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Fossil Fuel CO_2 Emissions and Economic Growth in the Visegrád Region: A Study Based on the Environmental Kuznets Curve Hypothesis

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Abstract: The relationship between fossil fuel CO_2 emissions and economic growth in the Visegrád (V4) countries (Czechia, Hungary, Poland, and Slovakia) is examined through the lens of the environmental Kuznets curve (EKC) hypothesis. Employing the modified environmental Kuznets curve (MEKC) hypothesis, time-series data from 2010 to 2022 were analyzed. The methodology encompasses a range of econometric techniques, including temporal, comparative, correlational, and regression analyses, to unravel the intricate relationship between economic development (measured by GDP per capita) and environmental pollution (CO_2 emissions). Results reveal a complex nonlinear correlation between GDP per capita and CO_2 emissions in the V4 countries, following an inverted U-shaped pattern. Specifically, Czechia and Hungary exhibited peak emissions at approximately USD 5000 and USD 4500 GDP per capita, respectively, with corresponding emission levels of 1.15 and 0.64 metric tons. In contrast, Slovakia's emissions decreased after its GDP per capita exceeded USD 5000 and carbon dioxide emissions reached 0.15 metric tons. However, Poland's data deviate from the MEKC pattern, exhibiting a consistent rise in CO_2 emissions across all levels of GDP per capita. The study highlights that the power industry is the largest source of CO_2 emissions in all four countries, contributing 88.09% of total emissions. The transportation and industrial combustion sectors account for about 2.12% and 1.28% of annual emissions, respectively. GDP–CO_2 emission correlations vary across the V4 countries. While Czechia exhibits a positive correlation of 0.35, Hungary (−0.37), Poland (−0.21), and Slovakia (−0.11) display negative relationships. Notably, Poland experiences the most significant increase in CO_2 emissions from both road transport and air traffic. The conclusions drawn from this study provide a robust foundation for developing tailored environmental policies that support sustainable growth in the Visegrád region and other transitioning economies.

Keywords: carbon emissions; modified environmental Kuznets curve; environmental impact; fossil fuel combustion; pollution–income relationship; V4 countries

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1. Introduction

Economic development is a crucial objective for nations worldwide, but protecting the health of the environment often presents a major concern in terms of the increasing carbon dioxide (CO_2) emissions. Balancing economic growth with the mitigation of CO_2 emissions is a pressing concern, as evidenced by the increasing focus on sustainable development [1]. Consequently, global leaders face a significant challenge in harmonizing economic advancement with environmental preservation. This acknowledges that unchecked economic activity can exacerbate pollution and contribute to climate change [2].

Economic growth is essential for every nation, but it must be achieved without exacerbating environmental pollution and rises in temperature. In this context, regional cooperation can play a crucial role. For instance, the Visegrád (V4) group, comprising Czechia, Hungary, Poland, and Slovakia, was formed in 1991 to enhance cooperation and mutual support in economic, political, and security matters [3–6]. Despite their distinct historical, cultural, and socioeconomic backgrounds, these V4 nations have a common goal of fostering economic development while ensuring environmental sustainability. This strategic alliance enables them to share resources, knowledge, and technology, thereby strengthening their collective efforts in achieving a greener and more prosperous future.

Environmental degradation, particularly from fossil fuel carbon dioxide ($FFCO_2$) emissions, has become increasingly prominent as a byproduct for the environment of economic prosperity. Moreover, the intricate relationship between economic growth, measured by gross domestic product (GDP), and CO_2 emissions has been a central theme in discussions of environmental, economic, and sustainable development. Numerous scholars have proposed diverse supervisory frameworks and conducted extensive research to comprehend the complex nature and multifaceted impacts of this dynamic.

Furthermore, the environmental Kuznets curve (EKC) hypothesis is a concept that has been significantly enhanced through extensive research on environmental and economic factors. However, empirical studies incorporating diverse environmental indicators and economic variables have refined and strengthened the EKC hypothesis. These studies provide valuable insights for shaping sustainable development strategies and informed environmental policies [7]. In addition, the EKC theory suggests an inverted U-shaped relationship between the natural rise of income (as measured by GDP) and environmental pollution (as measured by $FFCO_2$) [8]. The theory suggests that early stages of economic development typically coincide with higher pollution levels. The rapid pace of national economic growth has been accompanied by a corresponding increase in environmental concerns. This has led to a greater emphasis on measuring CO_2 emissions [9]. Considering the potential nonlinear relationship between fossil fuel carbon dioxide emissions and GDP, we employed a modified environmental Kuznets curve (MEKC) framework in our study.

However, empirical evidence for the EKC hypothesis has been mixed, with some studies supporting it while others find no clear evidence. Recent research has sought to refine and expand upon the EKC hypothesis. Studies by Kostakis [10], Leal and Marques [11], and Stern [12] provide evidence supporting the EKC hypothesis in developed and developing countries. Despite evidence supporting the pattern, a significant body of research presents conflicting findings. For instance, a study conducted by Chng [13], did not find evidence of the EKC in ASEAN nations, suggesting that economic growth alone is likely not consistent enough to ensure CO_2 emission reductions.

In contrast, the energy consumption–economic growth nexus theory suggests a positive correlation between GDP and CO_2 emissions. Economic activity significantly influences the global economy by increasing CO_2 emissions and energy consumption [14–16]. However, the correlation between economic (GDP) development and CO_2 emissions is multifaceted and depends on several factors [17]. The dynamic understanding represents a significant advancement over the EKC and energy consumption theories, but the empirical evidence is exceptional [18]. Therefore, researchers and global leaders acknowledge the limitations of the existing frameworks and emphasize the need to incorporate additional factors such as energy efficiency enhancements, technological advancements, and environmental regulations [19–21].

Earlier research has largely focused on the relationship between GDP and total CO_2 emissions. These studies tend to generalize their results across wide regions or concentrate on different economic sectors, thus neglecting the distinct economic and environmental conditions [22,23]. The EKC hypothesis has been widely studied, but its interaction with economic growth in the Visegrád region is not yet fully understood. The complexities of this relationship within specific sectors remain largely unexplored, resulting in substantial knowledge gaps. For example, the roles of agriculture and building management as sources of CO_2 emissions are still not entirely defined. Similarly, the effects of industrial combustion and power generation require further investigation. More research is also needed to understand the impact of industrial processes and waste management practices. Additionally, fuel exploitation, along with transportation and air traffic dynamics, needs closer examination. Each of these sectors plays a distinct role in shaping the economic growth and environmental dynamics of the V4 region, emphasizing the importance of more focused research [24–26]. Addressing this gap could provide valuable insights into the unique contributions of each sector to CO_2 emissions in the V4 countries.

Addressing this research gap is crucial for developing effective policy interventions and sustainable development strategies tailored to the unique environmental and economic contexts of the V4 countries. Understanding complex interactions can lead to the implementation of strategies to reverse environmental degradation and promote economic prosperity and societal well-being. Reviewing these additional factors can offer a fundamental perspective on how global leaders influence interactions and can inform evidence-based decisions for effective policies on long-term environmental degradation.

This study investigates how economic growth and CO_2 emissions are connected in the Visegrád group of countries. It considers the role of different sectors and country-specific policies and economic situations. The study strives to uncover essential insights that can underpin well-informed decisions. These insights will contribute to the development of effective environmental and economic policies. Ultimately, this will support the Visegrád region's long-term sustainability.

