	0.018	0.619

Table 3 presents the ADF test results indicating that all variables are non-stationary in levels (i.e., they have unit roots). Table 4 also presents the ADF test results (first differences). Further, Table 5 presents ADF test results, including the log transformation of URB.

Table 3. ADF test results (source: by authors)

Variable	Test Statistic	p-value	Stationary
URB	–0.786	0.823	No
GDP	0.454	0.983	No
RENC	–2.349	0.157	No
CO_2	–0.098	0.950	No
TO	0.431	0.983	No

Table 4. ADF test results (first differences) (source: by authors)

Variable	Test Statistic	p-value	Stationary at 1st Diff
URB	–1.703	0.430	No
GDP	–3.692	0.004	Yes
RENC	–5.121	≈ 0.000	Yes
CO_2	–3.137	0.024	Yes
TO	–5.499	≈ 0.000	Yes

Table 5. Log transformation of URB, ADF test results (source: by authors)

Transformation	Test Statistic	p-value	Stationary
Log(URB)	–0.942	0.774	No
ΔLog(URB)	–1.648	0.458	No

Additionally, we further attempt alternative transformations (e.g., polynomial detrending or Hodrick–Prescott (HP) filter) for URB. Hodrick–Prescott filter, is a widely used technique in time series analysis to separate a time series into a trend and a cyclical component. Both alternative transformations successfully rendered the URB variable stationary. The HP filter (cycle component) produced an ADF test statistic of –4.16 with a p-value of approximately 0.0008, indicating stationarity. Similarly, polynomial detrending of second degree yielded an ADF test statistic of –4.53 with a p-value near 0.0002, also confirming stationarity. Therefore, we include URB in the VECM model using the HP-filtered cycle as the adjusted input for urbanization (URB_HP). Table 6 shows the Johansen cointegration test results.

Table 6. Johansen cointegration test (trace statistic vs. 5% critical values) (source: by authors)

Cointegration Rank (r)	Trace Statistic	5% Critical Value	Conclusion
$r = 0$	97.996	69.820	Reject H_0
$r \leq 1$	58.928	47.850	Reject H_0
$r \leq 2$	30.505	29.800	Reject H_0
$r \leq 3$	12.777	15.490	Fail to reject H_0
$r \leq 4$	0.587	3.840	Fail to reject H_0

As there are 3 cointegrating vectors, a long-run equilibrium relationship does exist among the variables. The results of the VECM coefficients are presented in Tables 7–11.

The VECM with five variables: GDP, CO_2, RENC, TO and URB_HP, and a cointegration rank of 3 has been successfully estimated. In terms of short-run dynamics, each equation demonstrates how the first differences of variables respond to their own and others' lagged values. In the GDP equation, lagged GDP, CO_2 and RENC all have significant negative coefficients ($p < 0.01$), suggesting they negatively impact GDP growth in the short term. In the CO_2 equation, lagged CO_2 and RENC have significant negative effects, while GDP is not significant, indicating that CO_2 emissions are influenced more by their own past values and RENC than by short-run GDP fluctuations. In the RENC equation, CO_2, RENC and URB_HP are significant and positive, implying that higher past emissions and greater urbanization promote RENC. The TO equation shows that RENC, TO and URB_HP are significant, highlighting that short-run

TO dynamics are sensitive to energy structures and urban development. For URB_HP, which represents the HP-cycle component of urbanization, both CO_2 and TO significantly explain its short-run behavior.

Table 7. GDP equation (source: by authors)

Variable	Coef	std_err	Z	P>|z|	CI_lower	CI_upper
const	–4762.127	892.988	–5.333	0.000	–6512.351	–3011.903
L1.GDP	–0.662	0.228	–2.908	0.004	–1.109	–0.216
L1.CO_2	–251.953	74.259	–3.393	0.001	–397.498	–106.409
L1.RENC	–84.167	23.274	–3.616	0.000	–129.784	–38.550
L1.TO	–2.558	3.935	–0.650	0.515	–10.270	5.153
L1.URB_HP	–2245.790	1240.371	–1.811	0.070	–4676.872	185.291

Regarding long-run equilibrium, there are three cointegrating vectors, confirming that the system maintains stable long-term relationships. For instance, the first vector can be expressed as: GDP = 47.11 × TO + 1614.89 × URB_HP + error, indicating a positive long-run association between GDP, TO and URB_HP. The second and third vectors emphasize CO_2 and RENC, respectively, revealing further stable long-run interdependencies.

