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Strengthening Institutional Governance to Counteract Urban-Driven Carbon Emissions in Central Europe: Insights from Economies in the Black Triangle Industrial Zone

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ABSTRACT

Urban expansion and industrial concentration in Central Europe's historic Black Triangle zone-encompassing Germany, Poland, and the Czech Republic-continue to drive elevated carbon dioxide (CO₂) emissions, posing significant challenges to regional climate goals and the downstream ecological stability of the Baltic and North Sea basins. Rapid employment-based urban migration expands built environments, alters land-use patterns, and intensifies energy demand across industrial corridors. This research empirically examines the dynamic long-run impacts of institutional governance, urban migration, and fossil energy consumption on CO₂ emissions in three economies across the Black Triangle Industrial zone of Central Europe over the period 1998:Q4 to 2021:Q4. Utilizing the Pooled Mean Group (PMG) estimator within a Panel Autoregressive Distributed Lag (ARDL) framework, the long-run empirical results reveal that: (i) strengthening institutional quality significantly abates CO₂ emissions, whereas (ii) both fossil fuel consumption and urban migration exert a statistically significant positive effect on long-run carbon emissions. These insights underscore that robust institutional governance is essential to decoupling urban economic growth from environmental degradation. To achieve UN Agenda 2030 targets and mitigate transboundary environmental impacts-including marine resource degradation and eutrophication in connected Central and Northern European catchments-policy interventions must prioritize institutional capacity building, accelerated investments in renewable energy alternatives, and the deployment of smart, green technology-driven transport systems leveraging artificial intelligence and the Internet of Things (IoT).

INTRODUCTION

The urgency of global climate change has shifted institutional focus toward understanding how macro-economic determinants interact to dictate environmental trajectories. Across Europe, urban areas account for the vast majority of energy-related greenhouse gas emissions (GHGE), serving as both engines of economic development and concentrated nodes of environmental degradation. Empirical research in environmental economics highlights that structural shifts toward urbanization and energy-intensive manufacturing are primary determinants of greenhouse gas emissions. While macro-regional climate initiatives such as the European Green Deal establish ambitious decarbonization targets, their operational success relies on effective governance within contiguous, high-emitting industrial zones.

A critical yet underexplored dimension of European climate policy is the environmental role of Central European industrial corridors within the broader Central and Northern river basins. Chief among these is the historic Black Triangle industrial zone (Figure 1)-a contiguous trilateral region encompassing eastern Germany (Saxony), southwestern Poland (Lower Silesia), and northern Czech Republic (Bohemia). In these countries, expanding urban and industrial hubs demand substantial energy inputs to power commercial enterprises, residential heating, and logistics networks. Because regional energy portfolios rely heavily on non-

renewable sources-particularly legacy fossil fuels like coal and natural gas-urbanization directly escalates fossil energy consumption, accelerating atmospheric CO₂ emissions (CO₂E).

It is an area shared by Germany, Poland and the Czech Republic. Source: EEA at <https://www.eea.europa.eu/en/analysis/maps-and-charts/deposition-of-sulphur-in-the-black-triangle-1997>

Historically infamous as one of Europe's most polluted areas due to concentrated open-cast lignite mining and heavy power generation, the Black Triangle represents a core industrial dynamic. In particular, the region has long suffered from localized industrial pollution, cross-border toxic output, and historically high rates of acid deposition. Additionally, because this portion of Central Europe falls within the macro-regional drainage basins and atmospheric catchments of major river systems like the Elbe and the Oder, emissions and environmental pollution originating in these Central European hubs ripple across transnational ecosystems into the Baltic and North Seas via hydrological networks and transboundary air flows.

In the global call to restrain GHGE especially CO₂ emissions (CO₂E), the key challenge remains how to address the problems of the ever-increasing energy demand. In this regard, numerous action plans have been implemented worldwide to prioritize cleaner energy sources, boost energy efficiency and restrain CO₂E (Žak

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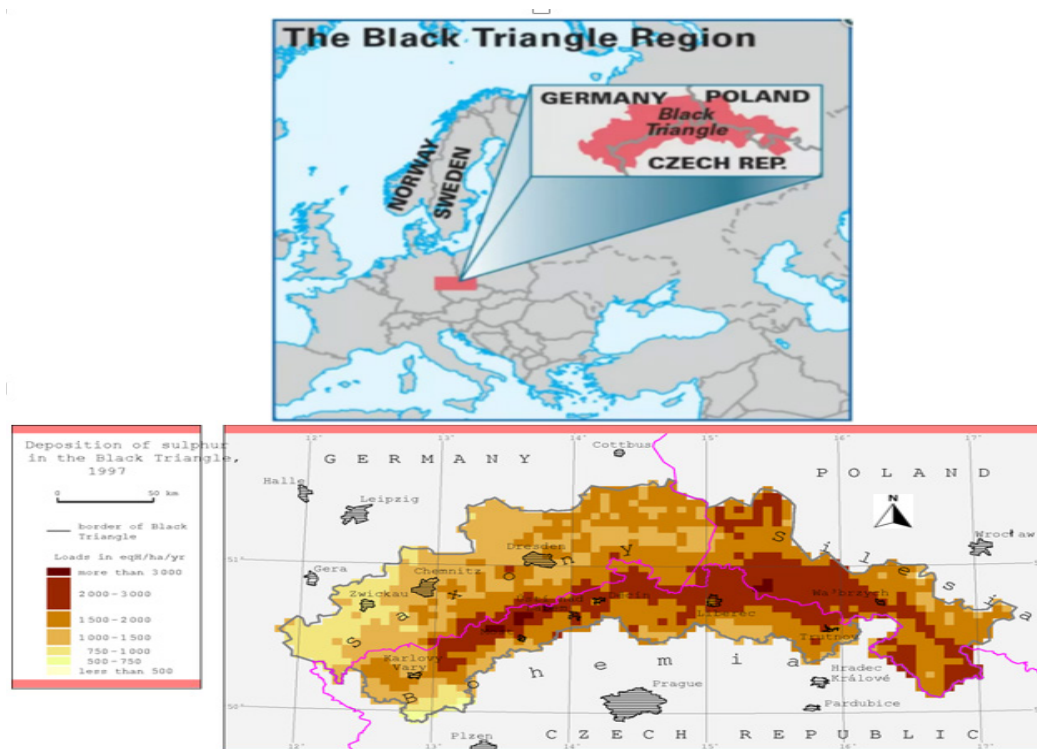


Figure 1: Location of Black Triangle in Europe

& Pyra, 2024; Kadioglu & Gurbuz, 2024). However, countries in the Black Triangle Industrial Zone have historically experienced severe environmental strain resulting from dense industrialization (Blažková, 1996). Due to its significance to the entire European Union, policy actions to reverse the worsening environmental pollution are critical. Mitigating urban-driven emissions in this trilateral hub is a prerequisite for achieving environmental sustainability across connected Central European and maritime macro-regions.

The European Energy and Climate Policy requires these nations to develop policies to attain climate neutrality by 2050 (Kochanek, 2024). Examining sustainable energy development trends in these nations from 2017 to 2021 enables an evaluation of policy efficacy and the identification of primary problems and possibilities in the energy transition. Although Germany has pioneered the energy transition, it has consistently prioritized advancing renewable energy sources within its Energiewende agenda (Scholz *et al.*, 2014).

Since the year 2000, Germany has achieved a considerable reduction in CO₂E, largely driven by capital allocation toward solar and wind infrastructure. Consequently, it serves as a regional benchmark for decarbonization when contrasted with the Czech Republic and Poland. The region has been a hub for several national parks and forest zones, which attract tourists throughout the year for the three countries sharing it.

Historically, the region received significant funding from the European Commission, beginning in the 1980s, to improve environmental quality. Additionally,

corporations such as Tullow have invested heavily in electricity generation across the enclave to deal with noxious emissions and acid rains for decades. Forming part of the European Union, economies across the Black Triangular region have been bound by the EU's environmental laws, including setting emissions standards to limit transport-based pollution since the 1990s. The EU's funding instruments, such as PHARE, offered significant financial flows to help minimize cross-border atmospheric pollution through coal utilization in the region (Novy, 1996; Peet *et al.*, 2010).

Unfortunately, the region has for several years been confirmed to have high levels of environmental pollution due to fossil energy consumption for both transportation and industrial development (Triassi, *et al.*, 2015). Across Europe, the Black Triangle industrial region is historically distinguished by its abundant natural resources, particularly its rich reserves of anthracite, uranium, and diverse metallic ores, including silver, tin, zinc, cobalt, nickel, copper, and lead. The region has served as an important industrial center for European mega corporations, (e.g., Turów Coal Mine around the Turoszowska Basin). Industrial development activity has been profound for decades in the North Bohemian Basin with the installation of steel industries, chemical plants refineries and uranium mines around the Czech Republic and East Germany. Furthermore, prolonged industrialization across the Black Triangle produced high concentrations of sulfur dioxide, nitrogen oxides, heavy metals, and airborne particulates. The resulting acid deposition inflicted extensive damage on neighboring

ecosystems, particularly the forested landscape of the Jizera Mountains. For many decades, these industrially generated air pollutants (i.e., Sulphur dioxide), acid rains, and water pollution have taken an enormous toll on the health across the region (Triassi, *et al.*, 2015).

Another factor cited for assessment of its pollution contribution across the region is the observed rising urbanization that has overstretched the region's physical, social health and ecological systems (Peet *et al.*, 2010). Experts have observed over the years that urban sprawls associated with increasing urbanization is gradually creating destructive landscape changes and generating carbon dioxide emissions through fossil-based vehicular use. The existential threats posed by air, water and soil pollution due to urbanization call for urgent scientific investigation and policy action (Peet *et al.*, 2010; Triassi *et al.*, 2015). In general, urban migration has been found an important contributor to the economic growth of nations and eventual environmental quality concerns (Gasimli *et al.*, 2019; Uttara *et al.*, 2012). Theoretically, urban migration also results in natural resource overexploitation and destruction of air, soil, water and forest quality. The joint effects of urbanization and associated energy demand have resulted in the most disastrous environmental destruction the region has ever known for centuries. Regrettably, according to Lapinskiene and Tvaronaviciene (2009), many countries around Eastern Europe have similar deteriorating sustainable development indicators or negative development trends and cross-border effects. Institutional governance acts as a critical regulatory mechanism in shaping environmental trajectories. However, the heavy scale pollution across countries in the Black Triangle have been evident because of regulatory governance lapses. Historically, prior to 1989 under communism, international environmental treaties addressed cross-border pollution from the Black Triangle industrial region and Upper Silesia (Poland, the Czech Republic and Germany). After 1989, these countries received financial investment promises from the USA and Western Europe after certain agreements were made on pollution of the enclave. Besides, these countries established their domestic environmental policies to regulate pollution across the region, especially on SO₂, NO_x, CO₂ and particulates. Unfortunately, critics have argued that these policies have most adopted the usual EU procedure of 'command and control' strategies instead of employing economic instruments. Although, these three countries raised environmental fines and fees and improve compliance enforcement, critics describe these actions as not effective to incentivize corporations to internalize pollution costs (Novy, 1996). Despite the theoretical importance of institutional governance, empirical estimations isolating how regulatory quality counteracts urban and fossil-driven emissions within these three Central European states remain sparse.