Accordingly, the study aims to address the following research questions: RQ1. How does economic growth impact CO_2 emissions in the V4 countries? RQ2. What are the sector-specific contributions to CO_2 emissions in these countries? RQ3. How do country-specific policies and economic contexts influence the relationship between GDP and CO_2 emissions in the V4 countries?

To achieve a comprehensive understanding, the following research objectives were established: Obj1. To analyze the relationship between GDP growth and CO_2 emissions in the V4 countries. Obj2. To identify the key sectors contributing to CO_2 emissions in the V4 countries and examine their respective trends. Obj3. To assess the effectiveness of environmental policies in mitigating CO_2 emissions while promoting economic growth within the V4 countries.

2. Literature Review

2.1. Environmental Kuznets Curve (EKC) Hypothesis

The environmental Kuznets curve (EKC) hypothesis has been a foundational concept in environmental economics, prompting significant research and debate over the years. This theory proposes a complex relationship between economic growth and environmental quality, where initial economic development leads to environmental degradation. Recent scholarship has shed new light on the EKC's validity and applicability across diverse contexts [27,28]. In addition, this theory suggests that when a country's economic development reaches a certain level, the pattern of environmental degradation begins to reverse. This shift leads to subsequent improvements in environmental quality [29]. However, the environment deteriorates in the initial stage, but the quality of the environment begins to improve after reaching a more developed economic level [30]. This is expressed by an inverted U-shaped curve, where initially economic growth and environmental degradation increase, but later environmental conditions improve with economic development [31,32].

Furthermore, Husnain et al. [33] conducted a comprehensive analysis of EKC. Their findings suggest that developing countries often prioritize economic growth to alleviate poverty and unemployment. However, the EKC hypothesis underscores the potential trade-off between economic expansion and environmental quality. A singular focus on growth may compromise long-term sustainability. Therefore, a balanced approach that integrates environmental considerations into the development strategies is imperative.

In a novel approach, Uche et al. [34] employed a novel methodology combining machine learning techniques with ARDL and KRLS models to re-examine the EKC hypothesis. Their analysis of 40 years of data provides evidence supporting the pollution haven hypothesis in Brazil in both the short and long term.

Despite its enduring influence, the EKC hypothesis faces several critiques [35]. Its validity varies significantly across countries and contexts, with many developing nations experiencing prolonged environmental degradation during economic growth phases [36,37]. Furthermore, the theory may apply only to select environmental indicators, such as air quality, while failing to account for others, like biodiversity loss and land degradation. Critics also argue that the EKC underestimates the role of technological advancements and environmental policies in shaping environmental outcomes [38].

Considering the insights from recent studies and the continuing debates, we propose the first hypothesis, tailored to the context of the Visegrád region:

Hypothesis 1 (H1): *The EKC hypothesis holds for the Visegrád region, with CO_2 emissions rising with economic growth and then declining after a specific income threshold.*

2.2. Carbon Emissions from Fossil Fuels in the Visegrád Region

The Visegrád countries have exhibited diverse trends in CO_2 emissions from fossil fuels over recent decades [39–41]. CO_2 emissions have increased with industrialization and economic development in these countries [42], especially since the 1990s [43]. This rise in development can be attributed to the growing utilization of oil, coal, and natural gas to fuel economic growth [44].

When compared to other European regions, the Visegrád countries generally demonstrate higher carbon dioxide emission levels than their Western European counterparts [45]. For example, Western European countries such as Germany and France have made significant progress in reducing carbon emissions through the implementation of robust environmental policies and a substantial shift towards renewable energy sources [46]. The Visegrád countries continue to rely heavily on fossil fuels to drive their economic development, which significantly impacts their emission rates [47].

Recent research has shed light on the latest trends and policy impacts on CO_2 emissions from fossil fuels in the Visegrád region. Rabbi et al. [16] conducted a comparative analysis of energy transitions in the Visegrád countries. Their findings revealed that while all four countries have made progress in reducing their reliance on fossil fuels, significant differences persist. Poland and Czechia continued to have higher CO_2 emissions due to their more extensive industrial sectors and greater reliance on coal for electricity generation.

Further insights came from Schlacke et al.'s [48] examination of the European Union's "Fit for 55" package and its impact on the Visegrád countries' energy sectors. Their projections suggested that this initiative would accelerate the transition away from fossil fuels, especially in Poland and Czechia. However, they also highlighted significant challenges that remain, particularly in terms of ensuring energy security and managing economic restructuring.

Based on findings from recent literature, we propose the following second hypothesis:

Hypothesis 2 (H2): *Poland and Czechia have higher fossil fuel CO_2 emissions than Hungary and Slovakia due to greater industrialization and fossil fuel reliance.*

This hypothesis underscores the complex interplay between economic development, energy policies, and environmental impact in the Visegrád region, highlighting the need for tailored approaches to emission reduction that consider each country's unique economic and industrial landscape.

2.3. The Environmental Footprint of Visegrád's Economic Expansion

The Visegrád region has experienced a complex correlation between economic growth and environmental impact, particularly with regard to CO_2 emissions. Emerging research indicates the varied trajectories of the four nations, highlighting the multifaceted nature of this relationship [40]. As these nations have pursued industrialization and economic expansion, their energy consumption has risen correspondingly [49]. This growth has been largely fueled by fossil energy sources, leading to a marked increase in carbon emissions [50]. The manufacturing sector has seen significant expansion, contributing substantially to the overall environmental footprint of the region [51]. The environmental consequences of this economic trajectory are manifold. Both the industrial and the transportation sectors rely heavily on fossil fuels, exerting considerable pressure on the environment [46].

The modernization of the energy sector has paradoxically led to a reduction in the adoption of renewable energy in some cases, perpetuating existing emissions problems [52]. Contemporary research offers valuable perspectives on these complexities. For example, a study by Asjad Naqvi [53] explored the decoupling of economic growth from CO_2 emissions of EU countries from 1995 to 2015. His study reveals a mixed pattern in response to environmental policies across different regions, with emission types reacting differently. Lower-income regions exhibited a stronger response to these policies compared to higher-income regions. While EU countries have demonstrated some progress in relative decoupling, achieving absolute decoupling remains a formidable challenge.

Expanding on this topic, Gołaś [54] examined the link between industrial growth and CO_2 emissions in Poland. His study revealed a consistent positive correlation between industrial output and carbon emissions, indicating that Poland's economic growth remains closely tied to carbon-intensive activities.

These findings contribute to the formulation of the third hypothesis, providing evidence aligned with its predictions:

Hypothesis 3 (H3): *There is a positive correlation between economic growth and CO_2 emissions in Poland.*

However, the Visegrád region faces challenges in balancing economic aspirations with environmental sustainability. While efforts towards sustainable practices are underway, economic policies still result in environmental consequences. Policymakers must use ongoing research to craft strategies that promote growth while minimizing environmental impact.

2.4. Visegrád Region under the Lens of the EKC Hypothesis

In the Visegrád countries, the evidence supporting the EKC hypothesis is mixed. While some studies indicate that economic development leads to improvements in environmental indicators, the overall picture remains uncertain. [55]. Although some environmental indicators have shown improvement as economies have developed, the evidence remains mixed, suggesting a complex relationship between economic growth and environmental quality. For instance, air quality has improved somewhat, but water pollution and loss of biodiversity remain significant problems [56,57].

Recent literature has provided novel insights into the applicability of the EKC hypothesis within the Visegrád region, considering the region's dynamic economic and environmental context. For example, Németh-Durkó [58] examined the EKC hypothesis for various air pollutants in the Visegrád countries from 1995 to 2022. Her work revealed that although certain pollutants adhered to the EKC pattern, carbon dioxide emissions did not exhibit a definitive turning point, especially in Poland and Czechia. This finding underscores the persistent challenge of decoupling economic growth from carbon emissions in these nations.