Table 8. CO_2 equation (source: by authors)

Variable	Coef	std_err	Z	P>|z|	CI_lower	CI_upper
Const	–11.099	5.037	–2.204	0.028	–20.971	–1.228
L1.GDP	–0.002	0.001	–1.519	0.129	–0.004	0.001
L1.CO_2	–1.064	0.419	–2.541	0.011	–1.885	–0.243
L1.RENC	–0.303	0.131	–2.314	0.021	–0.561	–0.046
L1.TO	–0.011	0.022	–0.524	0.601	–0.055	0.032
L1.URB_HP	–10.791	6.996	–1.543	0.123	–24.503	2.920

Table 9. RENC equation (source: by authors)

Variable	coef	std_err	Z	P>|z|	CI_lower	CI_upper
Const	61.362	15.210	4.034	0.000	31.551	91.175
L1.GDP	0.003	0.004	1.011	0.312	–0.004	0.012
L1.CO_2	3.640	1.265	2.878	0.004	1.161	6.120
L1.RENC	1.293	0.396	3.261	0.001	0.516	2.070
L1.TO	0.033	0.067	0.506	0.613	–0.097	0.165
L1.URB_HP	44.917	21.127	2.126	0.034	3.508	86.326

Table 10. TO equation (source: by authors)

Variable	coef	std_err	Z	P>|z|	CI_lower	CI_upper
Const	–187.796	45.059	–4.168	0.000	–276.111	–99.482
L1.GDP	0.007	0.011	0.678	0.498	–0.015	0.030

End of Table 10

Variable	coef	std_err	Z	P>|z|	CI_lower	CI_upper
L1.CO_2	–5.3759	3.747	–1.435	0.151	–12.720	1.968
L1.RENC	–3.129	1.174	–2.664	0.008	–5.431	–0.827
L1.TO	–0.493	0.199	–2.486	0.013	–0.883	–0.104
L1.URB_HP	–198.769	62.588	–3.176	0.001	–321.439	–76.100

Table 11. URB_HP equation (source: by authors)

Variable	coef	std_err	Z	P>|z|	CI_lower	CI_upper
Const	–0.296	0.076	–3.880	0.000	–0.446	–0.147
L1.GDP	–2.479e-05	1.95e-05	–1.272	0.203	–6.3e-05	1.34e-05
L1.CO_2	–0.014	0.006	–2.236	0.025	–0.027	–0.002
L1.RENC	1.524e-05	0.002	0.008	0.994	–0.004	0.004
L1.TO	0.001	0.000	3.486	0.000	0.001	0.002
L1.URB_HP	0.571	0.106	5.388	0.000	0.364	0.780

The adjustment speeds, represented by the alpha coefficients, show how quickly each variable corrects deviations from long-run equilibrium. GDP, CO_2 and RENC exhibit strong and statistically significant adjustment to the second and third cointegration relationships. URB_HP shows significant adjustment to all three long-run vectors, suggesting that urban dynamics are highly responsive to long-run imbalances (Tables 12–14).

Table 12. Loading coefficients Alpha_GDP (source: by authors)

Variable	coef	std_err	Z	P>|z|	CI_lower	CI_upper
ec1	0.025	0.114	0.220	0.826	–0.198	0.249
ec2	500.156	85.727	5.834	0.000	332.134	668.179
ec3	113.348	20.371	5.564	0.000	73.421	153.275

Table 13. Loading coefficients Alpha_ RENC (source: by authors)

Variable	coef	std_err	Z	P>|z|	CI_lower	CI_upper
ec1	0.000	0.002	0.282	0.778	–0.003	0.004
ec2	–5.741	1.460	–3.932	0.000	–8.604	–2.880
ec3	–1.712	0.347	–4.936	0.000	–2.393	–1.033

Table 14. Loading coefficients Alpha_ URB_HP (source: by authors)

Variable	Coef	std_err	z	P>|z|	CI_lower	CI_upper
ec1	4.332e-05	9.76e-06	4.441	0.000	2.42e-05	6.24e-05
ec2	0.027	0.007	3.797	0.000	0.013	0.042
ec3	0.003	0.002	1.828	0.068	–0.000	0.007

In a VECM, the cointegration matrix β defines the long-run equilibrium relationships among the variables. Each column represents one cointegrating vector. Our model has three cointegrating relationships, meaning there are three distinct long-run equilibrium equations. Assuming the variables were ordered as follows: beta.1 corresponds to GDP, beta.2 to CO_2, beta.3 to RENC, beta.4 to TO and beta.5 to URB_HP. The first cointegration vector is: GDP − 47.11 × TO − 1614.89 × URB_HP = long-run equilibrium. This vector implies that, in the long run, GDP is positively associated with both TO and URB_HP. A 1-unit increase in TO leads to a 47.11 unit increase in GDP, and a unit increase in URB_HP (as captured by the HP component) is associated with a large increase in GDP, approximately 1615 units, holding other factors constant. It is important to note that the relatively large coefficient magnitudes, particularly the estimated effect of URB_HP on GDP, should not be interpreted in absolute quantitative terms. It arises from differences in the scaling and transformation of variables. Consequently, these coefficients reflect the direction and relative strength of the long-run associations rather than direct elasticities or one-to-one changes. The interpretation therefore focuses on the sign and significance of relationships, which robustly indicate that URB dynamics contribute positively to long-run economic growth in Serbia. The near-zero coefficients for CO_2 and RENC indicate they do not significantly contribute to this particular long-run relationship. The first vector (GDP–TO–URB_HP) represents a structural growth equilibrium, where long-run economic expansion is supported by TO and URB development. This implies that Serbian policies fostering export diversification, urban infrastructure investment and sustainable city growth are essential for maintaining economic stability.

The second cointegration vector is: CO_2 + 0.0132 × TO − 15.82 × URB_HP = equilibrium. This long-run relationship is dominated by CO_2. While TO and URB_HP appear in the equation, their coefficients are not statistically significant (with p-values of 0.482 and 0.989, respectively). This suggests that CO_2 emissions form a near-standalone equilibrium or that this particular relationship may be weakly identified. The second vector (CO_2-dominated) shows that CO_2 dynamics are only marginally influenced by TO and URB. This underlines the need for dedicated emission-reduction strategies in Serbia, such as decarbonizing the energy mix and enforcing environmental regulation, rather than relying solely on structural economic change.

The third cointegration vector (column 3) is: RENC − 0.0878 × TO + 61.10 × URB_HP = equilibrium. This vector suggests a strong positive long-run relationship between RENC and URB_HP. The coefficient on URB_HP is statistically significant ($p < 0.001$), while the coefficient on TO is not ($p = 0.974$). This implies that URB_HP is a long-run driver of RENC, due to factors such as energy policy, infrastructure development or increased energy demand in urban areas. The third vector (RENC–URB_HP) also captures the renewable–urbanization linkage, indicating that urban growth drives RES adoption through higher energy demand, infrastructure modernization and policy support. It supports policies aimed at urban RES integration, such as distributed generation/storage and energy-efficient urban planning.

These relationships indicate that Serbia's long-run equilibrium rests on the alignment of growth, energy transition and urban policy, emphasizing the importance of integrated strategies for sustainable development rather than isolated interventions.

Summary of the long-run equilibrium relationships among the variables is depicted in Table 15. Cointegration relations (beta) are presented in Tables 16–18.

Table 15. Summary of the long-run equilibrium relationships among the variables (source: by authors)

Vector	Main driver(s)	Long-Run insight
β_1	GDP, TO, URB_HP	Economic growth depends on trade and urban development
β_2	CO_2	Emissions trend weakly connected to trade or urbanization
β_3	RENC, URB_HP	Renewable energy is strongly linked to long-term urban dynamics

Table 16. First cointegration vector (source: by authors)

Variable	coef	std_err	z	P>|z|	CI_lower	CI_upper
beta.1	1.000	0.000	0.000	0.000	1.000	1.000
beta.2	–8.932e-15	0.000	0.000	0.000	–8.93e-15	–8.93e-15
beta.3	1.65e-14	0.000	0.000	0.000	1.65e-14	1.65e-14
beta.4	–47.111	2.066	–22.802	0.000	–51.161	–43.062
beta.5	–1614.894	0.005	–336000.000	0.000	–1614.904	–1614.885

Table 17. Second cointegration vector (source: by authors)

Variable	coef	std err	z	P>|z|	CI lower	CI upper
beta.1	9.943e-20	0.000	0.000	0.000	9.94e-20	9.94e-20
beta.2	1.000	0.000	0.000	0.000	1.000	1.000
beta.3	–5.175e-17	0.000	0.000	0.000	–5.17e-17	–5.17e-17
beta.4	0.013	0.019	0.704	0.482	–0.024	0.050
beta.5	–15.820	1170.324	–0.014	0.989	–2309.614	2277.972

Table 18. Third cointegration vector (source: by authors)

Variable	coef	std_err	z	P>|z|	CI_lower	CI_upper
beta.1	–5.182e-19	0.000	0.000	0.000	–5.18e-19	–5.18e-19
beta.2	1.225e-15	0.000	0.000	0.000	1.23e-15	1.23e-15
beta.3	1.000	0.000	0.000	0.000	1.000	1.000
beta.4	–0.087	2.723	–0.032	0.974	–5.424	5.248
beta.5	61.100	10.611	5.758	0.000	40.303	81.899

In conclusion, the VECM confirms the presence of a long-run relationship among economic growth, CO_2 emissions, RENC, TO and URB_HP. It also highlights how the short-run dynamics and speed of adjustment differ across variables, with urbanization and renewables playing central roles in how the system reacts to both short-term changes and long-term trends.

In a VECM, long-run causality is identified by examining the significance of the Error Correction Term (ECT) in each equation. The ECT captures deviations from the long-run equilibrium. If a variable significantly responds to the ECT (i.e., the coefficient is statistically significant), that variable is adjusting to restore equilibrium, indicating it is influenced in the long run by the other variables. We have three cointegrating vectors (ec1, ec2 and ec3) and the loading coefficients (α) as in Table 19.

In the VECM framework, all variables are treated as jointly endogenous, allowing the model to capture both short-run adjustments and long-run equilibrium relationships among them. Although CO_2 emissions are not formally designated as the dependent variable, they represent the sustainability outcome of interest and therefore receive particular attention in the interpretation of results. This dual treatment aligns with the multivariate structure of the VECM: CO_2 emissions are analyzed both as a variable responding to short-run economic, and energy dynamics and as part of the system's long-run cointegrating relationships that define the equilibrium interactions among economic growth, energy transition and urban development.

Table 19. Cointegrating vectors and loading coefficients (source: by authors)

Variable	ec1	ec2	ec3	Significant ECTs ($p < 0.05$)
GDP	0.025	500.156	113.348	ec2, ec3
CO_2	7.53e-05	1.076	0.293	ec2, ec3
RENC	0.000	–5.741	–1.712	ec2, ec3
TO	0.005	16.588	5.291	ec2, ec3
URB_HP	4.33e-05	0.027	0.003	ec1, ec2 (marginal for ec3: $p = 0.068$)

5. Conclusions

The results from the VECM analysis offer a detailed answer to the question of whether economic growth conflicts with environmental sustainability in the case of Serbia. The evidence points to a short-run tension between growth and environmental objectives, while also suggesting that long-run alignment is possible, especially when URB and RENC are central to development strategies.

In the short run, there is clear evidence of trade-offs. The GDP equation reveals that lagged values of CO_2 emissions and RENC have statistically significant negative coefficients. This suggests that reductions in emissions or increased adoption of renewables may hinder economic growth in the immediate term. These results are consistent with the idea that developing economies like Serbia, when prioritizing environmental measures, might temporarily sacrifice growth, especially if those policies are not matched by productivity gains or infrastructure support.

At the same time, the short-run dynamics of emissions themselves show that GDP does not significantly influence CO_2 levels, indicating that economic fluctuations are not the immediate drivers of environmental degradation, and it could be linked to Serbia's industrial structure and energy policy inertia. This weak short-run feedback may imply that Serbia's emissions are shaped more by structural factors, such as energy mix or industrial composition, rather than by short-term changes in output.

However, RENC is positively influenced by past values of CO_2, RENC itself and the URB. This pattern indicates that emissions and urbanization are both contributing factors to Serbia's transition toward renewables, reflecting policy responses to pollution or rising urban demand for cleaner energy. Likewise, urbanization appears to be significantly explained in the short run by CO_2 emissions and TO, suggesting an interconnectedness between environmental conditions, globalization and urban growth.

The long-run relationships, as captured by the cointegration vectors, indicate a more optimistic perspective. The model confirms the existence of three cointegrating relationships, demonstrating that GDP, CO_2, RENC, TO and URB are bound together in stable long-term equilibria. The first cointegration vector shows that economic growth is positively associated with TO and urban development. This implies that, over time, Serbia's GDP may expand alongside greater URB and TO integration, without necessarily increasing environmental pressures.

The second vector centers around CO_2, but the weak significance of TO and URB in this equation indicates that emissions do not have a strong long-run dependence on these factors. It can be evidence of (i) omitted structural determinants of emissions, e.g., electricity fuel mix (lignite/gas/hydro/RES shares), energy intensity, industrial composition, cross-border power trade, fuel and carbon prices and environmental policy stringency, and/or (ii) structural rigidity in the energy system that decouples CO_2 from macro-demographic drivers.

The third vector establishes a strong long-run relationship between RENC and URB. As urban areas grow and modernize, they drive greater consumption of renewables, suggesting that sustainable URB can be a key lever for Serbia's environmental strategy.

The loading coefficients further reinforce these dynamics. GDP, CO_2 and RENC all significantly adjust to deviations from the second and third cointegration vectors, confirming that these variables are responsive to long-run disequilibria. This responsiveness indicates the presence of long-run causality, with GDP being indirectly influenced by CO_2 and RENC. URB is particularly notable for its sensitivity to all three long-run vectors, highlighting its role in maintaining system equilibrium. This positions urbanization as a dynamic force that simultaneously supports growth and environmental adaptation.

In conclusion, the empirical findings demonstrate that economic growth and environmental sustainability in Serbia are not inherently contradictory, but rather conditionally compatible. While short-term trade-offs exist, especially when environmental measures impose immediate costs on output, there is clear evidence of long-term complementarities. Urbanization emerges as an important mechanism that supports renewables expansion and aligns with economic development. Thus, Serbia's environmental strategy does not need to choose strictly between Western environmental standards and Eastern growth-oriented models. Instead, by leveraging urban policy and renewable investment, it can pursue a hybrid approach that integrates both visions in a coherent and sustainable development path.

Translating the results into actionable strategies requires focusing on Serbia's emitting and growth-driving sectors. In the energy sector, priority should be given to modernizing the electricity grid, accelerating solar PV and small hydro deployment and improving system flexibility through storage and demand-response programs. These actions will reduce coal dependency and support the RES-urbanization link found in the analysis.

In urban policy, the results highlight the value of electrifying public transport, promoting energy-efficient building retrofits and expanding district heating decarbonization via heat pumps and waste heat recovery, measures that also enhance urban sustainability and stimulate local employment.

In trade and industry, Serbia could promote low-carbon exports by introducing green tax incentives and eco-certification schemes for manufacturing and construction materials. These sector-specific policies translate the model's empirical findings into a realistic pathway toward climate-aligned growth and long-term energy security.

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Adela Bâra. The first draft of the manuscript was written by Simona-Vasilica Oprea and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Disclosure statement

The authors report there are no competing interests to declare.

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