The questions that remain unanswered is (i) to what extent does strengthening regulatory quality act as an effective institutional governance mechanism to mitigate

urban-driven CO₂E and accelerate the low-carbon transition in Central Europe's Black Triangle region? It is anticipated that answering this question will inform and support environmental sustainability policies in the study area and globally. Thus, countries in the Black Triangle presents an interesting yet revealing case worth investigating. To ensure successful policy action, this research seeks to assess the asymmetry in the relationship between institutional governance, urban migration, energy consumption and CO₂E across countries in the Black Triangle industrial zone of Central Europe. The study emphasizes on these critical factors influencing environmental degradation, since, their impacts on economies typically occur in the long run (Stern & Cubbin, 2005). Furthermore, the study utilized dynamic analytical approaches, involving several estimators such as Cross-section augmented IPS; Augmented Dickey-Fuller Unit Root, Westerlund cointegration test; while utilizing the ARDL model estimated via PMG estimator. This panel methodology is suitable when estimating both dynamic short-run variabilities and long-run equilibrium connections across varied panels, accommodating potential fractional integration I (0) I (1) among variables. By applying PMG estimation, the model allows short-run dynamics, error correction terms, and intercept variance to remain country-specific, while constraining the long-run slope coefficients to be identical across Germany, the Czech Republic, and Poland. Furthermore, time-series country-level data from these countries are sourced for the analysis since they all constitute the Black Triangular core. Literature relevant to this research is reviewed in the next section.

LITERATURE REVIEW

Globally, the recent growing concerns about the worsening global environmental quality have called for investigations into linkages between CO₂E and many other macroeconomic factors (Jafari *et al.*, 2015). After studying the long-term nexus between energy consumption, economic growth, and CO₂E in Bahrain from 1980 to 2007, they reported that both factors affect CO₂E (Jafari *et al.*, 2015). A recent study by Pao & Tsai (2011) assessed the nexus between CO₂E, economic growth and energy consumption in the BRICS economies from 1971 to 2005, and between 1990 and 2005 in Russia. The results confirmed the inverted U-shape of the Environmental Kuznets Curve (EKC). Several environmental regulation theories claim that a vital aspect of such regulation conserve energy and control carbon emissions (Harrison *et al.*, 2015).

Hypothesis 1 (H1): *Fossil energy consumption positively causes CO₂ emissions*

Historically, global environmental scientists and economists have struggled to find policy and managerial opportunities required to reduce carbon emissions. Theoretically, environmental experts have utilized the EKC (Grossman & Krueger, 1995) to explained the linkage between a growing economy, energy consumption

and environmental pollution. This hypothesis posits a trade-off between growth and environmental pollution, which reverses at a specific threshold in economic growth when income surges adequately and sound environmental regulations are implemented. With the awareness that carbon dioxide emissions (CO₂) has reached over 80% of recorded greenhouse gas emissions – a situation found to be caused by fossil fuel use (IFCC report 2019) – the need for scholarly investigation for insightful policy action is vital.

Numerous scholars, as referenced in have investigated energy consumption and CO₂ emissions. Over the last decade, several studies have uncovered the relevant energy mix responsible for escalating CO₂E. Several of such scholarships have utilized fragmented energy consumption data (Majeed *et al.*, 2021). Others who focused on electricity use and heat generation realized a substantial percentage increase in CO₂E resulting from aggregate energy consumption (Acheampong *et al.*, 2019). Based on this review, we hypothesize that fossil energy utilization has long-run positive impacts on environment degradation, i.e., $\beta_1 = > 0$. A study by Cheng *et al.*, (2017) corroborates with this hypothesis, which also aligns with the EKC framework (Grossman and Krueger, 1995), that explains how increasing production results in high fossil energy consumption, leading to pollution. Empirical studies by Buonocore *et al.* (2019) find that fossil energy consumption aggregately make up 84% of the planets' primary energy consumption. Renner (2002) recognized that atmospheric pollution within the Black Triangle region primarily stems from sulfur and particulate emissions generated by power plants, industrial installations, residential heating units utilizing lignite coal, and vehicular traffic.

Hypothesis 2 (H2): *Urban migration has positive linkages with CO₂ emissions in economies within the Black Triangle industrial zone*

With recent problems of CO₂ emissions, urban migration has received scholarly attention for its role in rising carbon dioxide emissions. Theoretically, experts claim that emerging economies require increasing demand for energy use, essentially generating CO₂ emissions (Mardani *et al.*, 2019). The neutrality theory argues that no causality runs between urbanization and pollution. Recently, urban transitions theory has been employed to explain environmental pollution issues in cities due to massive biocapacity destruction and industrialization of air and water. Notwithstanding, a study by Dogan and Turkekul (2016) asserts that the adverse environmental effects of urbanization are transient and can be mitigated through strategic regulatory mechanisms. Furthermore, the implementation of targeted energy conservation policies can effectively curb rising CO₂E without compromising macroeconomic growth.

Studies by Jones (1991) on linkages between urbanized communities and energy use in 59 developing economies indicated that urbanization causes a rise in energy consumption. Scholars have found that rising population

growth rate in cities causes harm to the natural environment (Ityavyar & Thomas, 2012). Conflicting findings abound on the link between urban migration and the environment. While some studies find urbanization to impact environmental degradation positively (Wu *et al.*, 2016), several scholars find urbanization to reduce environmental degradation (Azam and Khan, 2016; Effiong, 2016). For example, compact city theory claims, all activities and available spaces tend to be more clustered, causing easy transportation, thereby reducing CO₂E (Breheny, 1995; Holden and Norland, 2005; Sadorsky, 2014; Adams *et al.*, 2016; Yi *et al.*, 2017).

There are other studies that focus on the effect of demographic factors on CO₂E. Cole and Neumayer (2004) found that urban migration heightened CO₂E in 186 countries from 1975 to 1998. Other studies on urbanization and CO₂ emissions focused on the EKC framework (Panayotou, 2000; Dinda, 2004) but indicate mixed and uncertain results because of less robust econometric methods used and data choice (Stern, 2004).

On the balance of these studies, this paper hypothesizes that urbanization exerts positive effects on environmental degradation for the case of emerging economies. i.e., this

$$\beta = \frac{\partial CO_2E}{\partial IGN_{it}} < 0;$$

supposition finds support from Serener *et al.* (2022) and urban transition theory, which explains how environmental pollution issues in cities relate to increasing urbanization and industrialization (Marcotullio and Lee, 2003).

Hypothesis 3 (H3): *Institutional governance has negative effects on CO₂ emissions*

Experts claim that environmental regulations theoretically reflect the environmental policy objectives of political institutions. These environmental regulations tend to conflict with a country's growth plans, pollution targets, and consumption expectations. Generally, any sustainable human as well corporate action is largely dependent on economic returns, green behaviour, and regulatory requirements. In the area of institutional economics theory, regulatory policies moderate economic transactions (Aron, 2000; Al-Mulali & Ozturk, 2015).

Numerous empirical works have been done on the link between institutional quality and environmental quality. Outcomes of such studies have revealed that good governance and institutional quality tend to promote environmental quality (Al-Mulali & Ozturk, 2015; Ali *et al.*, 2019; Shah *et al.*, 2020). Azam *et al.*, (2020) recently found that institutional quality, environment and energy use are integration in developing economies. Wawrzyniak and Doryń (2020) and Gani (2012) validated this study. Based on these studies, we hypothesize that institutional governance abates environmental degradation, especially in emerging economies. i.e. $\beta = \partial CO_2E / \partial IGN_{it} < 0$; this hypothesis corroborates with Cheng *et al.* (2017). Theoretically, this hypothesis is supported by institutional theory, which describes how exterior factors affect firms' good environmental behavior (Akram, & Abrar-ul-Haq,

2019). The significance of institutional theory lies in its ability to bridge micro- and macro-level processes within a system, thereby enabling the diffusion of values and practices critical to environmental sustainability. Empirically, Rivera (2004) finds that environmental regulations, effective monitoring and explicit penalties meted out to people and corporations for noncompliance are shown to be an operational instrument for stirring up sustainable environmental practices.

Given this review, this manuscript contributes to regional environmental economics in several ways.

First, we find that until now there is no adequate empirical evidence on this topic, especially among economies in the Black Triangular region of Europe. New information from this region can inform policy in other emerging economies, especially on how to address environmental sustainability challenges practically.

Second, it isolates institutional regulatory quality as an active environmental governance tool rather than a static control variable as evident in numerous studies in the field.

Third, it delivers empirical insights tailored to the industrial corridor of Germany, Poland, and the Czech Republic, providing targeted policy direction for a region balancing heavy industrial heritage with European Union sustainability mandates.

Fourth, the findings inform multi-national policy frameworks aimed at aligning urban migration management and clean energy adoption with the global emission abatement goals of Agenda 2030. Our objective in this study is to contribute to environmental degradation policy modeling gaps in emerging economies.

With lessons of empirical weakness of carbon emissions studies, we employ advanced and dynamic econometric approaches for this heterogeneous panel assessment. This is important precisely because, evidence from literature indicate that biased estimation methods have been used to analyze panel CO₂ emissions and failed to recognize spillover factors. Advanced econometric tools such as Westerlund cointegration, autoregressive distributive lag

and the ARDL/PMG estimators have received validation, especially in cases of cross-section dependence data analyses and in cases where data exhibits a mixed order of integration. The next section focuses on the empirical strategy used in this research.

MATERIALS AND METHODS

Dataset

To realize our objectives, authors source time-series country-level data from the three countries (Germany, the Czech Republic and Poland) that intersect the Black Triangle industrial zone of Central Europe. Variables of interest for this research (i.e., environmental sustainability, urbanization, energy consumption and institutional governance) were based on theories and empirical studies reviewed. Data was sourced on (i) urban population (defined as % of total population) and usually determined by the total population living in cities (Addai *et al.*, 2022). Data was collected from the World Bank; (ii) Carbon dioxide emissions (CO₂E) data was obtained from our world in data as an environmental sustainability parameter and the outcome variable (Veleva *et al.*, 2003). It is calculated in metric tons (MtCO₂). (iii) Energy consumption (Turvey & Nobay, 1965) is represented by per capita primary energy consumed and was also obtained from our world in data; (iii) Regulatory quality (De Francesco & Radaelli, 2007) measuring institutional strength of the economy, and collected from Worldwide Governance Indicators. (iv) Data was sourced on Fossil energy consumption from the World Bank. Fossil energy consumption describes the utilization of energy from unclean sources (oil, natural gas and coal). Its measurement is done based on the average consumption of energy in kilowatts hours. To ensure objectives are achieved, data selection was mainly based on both theoretical and empirical insights from the review (Saboori *et al.*, 2012). These data were then transformed and expressed in natural logarithm form to avoid scaling issues (Tarazkar *et al.*, 2021). Figure 2 illustrates the methodological flowchart.

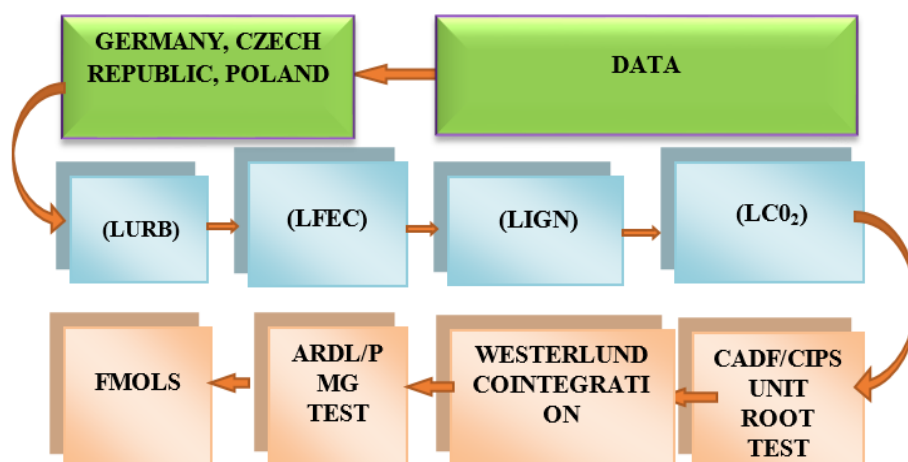


Figure 2: Methodological flowchart.

Source: Authors formulation.

Theoretical framework

Instead of using a stringent macroeconomic accounting identity like the STIRPAT model-which mandates the inclusion of economic affluence (GDP per capita)-this study anchors its empirical framework in the institutional-governance augmented energy demand theory. Classical energy demand models posit that pollutant discharges are a derived function of primary energy consumption inputs driven by structural shifts, such as spatial modernization and demographics.

However, standard energy demand models often suffer from omitted variable bias by overlooking the regulatory environment that dictates energy efficiency, enforcement of environmental laws, and the containment of industrial negative externalities. To address this gap, we augment the traditional energy demand function by integrating institutional economics theory. This incorporated approach acknowledges that formal regulatory institutions (such as regulatory quality and compliance enforcement mechanisms) serve as structural moderators and they have the ability to change the carbon intensity of energy utilization and manage the ecological pressures induced by rapid urban structural changes.

Model Construction and Specification

Based on this specialized demand-governance structure, the aggregate environmental degradation function for the Black Triangle industrial corridor is formulated as:

$$CO_2 = f(URB, FEC, IGN) \quad (1)$$

CO₂ is carbon emissions adopted to serve as dependent variable and transboundary metric for environmental quality; URB is total urban population expressed in % and capturing demographic shifts and spatial energy-demand pressures; FEC is fossil fuel consumption expressed in percentage form, and IGN is regulatory quality, serving as the proxy for governance capacity to mitigate pollution costs.

To assess both the dynamic short-run variabilities and long-run equilibrium associates within a panel framework, the empirical association is log-linearized to minimize scaling variations and prevent heteroscedasticity. The formalized panel Autoregressive Distributed Lag (ARDL) operational equation is specified as:

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln URB_{1it} + \beta_2 \ln FEC_{2it} + \beta_3 \ln IGN_{3it} + \epsilon_{it} \quad (2)$$

Here, β_0 functions as the country-specific constant intercept; β_1 , β_2 , β_3 represent elasticity of respective long run coefficients slopes; t denotes the time scope of the study (1998Q4-2021Q4; i refers to the countries in the panel. $\ln CO_2$ is the log value of CO₂E, and serve as environmental sustainability indicator; $\ln FEC$ is the log value of fossil fuel consumption; $\ln URB$ is log of urbanization, $\ln IGN$ is the log of institutional governance and ϵ , is error term;

By establishing this specific empirical specification, β_2 directly measures the elasticity of carbon emissions relative

to changes in legacy fossil-energy dependencies, while β_3 captures the possible robust institutional governance to act as an environmental abatement tool ($\beta_3 < 0$) within a heavily industrialized transnational enclave.

Empirical strategy

In panel econometric assessments, a series of tests are performed initially as they are critical to ensuring the accuracy of data before the estimation of the main model. After characterizing the data to examine their properties including abnormalities and outliers, the study checks presence of cross-section dependence, to avoid errors, usually common in panel data econometrics, and if not corrected creates grievous consequences, including causing distorted unit root tests results leading to inconsistent estimates (Chudik & Pesaran, 2013; (Sarafidis & Robertson, 2009). In this assessment, we used several LM-based approaches by Breusch-Pagan (1979); Levin *et al.* (2002); Im *et al.* (2003); Pesaran (2004); and Pesaran (2007). If such errors involving cross-section dependence are detected, advanced approaches by Bai and Ng's (2004) and Pesaran (2007) are adopted. These are panel non-stationarity assessments of Idiosyncratic and Common Components (PANIC) and Cross-section Augmented IPS (CIPS), respectively.

In panel data, slope parameters tend to vary because of dynamic and demographic factors. For several years, scholars have presumed slope coefficients to be homogeneous across individual units in panel data modelling. However, in recent panel studies, the slope homogeneity assumption is found as invalid, especially for panel cases with large N and T (Pesaran and Smith, 1995).

We also check variables for their co-integration to firm up the need for long-run estimation of the model, using Westerlund *et al.* (2025). This technique has been proved valid by recent scholars (Addai *et al.*, 2024).

Once integration is detected, long-run equilibrium linkages are assumed to exist in the panel. This research made use of the Pooled Mean Group (PMG) estimator within an Autoregressive Distributed Lag (ARDL) framework, a methodology originally developed by Pesaran *et al.* (1999). The PMG estimator amends for statistical errors arising from cross-sectional heterogeneity and captures the dynamic transitions between short-run and long-run equilibrium deviances, while remaining relevant irrespective of whether the parameters are integrated of order $I(0)$ or $I(1)$. In this regard, long term variables can be interpreted through the natural logarithm form. Thus, the estimated equation alongside cross-sectional average due to unobserved factors is written as in equation 3.

$$y_{it} = \alpha_i + \lambda_i y_{i,t-1} + \beta_{0,i} x_{i,t} + \beta_{1,i} x_{i,t-1} + \sum_{i=0}^{p_i} \delta_{i,1} \hat{z}_{t-1} + e_{i,t} \quad (3)$$

where $z \hat{t} = (y_{t-1}, x_{t-1})$ represents the cross-sectional averages of outcome and predictor variables accordingly. The mean group coefficient can further be assessed as unweighted means of the cross-sectional individual coefficients as in equation 4.

$$\hat{MG} = (\lambda' MG, \beta_0, MG, \beta_1, MG) = \frac{1}{N} \sum_{i=1}^N \pi \quad (4)$$

The long run effect of variable x is defined as:

$$\theta_i = \frac{\beta_{0,i} + \beta_{1,i}}{1 - \lambda_i} \quad (5)$$

Through the PMG within an ARDL model.

Here, $1 - \lambda_i$ is the adjustment speed of the ECM (Lee *et al.*, 1997; Shin *et al.*, 1999). Given that the PMG estimate assumes homogeneity in the long term and heterogeneity in its short term coefficients. The error correction uncertainty of the PMG model is specified as:

$$\Delta z_{it} = \delta_i (y_{it} - x_{it}) + \lambda \sum_{k=1}^p \delta_{ik} \Delta z_{it-k} + \sum_{k=0}^{p-1} \theta_{ik} \Delta z_{it-k} + \sum_{k=0}^{m-1} \alpha_{ik} \Delta x_{it-k} + \epsilon_{it} + \mu_{it} \quad (6)$$

Here, the predicted variable is z, $\delta_i = 0$ denotes the error correction term, $(y_{it} - x_{it})$ represents short to long run co-integration deviances for cross-sectional units, while i signifies 1, 2, 3, 4, ..., n, and t is the time scope of the study.

Furthermore, the vectors $(x_{it-1})'$, $(y_{it-1})'$, (α) , (ρ) and (ϵ_{it}) , represent the long run coefficients, elasticity of the

predicted variable in relation to changes in the predictor variables, factors specific to each economy, short-run coefficients, and the unseen error term.

The fully modified ordinary least square (FMOLS) estimator is further utilized to confirm the strength of our model, since it amends the normal least square model to explain potential serial correlation and endogeneity that may arise in the explanatory variable in the presence of co-integration linkages (Aljebrin, 2012). Moreover, we used the Granger (1969) and non-causality test initially proposed by Dumitrescu & Hurlin (2012) to identify causal connection between variables. This technique averages cross-sectional and heterogeneous units using specific Granger- Wald statistics.

RESULTS AND DISCUSSION

In Table 1, LCO2 is CO2E; LFEC is fossil energy use; LURB is Urbanization population and LIGN is Institutional Governance. The study finds no abnormalities in the data, indicating that further analysis could be conducted to obtain reliable results.

Table 1: Data description.

Description	LCO2	LURB	LFEC	LIGN
Mean	104.9932	21,779559	48.5796	0.974541
Median	105.315	7,629063	45.16068	0.983181
Maximum	128.7	1.08E+08	106.2605	1.333474
Minimum	74.93	1.508438.	1.547716	0.686718
Std. Dev.	16.50995	31.316405	47.09319	0.172461
Skewness	-0.27882	2.081463	0.013353	0.129463
Kurtosis	2.058769	5.927434	1.018052	2.070818
Jarque-Bera	7.67996	74.78576	25.20999	5.970202
Probability	0.021494*	0.000000*	0.000003*	0.050534***
Sum	16168.95	1.51E+10	7481.259	150.0793
Sum Sq. Dev.	41704.51	6.79E+17	339318.6	4.550664

Note: The asterisks (*, and ***) means statistically significant at 1% & 10% accordingly

Table 2: Residual Cross-Section Dependence (CSD) Test.

H0: No CSD (correlation) in residuals			
Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	51.32804	1	0*
Pesaran scaled LM	35.5873		0*
Pesaran CD	7.164359		0*

Note: The asterisk (*) indicates 1% level of significance.

Estimates in the second table (Table 2) implies that H0 of no CSD is discarded at 1% level of significance. Thus second_generation unit root tests are essential in the subsequent assessment (Peseran, 2007).

Table 3: CIPS/CADF Unit Root Test (2nd generation-based).

Variables	CIPS		CADF T-stats	
	I(0)	I(1)	I(0)	I(1)
LCO2	-2.54*	-2.33*	-3.91**	-3.26**
LURB	-2.54***	-2.33***	-3.91***	-3.26***
LFEC	-2.54*	-2.33*	-3.91**	-3.26**
LIGN	-2.54*	-2.33*	-3.91**	-3.26**

Note: The asterisks (*, ** and ***) means statistically significant at 1%, 5%, & 10% accordingly.

Given the significance of the p-values in Table 3, H_0 is discarded at various levels of significance (evident by the number of asterisks). This indicates the panel is non-stationary. Since parameters have a mixed order of

integration, determination of long-run relationships is required using Westerlund 2015 (see results in Table 6). This outcome agrees with Bai and Ng (2004) and Pesaran (2007).

Table 4: BAI & NG (2004) UNIT CD ROOT TEST (2nd generation-based).

Variables	Idiosyncratic Pooled Element		CADF T-stats	
	I(0)	I(1)	I(0)	I(1)
LCO2	4.348*	1.866*	-0.700	2.350***
LURB	0.154	-0.983	-1.645	-1.980*
LFEC	0.316	-1.161	-0.898	-2.782*
LIGN	-0.203	-0.263	-2.773**	-3.026*

Note: The asterisks (*, ** and ***) means statistically significant at 1%, 5%, & 10% accordingly

Given that, the p-values are significant (Table 4), we decline H_0 , which stands for no co-integration at the

statistically significant level of 1% indicating that the panel is non-stationary.

Table 5: Heterogeneity test.

Test/ Variables	LCO2	LURB	LFEC	LIGN
Pettitt test	<0.0001*	<0.0001*	<0.0001*	<0.0001*
SNHT test	<0.0001*	<0.0001*	<0.0001*	<0.0001*
Buishand test	<0.0001*	<0.0001*	<0.0001*	<0.0001*
von Neumann test	<0.0001*	<0.0001*	<0.0001*	<0.0001*

The asterisk (*) means level of statistical significance at 1%.

From Table 5 estimates, given that p-values are less than values ($\alpha=0.05$), H_0 of slope homogeneity is rejected,

indicating the panel is heterogeneous. These outcomes support Campello *et al.* (2019).

Table 6: Westerlund (2015) ECM panel co-integration tests.

Statistics	Value	z-value	p-value	Robust P-value
Gt	-3.572	-5.008	0*	0
Ga	-14.723	-2.677	0*	0
Pt	-10.439	-5.132	0*	0
Pa	-14.014	-4.372	0*	0

Note: The asterisk (*) indicates 1% level of significance

Estimates in Table 6 indicate highly significant probability values of the Ga, Gt, Pa and Pt statistics, and the variables are validly integrated at a 1% statistically significant level,

expressly indicating the future relationship among the variables. This outcome validates findings from Nathaniel *et al.* (2019).

Table 7: PMG estimates of the ARDL model: short & Long-run.

Long run estimates				
Variable	Coefficient	Std.Error	t-Statistic	Prob.*
LIGN	-3.486201	0.809431	-4.306979	0.0004
LURB	9.45E-05	2.47E-05	3.831311	0.0012
LFEC	63.86626	7.868926	8.116262	0.0000
R-squared	0.982244	Mean dependent var		126.2750
Short-run estimates				
Variable	Coefficient	Std.Error	t-Statistic	Prob.*
LIGN	-28.6814	21.4277	-1.339	0.183
LURB	3.97E-05	3.72E-05	1.0666	0.2881
LFEC	32.08493	32.0768	1.0003	0.319
Cointeq01	-0.0239	0.01415	-1.689	0.0936

Note: The asterisks (*, ** and ***) means statistically significant at 1%, 5%, & 10% accordingly

The long-run PMG outcomes of the ARDL model (Table 7) suggest: (i) institutional improvements reduce LCO2 emissions by 34.86%. (ii) However, the results indicate any unit rise in LURB causes an increase in LCO2 by 9.45E-05%; while in the same manner, a unit increase in LFEC indicates a rise in LCO2 emissions by 63.87%. These findings support Addai *et al.* (2022) who claims that in the entire Eastern Europe, laxities in regulatory quality have offered unscrupulous investors the opportunity to degrade the region, but tight regulatory policies have always yielded favourable environmental outcomes.

These outcomes imply that institutional governance has significant long-run negative effects on environmental degradation in the economies across the Black Triangle. Policy makers across the region could consider investments into strengthening regulatory institutions to reap the benefits of the environmental quality of the region. Given that Germany, Poland and Czech Republic are associated with environmental pollution in the Black Triangular region institutional measures across the region in the context of abundant natural resources, mineral deposits and industrial development are critical for ensuring sustainable regional environmental quality.

Similarly, given the positive effects of urbanization on CO2E in the PMG long run estimates of the ARDL model (Table 7), policy must promote renewable energy use in urban settings. These results confirm our hypothesis for this study and equally align with Addai *et al.* (2022) and Ali & Kirikkaleli (2022). With these outcomes, new policy insights could be drawn for both the Black Triangle member countries and other emerging countries where institutional governance is a necessity for attaining sustainable urban living and improving urban area good corporate environmental behavior. Corporations across the municipalities in the entire Black Sea region could ensure renewable energy use or utilization electric

vehicles towards improving on their environmental footprints. This corporate sustainability footprint could be spearheaded by regional governments and anchored in their environmental policies.

Further, from the PMG long run outcome of the ARDL model, any unit increase in LFEC culminates in whopping rise in LCO2 emissions by 63.87%. %. The implication is that across the region, the need to prioritize green innovations and research is very crucial. Theoretically, development of green innovations result in consumption of green products and production of green technologies. It is relevant to argue that the rise in LCO2 emissions over the long term does not align with the EKC hypothesis (Pata, 2018). This findings validates the claim that environmental issues and the level of affluence in the urban space are linked as explained by the urban transition theory (Marcotullio and Lee, 2003). The finding also corroborates Jones (1991) whose empirical study, indicated relations between urbanization and energy consumption.

Furthermore, it is instructive to observe that, a unit rise in LURB causes increases in LCO2 by 9.45E-05% in the PMG long run outcomes of the ARDL model. This implies that the more people run to cities across the Black Triangular region, the more they become reliant on fossil-based transport systems. Given that such a factor causes environmental degradation, policy measures could include ensuring corresponding rise of green innovation in the transport system. For example, governments could implement deliberate policies to introduce electric vehicle use, or introduce energy productivity behavior by both resident individuals and corporations. Additionally, government can implement specifically focused policies to send heavy industrial businesses away from the region to reduce the rate of pollution, material use and environmental degradation across the region.

Table 8: Robustness test

Method: Fully Modified Least Squares (FMOLS)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
LIGN	-3.535414	0.532312	-6.641619	0.0000*
LURB	0.000105	1.64E-05	6.414737	0.0000*
LFEC	64.73998	6.009847	10.77232	0.0000*
R-squared	0.960306	Mean dependent var		126.5762
Adjusted R-squared	0.934621	S.D. dependent var		1.493898
S.E. of regression	0.381978	Sum squared resid		2.480425
Long-run variance	0.058652			

Note: The asterisk (*) means statistically significant at 1%

Outcomes of the FMOLS estimates (Table 8) revealed an R-squared value of 0.960. This implies that 96% of changes in the outcome variable can be accounted for by the predictor variables, indicating that the PMG of the ARDL model is robust. We find this outcome aligns with Erdogan *et al.* (2020). By this test, we can infer that there is very limited on no potential biases in individual economies, which can influence the outcomes of the

estimated model. This assures the reliability of outcomes for policy insights.

Outcomes of the D-H causality test (Table 9) suggest that: (i) LURB unidirectionally causes LCO2, and (ii) LFEC has a unidirectional causal effect on LIGN without a feedback effect. The test aligns with Candelon *et al.* (2013).

Table 9: Causality outcome.

H0:	W-Stat.	Zbar-Stat.	Prob.
LURB $\neq$ LCO2	13.3265	2.03569	0.0418*
LFEC $\neq$ LIGN	15.2907	2.69528	0.007*

Note: The asterisks (*, ** and ***) means statistically significant at 1%, 5%, & 10% accordingly, while $\neq$ means does not homogeneously cause & H0 represents the Null Hypothesis.

Outcomes of the D-H causality test (Table 9) suggest that: (i) LURB unidirectionally causes LCO2, and (ii) LFEC has a unidirectional causal effect on LIGN without a feedback effect. The test aligns with Candelon *et al.* (2013).

CONCLUSION

This study evaluates the relationships between institutional governance, urban migration, fossil energy consumption, and carbon emissions across the Black Triangle enclave (Germany, Poland, and the Czech Republic) using data from 1998Q4 to 2021Q4. PMG and D-H causality estimates demonstrate that institutional improvements reduce CO2 emissions by 34.86%, whereas urbanization and fossil energy consumption drive up emissions. Unidirectional causality runs from urbanization to emissions and from fossil fuel consumption to institutional governance.

To mitigate environmental degradation and safeguard regional biodiversity, Germany, Poland, and the Czech Republic must enforce strict regulatory standards, improve compliance monitoring, and invest heavily in green innovation, cleaner energy, and smart transportation systems. Additionally, training stokers across heating systems offers an immediate path to reducing coal-based emissions.

While using national-level data as a proxy was necessary due to data scarcity in this cross-border region, future research should utilize localized datasets and comparative multi-region frameworks to further validate and refine these policy insights.

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