Further exploring this theme, Aydin and Degirmenci [59] examined the role of environmental policy stringency in shaping the EKC relationship in Central and Eastern European countries, including the Visegrád group. Their research indicated that countries implementing more rigorous environmental regulations tended to display EKC-like patterns for a range of environmental indicators. This suggests that policy interventions play a crucial role in shaping environmental outcomes as economies grow.

A pioneering study by Ahmadova et al. [60] investigated the impact of digital transformation on the EKC relationship in the Visegrád countries. Their findings pointed to the potential of advanced digital technologies, when adopted across various sectors, to alter the traditional EKC curve. Specifically, they proposed that such technologies could lead to a flattening of the curve and earlier turning points for CO_2 emissions, offering a promising avenue for sustainable development.

Drawing upon recent contributions to the literature, we formulated our fourth hypothesis:

Hypothesis 4 (H4): *Technological innovation and effective environmental regulations are key factors influencing the EKC relationship in the Visegrád countries.*

As V4 nations continue to navigate the challenges of economic development and environmental protection, the interplay between policy, technology, and environmental outcomes remains a critical area for ongoing research and policy consideration.

Furthermore, the EKC connection is influenced by many factors. First, the region's economic and environmental political effects are significant [61]. Second, the EKC relationship may become more and more prominent with technological development and the increase in the use of renewable energy [62]. Thirdly, the importance of international cooperation and environmental policy can also affect the EKC relationship [38].

3. Materials and Methods

This study examines the correlation between GDP and $FFCO_2$ emissions in four Visegrád (V4) regions, utilizing the modified environmental Kuznets curve (MEKC) framework. $FFCO_2$ emission data for 2010–2022 were obtained from the EDGAR version 8.0 (2023) inventory, and from the EDGAR 2023 report [63]. In addition, air traffic data for 2010–2022 were obtained from the EUROCONTROL [64] Aviation Sustainability Unit database. The main sources of environmental pollution are categorized into nine sectors: power generation, industrial combustion, buildings, agriculture, fuel production, industrial processes, waste treatment, road transportation, and air traffic. Power plants, both public and private, contribute to air pollution along with industrial facilities that burn fuel for manufacturing purposes. Small-scale combustion in buildings also adds to this issue. Emissions from vehicles on roads, railways, ships, and aero planes significantly impact air quality. Agricultural activities, including soil management, crop residue burning, animal digestion, manure handling, and indirect nitrous oxide (N_2O) emissions, are another source of air pollution. Additionally, the production, processing, and refining of fuels contribute to air pollution. Industrial processes, such as those involved in the production of cement, steel, aluminum, chemicals, and solvents, also release pollutants into the air. Waste disposal and wastewater treatment facilities are significant contributors to air pollution.

Historical CO_2 emission patterns were examined using econometric techniques, including temporal analysis, correlation matrices, and regression analysis, with data sourced from secondary sources. Based on the MEKC, the preliminary data analysis identified fundamental patterns and trends in the historical data on $FFCO_2$ emissions. These patterns, called open codes, captured specific concepts and trends observed in the data. The study conducted axial coding, systematically comparing each identified pattern or trend with a predefined quantitative measure of CO_2 emissions. This process involves classifying and analyzing patterns to provide a comprehensive understanding of historical $FFCO_2$ emission processes.

The MEKC graph visually depicts this correlation by employing a quadratic function to demonstrate the relationship between V4 nation's GDP per capita and its corresponding CO_2 emissions. The equation is as follows:

$$CO_2\text{Emis} = \beta_0 + \beta_1 * \text{GDP Per Capita} + \beta_2 * (\text{GDP Per Capita})^2 + \varepsilon$$

Here, β_0 represents the fundamental level of spatial CO_2 emissions in the reflection, even if there is no economic activity. B_1 reflects the initial increase in odor onset as an economic improvement, and its kinetic value confirms this direct relationship. Ambiguously, β_2 captures the phrase of the curve. The EKC theory suggests that a negative β_2 indicates an "inverse relationship" between high income levels of economic development (squared

GDP per capita) and CO_2 emissions. This essentially shows that although emissions may initially increase with economic development, they eventually begin to decline as countries become richer and environmental sustainability is prioritized.

Researchers have examined the temporal pattern of CO_2 emissions from various sectors, including agriculture, buildings, and industrial activities. Calculating total CO_2 emissions per country involves summing emissions across all sectors for that country. The CO_2 emissions for a country denoted by i and sector j at time t as $E_{ij}(t)$, the total emissions for country i can be obtained using the following equation:

$$E_i(t) = \sum_j E_{ij}(t)$$

This essentially sums the emissions from each sector (j) within a specific country (i) to determine the total $FFCO_2$ emissions for that country.

In addition, the temporal trends of $FFCO_2$ emissions are defined by calculating the rate of change over time. Researchers applied a linear regression formula to fit a line to the data points and calculate the slope, which indicates the rate of change.

$$y = mx + b$$

In the linear regression model, y is the dependent variable (CO_2 emissions), x is the independent variable (time), m is the slope (rate of change), and b is the y-intercept.

Python (Version 3.12.4) library's Matplotlib was used to identify the percentage of emissions [65]. This offers a visual representation of CO_2 emissions, with each bar signifying a year and its total emissions. Each segment within the bar represents a specific sector (e.g., transportation, industry), and the segment's length is proportional to the percentage of CO_2 emissions that sector contributed to that year.

$$\text{Percentage of Sectoral Emissions} = \frac{\text{Emissions from Sector}}{\text{Total Emissions for the Year}} \times 100\%$$

The analysis of emission data is significantly influenced by the percentage of sectoral emissions, which provides insight into the relative contribution of each sector to overall emissions. The below formula calculates the percentage (%) of each sector's emissions compared to the year's total emissions.

$$\text{Total Emissions for the Year} = \sum_{\text{sectors}} \text{Emissions from Sector}$$

The total emissions from all sectors in a year are crucial for understanding the environmental impact of human activities. The calculation of ratios and differences between emissions from different sectors or years aids in comparing and identifying trends.

$$\text{Ratio of Sector 1 to Sector 2} = \frac{\text{Percentage of Sector 1}}{\text{Percentage of Sector 2}}$$

Identifying trends over time goes beyond simply plotting data points. Smoothing fluctuations and revealing underlying patterns are achieved through moving averages. This paves the way for deeper understanding.

$$\text{Moving Average} = \frac{1}{n}\sum_{i=1}^{n} \text{Percentage of Emissions}_i$$

The *Moving Average* calculation technique is used to smooth out fluctuations in a series of data points. It does this by creating a new series of data points, each of which represents the average of a specific number (n) of preceding data points. This number

(n) is referred to as the entire dataset. Here, Percentage of Emissions_i, the percentage of emissions at each data point is i.

These calculations and techniques, applied to the data presented in the stacked bar graph, provide valuable insights into the trends, proportions, and relationships within the CO_2 emission data.

The formula to compute the correlation coefficient between GDP and total CO_2 emissions for V4 countries is composed as follows. X_i denotes the GDP of country i, where i ranges from 1 to 4 for the four countries. Similarly, Y_i represents the total CO_2 emissions of country i. Furthermore, $\overline{X}$ is used to denote the mean GDP across all countries and $\overline{Y}$ to denote the mean CO_2 emissions across all countries. The formula is written as:

$$r = \frac{\sum_{i=1}^{4} \left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{4} \left(X_i - \overline{X}\right)^2 \sum_{i=1}^{4} \left(Y_i - \overline{Y}\right)^2}}$$

The formula calculates the variance of GDP and CO_2 emissions across V4 countries. This is achieved by summing the squared deviations of each country's GDP and CO_2 emissions from their respective means. The sum extends across all four countries, represented by $(\sum_{i=1}^{4})$. $X_i - \overline{X}$ and $Y_i - \overline{Y}$ represent the deviations of GDP and CO_2 emissions of each country from their respective means, respectively, and $\sum_{i=1}^{4}\left(X_i - \overline{X}\right)^2$ and $\sum_{i=1}^{4}\left(Y_i - \overline{Y}\right)^2$ calculate the sum of squares of the deviations of GDP and CO_2 emissions, respectively.

Scatter plots effectively showcase the distribution of data points, revealing potential patterns or trends in the relationship between GDP and emissions, whether for road transport or air traffic. Each data point represents a specific year, with its position on the graph determined by the GDP on the x-axis and the corresponding emissions on the y-axis.

The upward slope of the regression line reveals a positive correlation between GDP and air traffic emissions. This suggests that as economies grow (reflected by increasing GDP), air traffic emissions tend to rise as well. This implies a potential link between economic activity and the level of air travel. Fitted regression lines, on the other hand, mathematically capture the overall trend observed in the scatter plots. These lines represent the "best-fit" linear models describing the relationship between GDP and emissions. The equations of these lines are expressed as

$$RT = \beta_0\_RT + \beta_1\_RT \times GDP + \varepsilon$$

for road transport; and for air traffic

$$AT = \beta_0\_AT + \beta_1\_AT \times GDP + \varepsilon$$

Here, β_0 is the intercept, indicating the estimated emission level when GDP is zero (0). In response, CO_2 indicates a decentralized relationship and refers to the magnitude of the change in emissions per unit increase in GDP, indicating a positive relationship where emissions increase with GDP growth.

By analyzing these regression lines mathematically, we obtain a qualitative understanding of the statistical relationship between GDP and CO_2 emissions. This analysis shows the magnitude of the additional effects related to economic (GDP) growth on transportation and the specific changes, dynamics, or strengths of nations.

All analyses were performed using MATLAB version R2024a and Python version 3.12.4 to explore the $FFCO_2$ emissions of the Visegrád countries. It should be noted that this research follows strong ethical standards, ensuring the confidentiality of the data sources and responsible handling of the data obtained from secondary data sources. The analytical procedures were followed accurately and appropriately, in accordance with ethical standards and procedures, and for reporting data with transparency.

4. Analysis and Results

The EKC theory suggested that economic growth leads to increased CO_2 emission levels due to environmental initiatives and increased energy consumption. However, as countries become richer, they prepare domestically for cleaner technologies and environmental regulations, causing a downward curve. The country's economic growth can be referred to as a combination of emission reduction and GDP growth.

However, Figure 1 establishes the theoretical foundation for our analysis. The EKC depicts the relationship between a nation's economic development (GDP per capita) and its environmental quality (CO_2 emissions). Figure 1 depicts an inverted U-shaped curve, commonly referred to as the MEKC. The country's economic well-being is represented on the horizontal X-axis, measured by GDP per capita on a scale from USD 0 to USD 10 thousand. The vertical Y-axis represents environmental impact, measured by CO_2 emissions (metric tons per capita) per person, ranging from 0 to 1.7 metric tons (Mt), with higher values indicating a greater contribution to climate change.

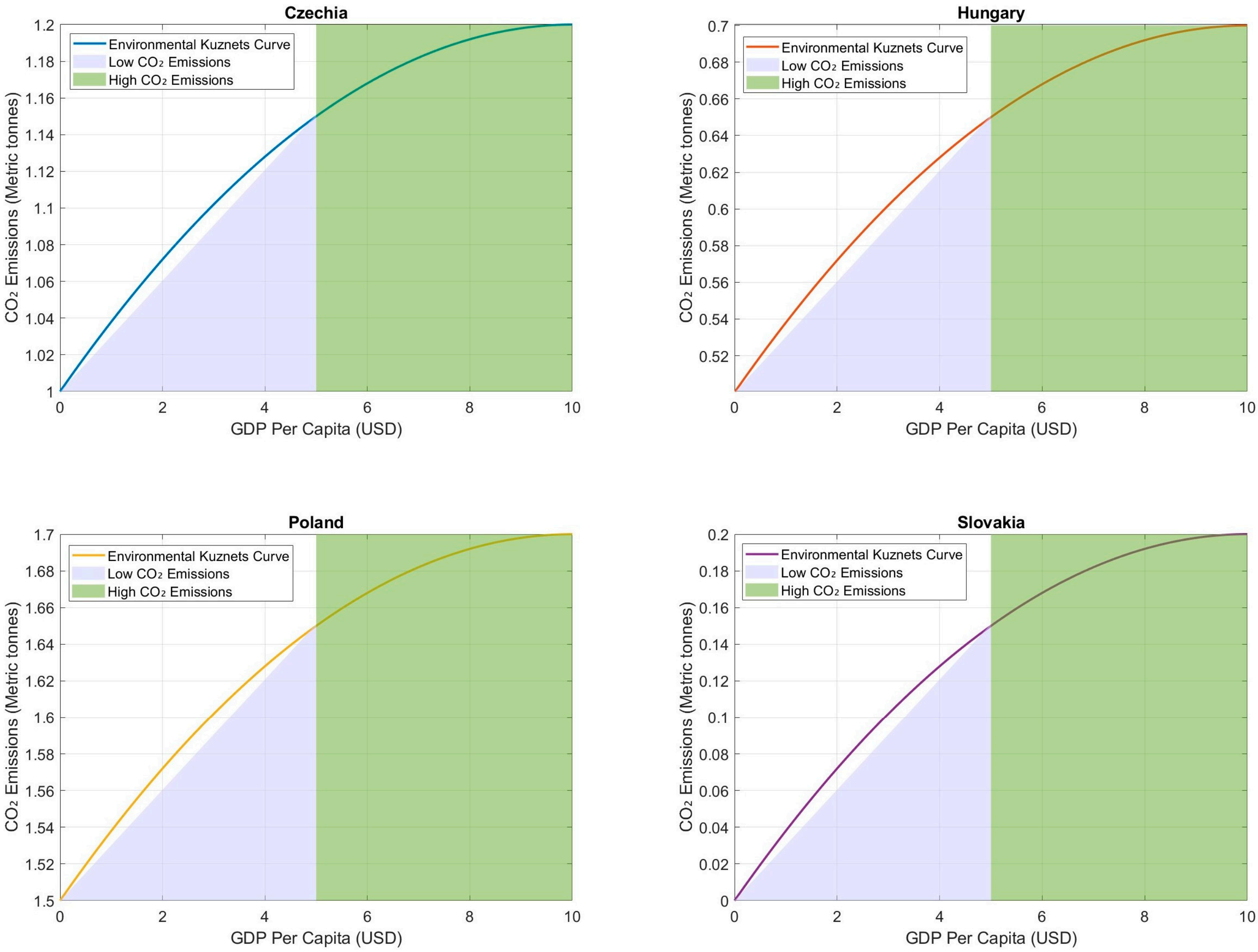

Figure 1. The modified environmental Kuznets curve (MEKC) showcasing CO_2 emission patterns in the V4 countries.

Furthermore, an interesting trend is illustrated for the V4 countries, e.g., Czechia (blue), Hungary (red), Poland (orange), and Slovakia (purple). These countries are experiencing rapid economic growth, which is often accompanied by rising CO_2 emissions. However, their emission rates are increasing at a slower pace. This could be a sign that these countries are finding ways to grow their economies while being more environmentally friendly.

In Figure 1, the MEKC framework depicted in these graphs reveals a nuanced relationship between economic growth and environmental impact for Czechia, Hungary, Poland, and Slovakia. As GDP per capita rises along the x-axis, we observe a corresponding shift in total CO_2 emissions on the y-axis, forming an inverted U-shaped pattern that tells a compelling story of development and sustainability.

In the early stages of economic expansion, CO_2 emissions climb steadily alongside GDP growth. This trend is particularly pronounced in Poland, where emissions rise sharply from 1.5 Mt to over 1.65 Mt as GDP per capita approaches USD 5000. The initial surge likely reflects the increased industrialization and energy consumption that typically accompany economic development.

However, a critical juncture emerges as each country's economy matures. For Czechia, this turning point occurs around USD 5000 GDP per capita, where CO_2 emissions peak at approximately 1.15 metric tons. Hungary experiences a similar transition near USD 4500 GDP per capita, with emissions cresting at about 0.65 metric tons. These inflection points signify a pivotal shift where further economic advancement begins to correlate with declining emissions.

The descending portion of the curve post-peak illustrates how more developed economies may decouple economic growth from environmental degradation. In Slovakia's case, emissions start to taper off after reaching about 0.15 Mt when GDP per capita surpasses USD 5000. This downward trajectory could stem from various factors, including technological innovations, a transition to service-based economies, or the implementation of stricter environmental policies.

Interestingly, the graphs also present low and high CO_2 emission scenarios, represented by the lighter and darker shaded areas, respectively. These alternative pathways suggest that countries have some agency in shaping their environmental outcomes through policy choices and technological adoption, even as they pursue economic growth.

The scale and steepness of the curves vary noticeably between countries, reflecting their distinct economic and environmental trajectories. Poland's graph, for instance, displays a much higher range of emissions compared to its neighbors, peaking at nearly 1.7 metric tons. In contrast, Slovakia's emissions remain relatively low, never exceeding 0.2 Mt across the entire GDP spectrum shown.

However, Figure 2 shows the overall emission trends analyzed within the MEKC framework. The $FFCO_2$ emission trends across various sectors reveals distinct patterns. Poland stands out as the leading emitter in three key sectors, such as power generation, transportation, and agriculture. Poland is followed by Czechia, Slovakia, and Hungary. Notably, Czechia has taken the lead in terms of building sector emissions, while other sectors, such as industrial combustion, processes, waste, and fuel exploitation, are dominated by either Czechia or Poland, followed by the remaining countries.

While the overall trend across all four nations points toward a decrease in $FFCO_2$ emissions, a closer look reveals some nuances. Although Poland remains the highest emitter, its emissions decreased significantly, dropping from 1653.87 Mt in 2010 to 1310.83 Mt in 2020, representing a decrease of 20.8%. This decrease is most prominent in the power industry, the largest source of $FFCO_2$ emissions in all four countries. Following a similar trend, emissions from this sector have declined considerably, with Poland experiencing a decrease from 161.17 Mt in 2010 to 126.03 Mt in 2020, translating to a 21.8% reduction.

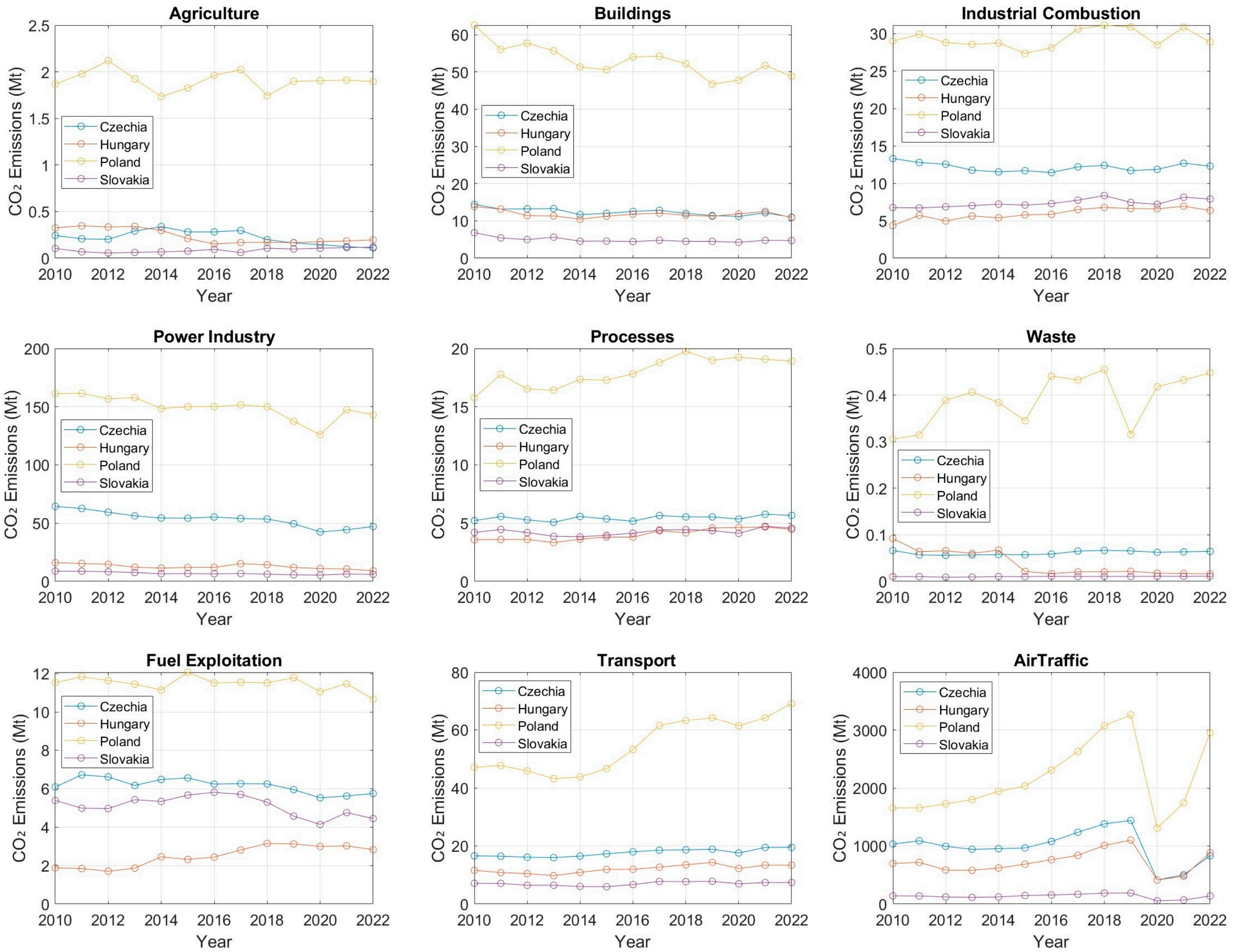

Figure 2. Evolution of $FFCO_2$ emissions over time in the Visegrád countries.

The transport sector is the second-largest contributor to $FFCO_2$ emissions, and shows a downward trend in all four countries, albeit less pronounced than that of the power industry. Interestingly, Poland's transport sector deviates from this trend, exhibiting a slight increase from 47.12 Mt in 2010 to 61.38 Mt in 2020, representing a 30.3% increase. Emissions from other sectors, such as agriculture, buildings, and industry, while lower than those from the power and transport sectors, also exhibit a decreasing trend across the four nations, although at a slower pace.

While the trends generally support the EKC theory, there are some outliers. For example, emissions are increasing in Poland's transportation sector and Hungary's fuel production sector. A closer look at these specific cases is essential to fully understand the complexities of CO_2 emissions in these areas.

Figure 3 provides percentage (%) of $FFCO_2$ emission data by year and sector. Each bar represents a year, with its height reflecting the total emissions. Within each bar, various segments represent different sectors (e.g., agriculture, industry, and transportation), and their lengths are proportional to the percentage of $FFCO_2$ emissions each sector contributed to the total for that year.

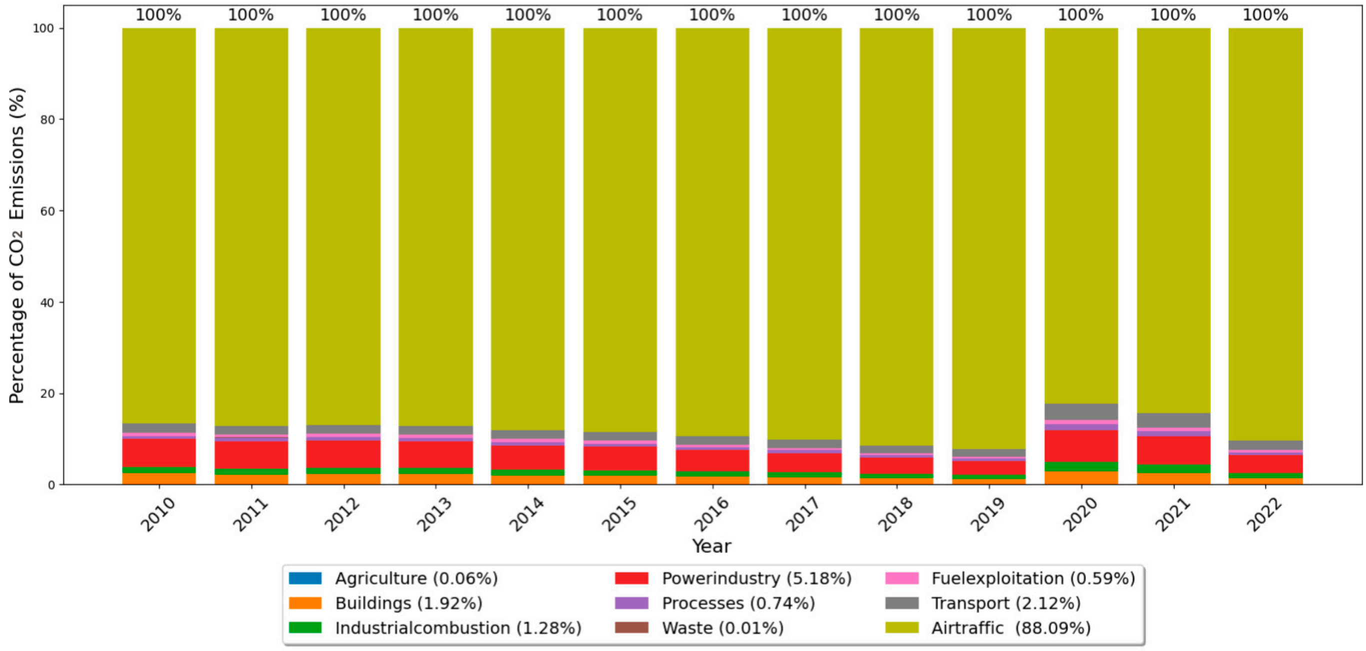

Figure 3. Annual sectoral distribution (%) of fossil fuel CO_2 emissions.

The power industry (represented in yellow) consistently accounts for the largest share of $FFCO_2$ emissions, averaging approximately 88.09%. This dominance highlights the significant reliance on fossil fuels for electricity generation, making the power industry a crucial area for efforts to reduce emissions. In comparison, the transport and industrial combustion sectors also contribute notable amounts, with transport averaging 2.12% and industrial combustion 1.28% annually. These sectors show relatively stable patterns in their emissions over the years.

Smaller contributors include agriculture (blue), buildings (orange), processes (purple), waste (pink), and fuel exploitation (brown). Buildings, for example, average a 1.92% contribution, processes 0.74%, and agriculture a mere 0.06%. Despite their smaller shares, these sectors still offer opportunities for targeted emission-reduction strategies.

Some variations can be observed over the years, particularly in the transport and power industry sectors, which reflect the potential impacts of global events like the COVID-19 pandemic in 2020 and 2021. These fluctuations provide valuable insights into how external factors can influence sectoral emissions.

Overall, Figure 3 emphasizes the critical need for cleaner energy sources in the power industry to achieve significant reductions in CO_2 emissions. The transport sector's contribution suggests that promoting electric vehicles and other sustainable transport solutions could be effective in reducing emissions. Although smaller in their contributions, sectors such as processes and buildings also present opportunities for meaningful interventions.

In Figure 4, scatter plots take this a step further by showing these connections visually, helping spot trends and clusters in the data. Histograms show how CO_2 emissions are distributed across the different sectors, providing a better understanding of the overall data. The correlation matrix shows how closely changes in one factor (such as agricultural emissions) are linked to changes in another (such as emissions from buildings). High positive numbers (closer to 1) indicate strong growth or a collective decline in emissions. Conversely, large negative numbers (closer to -1) indicate that the relevant factor is moving in the direction or in the opposite direction.

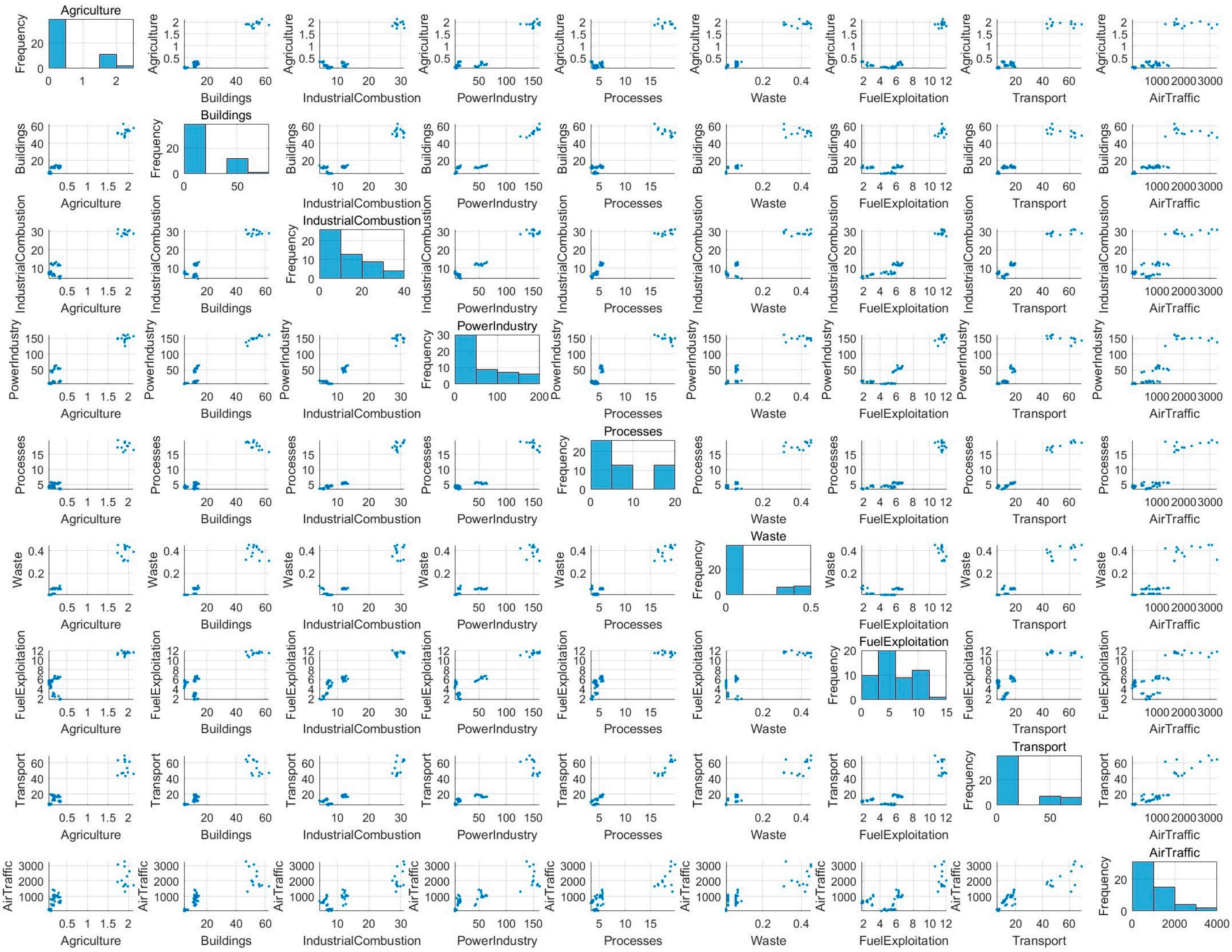

Figure 4. Distribution and sectoral interconnectivity of CO_2 emissions.

In the lower half of the analysis, joint relationships between all the measurable factors were explored. Each square displays a scatter plot for a particular factor. Analyzing these plots facilitates identifying potential growth, such as strong positive or negative correlations between sectors, and identify these correlations between throws. For example, the positive relationship between "transportation" and "industrial combustion" is significant, meaning that when transportation emissions increase, industrial combustion may follow. This suggests a link between a crop's dependence on the environment or transport readiness and industrial performance. Conversely, the negative relationship between "renewable energy" and "fossil fuels" is consistent while renewable energy use is increasing and fossil fuel emissions are decreasing, thus demonstrating a trend toward cleaner energy sources [16]. The data points clustered within a subplot indicate a strong correlation between the corresponding factors.

The analysis indicates potential interdependencies between sectors. For instance, the aviation and transport sectors exhibit a correlated relationship, whereby increased air traffic tends to stimulate broader transport activity. Similarly, more transport activity could generate more waste. There is also a potential connection between processes and the power industry. Industrial processes often rely on power, so a rise in industrial activity could lead to a greater demand for electricity. The same logic might apply to the power industry and industrial combustion, where some power plants utilize combustion processes to generate electricity.

Across the various sectors, regardless of the fuel, consumption generates waste. Additionally, a power industry reliant on fossil fuels could negatively impact air quality in other sectors, such as buildings and agriculture.

The relationship between buildings and agriculture is slightly more nuanced. Increased agricultural activity could lead to higher energy demands for buildings used in food processing and storage. However, advancements in building efficiency could reduce energy consumption despite agricultural growth.

Figure 5 displays the results of introducing economic factors after establishing the emission trends. The correlation coefficients between GDP and total CO_2 emissions for V4 countries are shown. These coefficients range from −1 to 1, indicating the strength and direction of the linear relationship between the two variables. A positive coefficient (between 0 and 1) ensures that when GDP increases, CO_2 emissions also increase. A negative number (between −1 and 0) indicates that as economic growth increases, emissions decrease. Values close to 0 indicate a weak or absent linear relationship.

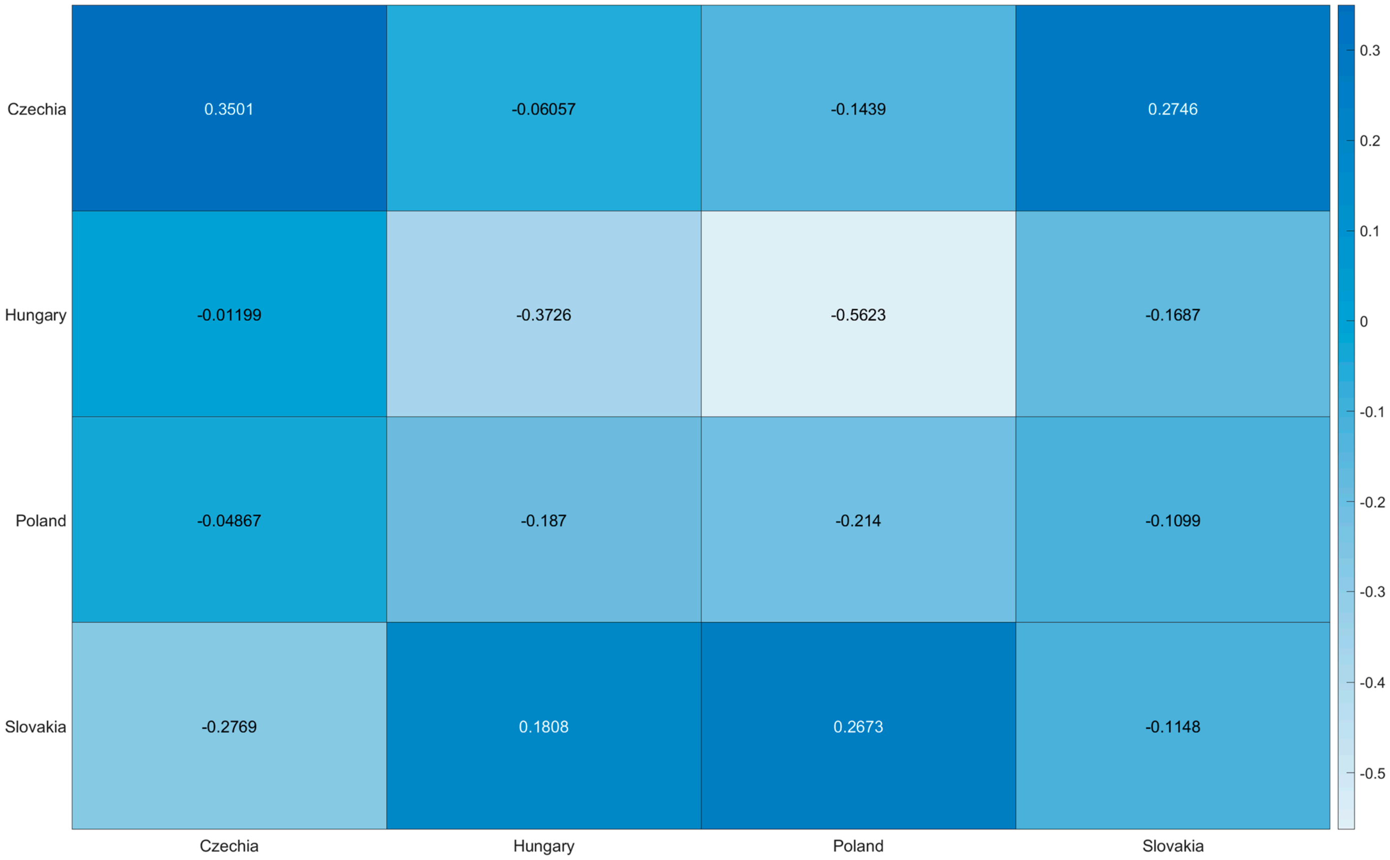

Figure 5. Country-level correlation matrix of GDP and total CO_2 emissions.

The correlation matrix reveals a significant relationship between economic growth and CO_2 emissions in V4 countries. In Czechia, there is a positive correlation (0.35) between economic growth (GDP) and CO_2 emissions. This means that as their economy increases, their emissions also tend to increase. It is like stepping on the gas pedal—the faster they go economically, the more emissions they produce.

Hungary's situation is interesting. There is a negative correlation (−0.37) between GDP and emissions. This suggests that their economic growth is increasing alongside a decrease in emissions. Perhaps they are becoming more efficient or adopting cleaner energy sources. Poland and Slovakia also exhibit negative correlations, though not as strong as those observed in Hungary. Their respective correlation values are −0.21 and −0.11, which makes the link between economic growth and emissions less clear. It is possible that their economies are undergoing changes that affect emissions, but the connection is not particularly strong.

Overall, coefficient values near zero between Poland's GDP and the emissions of other countries suggest a minimal to no linear connection between its economic activity and its CO_2 emissions. While the correlation matrix provides valuable information about how economic activity and emissions are associated, economic output, however, is a significant factor in determining CO_2 emissions. Various other elements can also play a role in influencing these emissions. These may include technological advancements, policy regulations, and societal behavior.

Figure 6 provides a detailed visualization within the broader economic factor analysis. It demonstrates a clear positive correlation between GDP (gross domestic product) and both road transport and air traffic emissions for each country (Czechia in blue, Hungary in orange, Poland in yellow, and Slovakia in purple). Each circle on the scatter plot signifies a specific year, with GDP on the x-axis and emissions on the y-axis. The visual trends of the fitted regression lines clearly demonstrate a direct correlation between GDP and emissions, indicating that economic growth and transportation activity are closely linked.

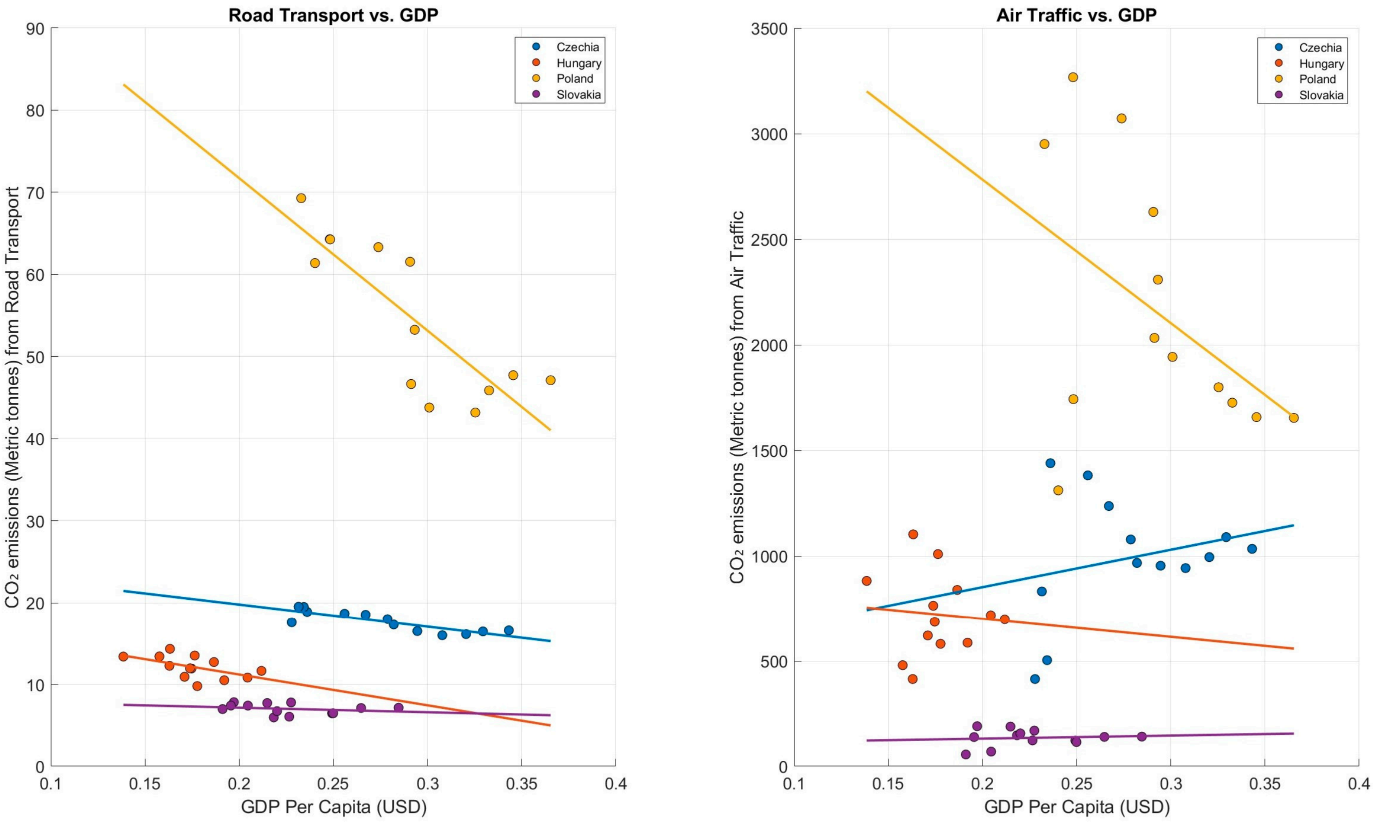

Figure 6. GDP-driven variations in CO_2 emissions from road and air transport.

Going beyond the visual, for instance, the data points circled on Hungary's road transport graph for 2010 show a GDP of approximately 0.21 and emissions of approximately 11.65 Mt. This emphasizes that the upward trend observed in the fitted lines is not merely a visual representation but reflects real-world year-by-year data. Additionally, the R-squared value quantifies the strength of the relationship; for example, Czechia's air traffic with an R-squared of 0.85 signifies that 85% of the variation in air traffic emissions is explained by variations in GDP.

However, it is crucial to recognize that the strength of this relationship is not uniform across countries and transportation modes. Poland exhibits the most substantial increase in emissions for both sectors, with steeper slopes on their regression lines indicating an approximately 158.29 Mt increase in emissions per unit GDP increase. This highlights the importance of sustainable solutions.

A more nuanced picture emerges when we examine factors beyond GDP. Hungarian air travel emission data for 2018 display greater consistency than their road traffic counterparts. This suggests that influences other than economic growth, such as tourism patterns or regulatory changes, impact air travel behavior.

Similarly, Figure 6 shows a weaker correlation between air traffic and GDP in Slovakia compared to the other countries. These findings suggest that additional factors, such as technological advancements in the power industry and related processes, may also influence emissions [25]. This indicates that solving transportation challenges in these countries requires a multipronged approach. Initially, they need to continue investing in infrastructure to handle more traffic as their economies grow. However, they also need to ensure that their transportation systems are sustainable for the environment.

5. Discussion

The investigation into the relationship between GDP per capita and CO_2 emissions reveals a nuanced interaction. This relationship is characterized by an inverted U-shaped curve, indicating that environmental impact initially escalates with economic growth but eventually diminishes as economies mature. The distinct emission turning points observed in the V4 countries reinforce this tendency. For instance, in Czechia (Figure 1), peak CO_2 emissions of approximately 1.15 Mt coincided with a GDP per capita of around USD 5000. Similarly, