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Original Research

DETERMINANTS OF CO_2 EMISSIONS IN CENTRAL AND EASTERN EUROPE: AN EMPIRICAL PANEL DATA ANALYSIS

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Abstract: This paper investigates the impact of GDP growth, regulatory quality, electricity consumption, human development, and research and development (R&D) expenditures on carbon dioxide emissions (CO_2) in 15 Central and Eastern European (CEE) countries over the period 2002–2020. A three-step empirical strategy is employed, beginning with the specification of a panel data model, followed by diagnostic testing of model residuals, and concluding with the application of multiple panel estimators to ensure robustness of the results. The findings reveal that, with the exception of the Human Development Index (HDI), all other variables show statistically significant associations with CO_2 emissions. In particular, real GDP per capita growth has a strong and consistent positive effect: a one-percentage-point increase in GDP per capita is associated with a rise in CO_2 emissions per capita by approximately 0.3 to 0.35 tons. These results underscore the environmental cost of economic expansion in the region and highlight the critical role of regulatory quality and R&D in designing effective mitigation strategies. The paper contributes to the literature by providing a comprehensive, data-driven assessment of emission determinants in emerging European economies and offers valuable insights for policymakers aiming to align economic growth with environmental sustainability.

Keywords: CO_2 emissions, Central and Eastern European countries, environmental costs, economic expansion, effective mitigation strategies.

1. INTRODUCTION

Climate change stands as one of the most significant global threats of our time (Wang et al., 2018; Claudelin et al., 2020; Bouman et al., 2020). The increasing pace of environmental

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degradation, largely driven by human activity and growing energy demands, has placed mounting pressure on governments to develop effective environmental strategies (Zeiger et al., 2019; Akhter et al., 2020). The rising concentration of carbon dioxide (CO_2) and other greenhouse gases (now well above pre-industrial levels) has sparked serious concerns about the potential for long-term and possibly irreversible ecological damage. Current projections suggest a global temperature increase of at least 1.5°C by the century's end, a scenario that presents serious environmental and socio-economic risks (Valone, 2021; Baek, 2015; Laverde-Rojas et al., 2021).

Despite growing awareness and global efforts, many low- and middle-income countries continue to depend on conventional energy systems, particularly those based on coal, which remains one of the most carbon-intensive sources (Ptak, 2014; Lin et al., 2022; Mahalik et al., 2022). These economies face the dual challenge of pursuing development and poverty reduction, while also needing to limit their environmental footprint (Santos & Forte, 2021; Cansino et al., 2021). The situation is particularly complex because while economic progress is essential for improving quality of life, it often contributes to higher emissions, creating a tension between growth and sustainability.

However, economic development can also open opportunities for environmental improvements. Increased wealth can support the implementation of cleaner technologies and promote knowledge sharing among neighboring countries (Bumpus & Comello, 2017). Additionally, economies undergoing structural transformation (from heavy industry toward less resource-intensive sectors and service-oriented industries) may see a decline in pollution intensity. Romero et al. (2021) has found that industries based on medium and high technology tend to produce fewer emissions compared to those involved in raw material extraction or basic goods production. These structural and technological shifts are seen as vital for achieving a balance between continued economic advancement and environmental preservation.

In this context, regulatory quality plays a pivotal role in steering economies toward sustainable pathways, as stronger institutions are more capable of enforcing environmental standards and guiding investment toward cleaner sectors (Boateng et al., 2024; Kashif et al., 2024). Similarly, improvements in human development (reflected in better education, health, and living standards) can raise public awareness of environmental issues and promote behavioral shifts that reduce ecological footprints (Patel et al., 2024; Khan et al., 2023). Furthermore, investment in research and development (R&D) fosters innovation in energy efficiency, renewable energy technologies, and low-carbon solutions, all of which are crucial for reducing CO_2 emissions without compromising economic growth (Bilgili et al., 2024; Saia, 2023).

Given the persistent reliance on fossil fuels, some experts argue that in addition to transitioning to renewable energy sources (RES), it is critical to invest in technologies capable of capturing and storing carbon before it reaches the atmosphere (Simionescu et al., 2022). Although these technologies remain costly, future advancements may improve their feasibility, particularly for nations with fewer financial resources.

In light of these challenges, identifying the most influential factors affecting CO_2 emissions is vital for shaping effective environmental and economic policies. Previous studies have highlighted several key variables, such as economic growth, institutional quality, energy usage patterns, levels of human development, and investment in research and development, as central to understanding the dynamics of emissions.

This study focuses on analyzing how GDP growth, regulatory quality, electricity consumption, human development, and R&D spending have influenced carbon dioxide emissions across 15 Central and Eastern European (CEE) countries between 2002 and 2020. The novelty of this paper lies in its comprehensive econometric investigation of the key drivers of CO_2 emissions. While existing literature has often explored these variables in isolation or limited combinations, this study offers an integrated framework that captures both economic and institutional dimensions influencing environmental outcomes. Furthermore, the paper contributes methodologically by employing a three-step empirical strategy. It begins with the specification of a panel data model linking CO_2 emissions to the selected explanatory variables. It then proceeds with a rigorous examination of model residuals to detect potential estimation issues—particularly violations of assumptions such as error independence, homoscedasticity, and exogeneity. Finally, the study enhances the robustness and credibility of its findings by applying multiple panel estimators tailored to the data structure and statistical properties identified. This meticulous approach ensures that the results are not only statistically sound but also policy-relevant, making a meaningful contribution to the empirical literature on sustainable development and environmental governance in emerging European economies.

2. LITERATURE REVIEW

Understanding the factors influencing CO_2 emissions is crucial for designing effective environmental and economic policies. Numerous studies have explored the dynamic relationship between CO_2 emissions and variables such as human development, electricity consumption, regulatory quality, economic growth, and R&D expenditures. These factors interact in complex ways, often producing varying effects across different income groups, regions, and institutional contexts.

Developing economies increasingly view green technologies and renewable energy as viable development paths, balancing economic growth with environmental preservation. Environmental taxes serve as effective tools in reducing carbon emissions and promoting sustainable development (Wolde-Rufael & Mulat-Weldemeskel, 2023). However, a comprehensive approach should go beyond taxation to include R&D investment, particularly in the energy sector, to foster innovation and support carbon mitigation strategies (Guzowska et al., 2021). Empirical studies confirm the critical role of R&D in reducing emissions. For instance, Fernández et al. (2018) found that R&D spending significantly contributes to CO_2 emissions reduction in developed countries, while increased energy consumption correlates with rising emissions. Similarly, Tamazian and Rao (2010) also report that increased R&D efforts help mitigate environmental pollution.

Still, the effectiveness of R&D varies. Garrone and Grilli (2010) highlight that while public R&D spending improves energy efficiency, it has limited impact on emission intensity and the carbonization factor, underscoring that R&D alone may not suffice. Kahouli (2018) further emphasizes complex interdependencies among R&D, CO_2 emissions, electricity consumption, and economic growth in Mediterranean countries, identifying unidirectional causality from R&D to emissions and growth. This suggests that R&D drives environmental improvements, albeit within interconnected systems.

Despite its importance, green innovation remains less attractive to private firms due to limited immediate returns, necessitating strong governmental support (Ullah et al., 2023). Lee and Lee (2013) underline the strategic importance of energy R&D for industry competitiveness and the transition away from fossil fuels. This is echoed by Siddiqui and Fleten (2010), who argue that significant investment is required to meet rising energy demands through innovative technologies. In addition, Dmytrenko et al. (2024) found that while environmental policy stringency has varied effects across Europe, R&D expenditure consistently emerges as the most influential factor in reducing greenhouse gas emissions.

In addition to R&D efforts, the role of human development in influencing CO_2 emissions has gained increasing attention in recent empirical studies. Li and Ouyang (2019), examining China from 1978 to 2015, found an inverted N-shaped relationship between human capital and CO_2 emissions. This suggests that initial improvements in human capital can temporarily increase emissions due to intensified resource use, while long-term effects become beneficial through enhanced efficiency and reduced emission intensity. Similarly, Sezgin et al. (2021) confirmed that in G7 and BRICS countries, human development (alongside stringent environmental policies) contributes to lowering emissions over time. Notably, bilateral causality between human development and CO_2 emissions was identified for countries like Germany, Japan, the UK, and the US, highlighting dynamic interactions.

Khan (2020) emphasized the threshold effect of human capital, arguing that at early development stages, more education may increase pollution, but once a critical level is reached, it fosters environmental awareness and adoption of cleaner technologies. This conditional relationship was validated across 122 countries over the 1980–2014 period. However, not all studies agree. Earlier works by Gangadharan and Valenzuela (2001) and Cole et al. (2005) found that human capital could exacerbate emissions, pointing to varying contextual effects.

Recent findings by Patel et al. (2024) further support these patterns. While high-income countries have used human development to curb emissions, low-income countries still face a U-shaped trajectory, where initial HDI growth increases emissions. Hao (2022) and Opoku et al. (2022) observed that HDI positively influences environmental sustainability in advanced economies. Supporting this, Xu et al. (2024) showed that countries with higher HDI levels have experienced declining per capita emissions. Chen et al. (2022) emphasize that strategic investment in human capital and eco-innovations remains crucial for long-term emission reductions and achieving sustainability goals.

Electricity consumption emerges as another critical factor influencing CO_2 emissions, with effects that vary across countries and contexts. Kwakwa (2021) confirmed the Environmental Kuznets Curve (EKC) hypothesis for Ghana, finding that while electricity consumption itself has an insignificant effect, power crises notably increase CO_2 emissions, highlighting the indirect role of energy reliability. In the Middle East, Al-Mulali and Che Sab (2018) identified a bidirectional Granger causality between electricity consumption, CO_2 emissions, and economic growth, underlining the central role electricity plays in economic activities and environmental outcomes in the region.

In Cameroon, multiple studies affirm a positive linkage between electricity use and emissions. Njoke et al. (2019) reported significant short- and long-run relationships between electricity consumption and CO_2 emissions using ARDL bounds testing. Similarly, Hilaire et al. (2014) found that increases in electricity consumption, urbanization, and economic growth all contribute positively to emissions.

Sectoral perspectives add further nuance. Çıtak et al. (2021), analyzing the Turkish context, found that the relationship between electricity consumption and emissions is not uniform across sectors. While industrial electricity use shows a positive but modest impact, commercial and public service sectors contribute significantly to emissions, whereas residential and transport electricity usage showed minimal effects.

In Kuwait, Salahuddin et al. (2018) observed a consistent positive relationship in both the short and long run between electricity consumption and CO_2 emissions. Conversely, Ahmad et al. (2017) found a negative association in Croatia, suggesting the potential role of clean energy in decoupling electricity use from environmental harm. Supporting these mixed results, Rahaman et al. (2022) identified electricity consumption, alongside FDI and economic growth, as a significant driver of emissions in Bangladesh. Likewise, Salahuddin et al. (2015) confirmed a strong emission-inducing role of electricity use in GCC countries.

The empirical results of Bashir et al. (2022) indicate that transitioning from a carbon-intensive economic growth model to another based on high-tech and renewable energy consumption is critical for overcoming environmental issues and climate change goals. It remains to be seen how emerging economies will find ways to strive without generating more carbon emissions. As the primary and manufacturing sectors are still important for these countries, their investment attractiveness may be determined by a less strict regulatory environment with broader pollution limits (Santos & Forte, 2021; Cansino et al., 2021), transforming the lack of environmental protection regulations into comparative environmental advantages. On the positive side, economic growth would make it possible to devote more resources for the adoption of cleaner technologies (Bumpus & Comello, 2017), as well as technological learning processes in neighbouring economies.

Recent literature highlights the crucial role of regulatory quality in achieving environmental sustainability, particularly in the context of reducing CO_2 emissions. Addai et al. (2023), examining Eastern European countries from 1998Q4 to 2017Q4, confirmed a long-run relationship between regulatory quality and environmental sustainability. Their findings emphasize that stronger regulatory frameworks significantly contribute to environmental improvements by curbing fossil fuel use and mitigating unsustainable development.

In the African context, Kwakwa and Aboagye (2024) analyzed data from 32 countries and found that robust regulatory quality, coupled with effective anti-corruption measures and institutional transparency, weakens the positive impact of natural resource consumption on CO_2 emissions. This suggests that well-designed regulations can offset some of the environmental damage associated with natural resource exploitation.

Similarly, Boateng et al. (2023), using data from 63 industrialized countries and system GMM estimation, demonstrated that multiple dimensions of institutional quality—particularly regulatory stringency, licensing procedures, and administrative controls—play a decisive role in reducing carbon emissions. The study reveals that stringent regulations, such as licensing restrictions, have both immediate and sustained positive environmental outcomes.

Contrasting findings emerge in the case of BRICS nations. Adedoyin et al. (2020) observed that while coal rents negatively influence CO_2 emissions, regulations like carbon damage costs paradoxically increase them. This points to the necessity of reinforcing regulatory frameworks if these economies are to align their growth trajectories with low-carbon development.

From a governance perspective, Mahmood et al. (2022) found that regulatory quality and rule of law significantly reduce CO_2 emissions across four South Asian economies, even when accounting for renewable energy and income levels. Likewise, Khan and Rana (2021), and Haldar and Sethi (2021), confirmed that institutional quality contributes to lower emissions by influencing both economic activity and energy consumption behavior in Asian and developing countries.

In summary, the literature consistently emphasizes the complex and interrelated effects of economic growth, human development, electricity consumption, regulatory quality, and R&D expenditures on CO_2 emissions. While economic growth is often linked to higher emissions, its environmental impact can be mitigated by improved human capital, cleaner energy use, and stringent regulatory frameworks. Additionally, R&D expenditures contribute to emissions reduction by fostering innovation and advancing eco-friendly technologies.

3. DATA AND METHODOLOGY

Following the theoretical discussion and literature overview, we proposed the empirical methodology to examine econometrically our research questions, which comprises three steps. First, the econometrical panel model that puts CO2 emission in relation to the set of our key explanatory variables were specified. Second, the characteristics of model residuals to get insight into possible estimation issues were examined. Finally, the empirical model using several panel estimators with respect to the characteristics of our data to ensure the reliability of estimates was estimated.

The specified model reads as:

$$CO2_{it} = \beta_0 CO2_{it-1} + \beta_1 GDP_{it} + \beta_2 RQ_{it} + \beta_3 ELFC_{it} + \beta_4 HDI_{it} + \beta_5 RDE_{it} + u_{it} \quad (1)$$

Where
$CO2_{it}$ is CO2 tons per capita;
GDP_{it} is GDP per capita real growth (%);
RQ_{it} is an indicator of regulatory quality from the World Bank WGI database;
$ELFC_{it}$ is growth in electricity consumption (%);
HDI_{it} is change in human development index (%);
RDE_{it} is the research and development expenditures (% of GDP);
u_{it} is a model error.

In the specified model, each variable serves as a proxy for a key economic or institutional factor influencing CO_2 emissions. GDP per capita real growth is used as a proxy for economic expansion, reflecting the pace of development in each country. Regulatory quality, drawn from the World Bank's Worldwide Governance Indicators, captures the institutional and policy environment, indicating the effectiveness of regulations relevant to environmental governance. Electricity consumption growth represents energy use intensity, serving as a proxy for the reliance on electricity as a driver of economic activity. Human Development Index change is used to reflect broader socioeconomic progress, encompassing education, health, and living standards. Lastly, research and development expenditures, expressed as a percentage of GDP, serve as a proxy for technological innovation and investment in eco-friendly solutions. These variables collectively aim to capture the multifaceted drivers of carbon emissions across the CEE region.

To examine the linkages between CO_2 emissions and selected variables, this study utilizes panel data for 15 Central and Eastern European (CEE) countries (Belarus, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, North Macedonia, Poland, Romania, Serbia, Slovakia, Slovenia, and Ukraine) for the period 2002–2020. Analysing these countries is particularly important given their shared post-transition economic structures, increasing environmental pressures, and integration processes with the European Union. The selected period captures significant economic, regulatory, and technological changes, allowing for a comprehensive assessment of the long-term trends and policy impacts on environmental sustainability.

In addition, the characteristics of model residuals are examined to figure out a proper estimation approach. It is common knowledge that OLS-based estimators require IID distributed errors and exogenous regressors to provide reliable estimates. In the case of panel data modelling, it is typically assumed that model errors are composite, i.e., that model errors can be decomposed into individual effects that capture time-invariant specifics of the panel units ν_i and disturbances ε_{it}that follows IID process, $u_{it} = \nu_i + \varepsilon_{it}$. However, when macroeconomic data are modelled, the assumption on IID distributed disturbances typically appears too strong. Therefore, analysis begins with the most general set of assumptions that model error is composite and model disturbances are heteroskedastic, autocorrelated and cross-sectionally dependent and then tested each of these assumptions. To this end, the LSDV model with country dummy variables is estimated and test if they are significant variables. Then, the Hausman test is applied to check if individual effects are fixed or random. Eventually, a set of residual tests is used to examine characteristics of the stochastic process that generates disturbances. The results of the tests are presented in Table 1.

Table 1. Tests of the panel model errors' characteristics

Test	**Null**	**Statistics**
Individual effects	All individual effects are equal to zero	F(13,232) =2.02**
Hausman test	The difference in coefficients is not systematic	chi2(6)=22.14***
Heteroskedasticity (Modified Wald)	All residual variances are equal	chi2 (14)=1933.72***
Autocorrelation (Wooldridge)	Residuals are not first-order autocorrelated	F(1,13) =21.050***
CSD dependency Breusch-Pagan LM test	Residuals are not cross-sectionally correlated	chi2(91) =88.111
CSD dependency Pesaran	Residuals are not cross-sectionally correlated	z=1.034

Note: *** indicates a 1% significance level.

The result of the F-test on the significance of country dummy variables indicates that individual effects are significant; therefore, the assumption on composite model error is valid. The nature of individual effects in macroeconomic panel models with countries as panel units are typically found to be fixed; as implied by the Hausman test, this is also the case in our model. The results of Wald (Greene, 2000) and Wooldridge (Wooldridge, 2002) tests validate assumptions on heteroskedastic and autocorrelated residuals, as expected. On the other hand, residuals seem to be not cross-sectionally correlated, which opposed intuitive expectations about cross-sectional panel dependency between the countries that belong to certain economic and geographic regions. However, the lack of cross-sectional dependency is robustly indicated by both the Breusch-Pagan LM (Greene, 2000) and Pesaran tests (Pesaran, 2004).

Summarizing findings from tests in Table 1, it appears that model errors are composed of fixed individual effects and heteroskedastic and autocorrelated disturbances. A proper estimation of the panel model, when OLS assumptions on residuals are not valid, is a challenging task, since all panel estimators proposed in the literature have some pros and cons. When fixed effects are present within the model error, the benchmark estimator is an OLS-based fixed effects estimator (FE OLS). The major advantage of the FE OLS estimator is that it produces a consistent estimate of regression coefficients as long as model disturbances are not correlated to the regressors, even in cases where individual effects are correlated with regressors (Wooldridge, 2002). The other advantage is that in cases when model disturbances are heteroskedastic and autocorrelated but not cross-sectionally dependent, the reliability of the inference on the significance of regression coefficients can be simply improved by using generalized Huber-Eicker-White (HEW) corrected residuals (robust to heteroskedasticity and correlation within panel units). The alternative LS-based estimator to FE is the Feasible Generalized Least Square estimator (FGLS), which also produced estimates of residuals robust to heteroskedasticity and autocorrelation. While theoretically more plausible, FGLS seems to lose the reliability of estimation if T is not considerably higher than N dimension of the panel data in the sample (Beck & Katz, 1995).

The main shortcoming of the FE OLS estimator is possible endogeinity issues in the estimation of dynamic panel models when the first lag of the dependent variable is included in the model, which undermines the reliability of the estimates; this issue is known as Nickel bias (Nickell, 1981). However, Nickel bias turns out to be considerable only in cases of "short" panels, i.e., panels in which the T dimension of the panel is very small; increasing T reduces the bias of OLS estimates (Baum, 2013). Since this model is specified in dynamic form, GMM-based estimators are considered as an alternative to LS-based estimators to get insight into the reliability of LS-based estimates. More specifically, Difference (Arellano & Bond, 1991) DIF GMM and System (Arellano & Bover, 1995; Blundell & Bond, 1998) SYS GMM estimators are used in addition to FE OLS and FGLS. The GMM-based estimators utilize moment conditions to estimate the regression coefficient using the lags of endogenous variables (the first differences and/or levels) as the internal instruments; in the case of DIF GMM, moment conditions are set only for model equation specified in the first differences, while in SYS GMM moment conditions are set for both model equations in difference and level terms. The main advantage of GMM-based estimators over LS is purging endogeneity from the model, while the main drawback is that lags of endogenous variables might be weak instruments. For further discussion on conditions in which GMM-based estimators outperform LS-based estimators, and the pros and cons of DIF GMM vis-à-vis SYS GMM, see, for example, Roodman (2007, 2009) or Li et al. (2021).

4. RESULTS AND DISCUSSION

In line with the methodological discussion, the appropriate model is estimated using four different estimators: FE OLS, FGLS, AB GMM and SYS GMM. In the case of FE OLS estimation, residuals are HEW corrected to address heteroskedasticity and autocorrelation of the residuals. Regarding FGLS, individual effects are removed using country dummies. In order to avoid issues of too many moment conditions, number of dependent variable lags being used as instruments in GMM estimation are collapsed and limited.

The obtained results are presented in the Table 2.

Table 2. Results of the defined model

Variable	**FE OLS**	**FGLS**	**AB GMM**	**SYS GMM**
CO2 (t-1)	0.8240*** (0.0522)	0.8598*** (0.0257)	0.7994*** (0.1294)	0.7827*** (0.1280)
GDP	0.3288*** (0.0989)	0.3519*** (0.0839)	0.3153*** (0.1109)	0.2921** (0.1290)
RQ	-0.0287** (0.0099)	-0.0235 (0.0149)	-0.0678*** (0.0243)	-0.0816*** (0.0259)
ELFC	0.7753*** (0.1286)	0.7296*** (0.0857)	0.8769*** (0.2009)	0.8804*** (0.2018)
HDI	0.9360 (0.8879)	0.2884 (0.5484)	0.7358 (1.2454)	1.0003 (1.1760)
RDE	-0.0333*** (0.0104)	-0.0329*** (0.0104)	-0.0898* (0.0475)	-0.0861* (0.0499)
AR(2) test Sargan test Hansen test			-1.33 3.69 3.85	-1.33 5.07 4.91

Note: *** indicates a 1% significance level; ** indicates a 5% significance level; and * indicates a 10% significance level.

The empirical results confirm that economic growth in CEE countries is significantly associated with increased CO_2 emissions, indicating that their development pathways remain heavily dependent on carbon-intensive activities. This is consistent with the findings of Bashir et al. (2022), who emphasized that growth driven by traditional industrial and energy sectors leads to environmental degradation. These results are in line with studies such as Salahuddin et al. (2015), Al-Mulali and Che Sab (2018), and Rahaman et al. (2022), which found a strong positive relationship between economic activity and emissions in emerging and energy-dependent economies.

Similarly, electricity consumption exerts a positive and statistically significant influence on CO_2 emissions, underscoring the continued reliance on non-renewable energy sources across the region. These findings are aligned with the results of Njoke et al. (2019), Hilaire et al. (2014), and Salahuddin et al. (2018), who reported similar outcomes in developing and fossil-fuel-dominated energy markets. They also confirm earlier evidence from sectoral analyses like those by Çıtak et al. (2021), indicating that electricity use (particularly in the industrial and public sectors) contributes significantly to environmental degradation. On the other hand, they diverge from studies such as Ahmad et al. (2017), which showed a negative correlation between electricity use and emissions in Croatia, where a higher share of renewable energy in the electricity mix may have altered the outcome.

In contrast, regulatory quality is shown to significantly reduce CO_2 emissions, supporting the argument that strong institutional and governance structures play a key role in promoting environmental sustainability. This aligns with the findings of Addai et al. (2023), Mahmood et al. (2022), and Boateng et al. (2023), who emphasized the importance of effective regulations and transparency in achieving environmental goals. These results indicate that, even in transitional economies, robust regulatory frameworks can help limit fossil fuel dependency and enforce environmentally responsible practices. However, they are at odds with studies such as Adedoyin et al. (2020), which identified counterproductive regulatory effects in some BRICS countries, suggesting that policy effectiveness may vary depending on implementation quality and broader governance context.

Furthermore, R&D expenditures exert a negative and significant effect on CO_2 emissions, highlighting the important role of innovation and technology development in environmental protection. This outcome supports the findings of Fernández et al. (2018), Tamazian and Rao (2010), and Dmytrenko et al. (2024), who identified R&D investment—particularly in the energy sector—as a key driver of emissions reduction. It also reinforces the arguments by Lee and Lee (2013) and Siddiqui and Fleten (2010), who stressed the strategic role of R&D in facilitating the shift away from fossil fuels. Nonetheless, the results contradict Garrone and Grilli (2010), who questioned the efficacy of public R&D in reducing emission intensity, indicating that in CEE countries, innovation policies may be relatively well-aligned with environmental goals.

Unlike the other variables, human development does not show a statistically significant relationship with CO_2 emissions in the context of CEE countries. This may suggest that improvements in education, health, and income have yet to translate into environmental awareness or the adoption of sustainable consumption patterns. While this result contrasts with Sezgin et al. (2021), Li and Ouyang (2019), and Xu et al. (2024), who identified various shapes of the relationship between human development and emissions, it is partially consistent with earlier findings from Cole et al. (2005) and Gangadharan and Valenzuela (2001), who emphasized that the environmental impact of human capital is highly context-dependent. It also supports the idea of a threshold effect (Khan, 2020), where the environmental benefits of human development may emerge only beyond a certain maturity level, which some CEE countries may not have yet reached.

5. CONCLUSION

This study assessed the effects of economic growth, human development, electricity consumption, regulatory quality, and R&D expenditures on CO_2 emissions in Central and Eastern European countries. The results indicate that economic growth and electricity consumption significantly increase emissions, pointing to persistent reliance on carbon-intensive practices. Conversely, regulatory quality and R&D expenditures are found to reduce emissions, underlining the importance of institutional governance and innovation in environmental protection. Human development, however, showed no significant impact, suggesting that its environmental benefits have yet to materialize in the region's current developmental context.

Theoretically, the findings contribute to the broader environmental economics literature by validating the Environmental Kuznets Curve in part, while emphasizing the need to incorporate governance and innovation factors into empirical models of emissions. The observed variation in impacts across variables supports multidimensional explanations for environmental performance and highlights the limitations of purely growth-based or human development-centered models in explaining emissions in transitional economies.

In terms of practical implications, the study suggests that policymakers in CEE countries should direct attention toward strengthening regulatory institutions and boosting investment in green R&D to mitigate emissions. Reliance on economic expansion and increased electricity use without structural transformation will only exacerbate environmental pressures. Integrating sustainability objectives into education and public awareness campaigns may help amplify the long-term environmental benefits of human development, while improving energy efficiency and diversifying the energy mix is essential for managing the carbon intensity of electricity consumption.

Despite offering important insights, the study has certain limitations. The use of aggregated panel data masks potential heterogeneity across countries and sectors. Moreover, the exclusion of key variables such as renewable energy usage, trade-related emissions, and environmental policy stringency limits the ability to capture the full complexity of the emissions drivers. The time horizon and data availability constraints also affect the interpretation of causality and long-term effects.

Future research should address these limitations by incorporating country-specific and sector-specific analyses, as well as a broader set of environmental and technological indicators. Disaggregating the effects of different types of R&D and regulatory instruments could further clarify their roles. Longitudinal case studies and dynamic panel approaches would allow for a deeper understanding of how institutional and innovation factors interact with economic and social development to shape environmental outcomes in the long run.

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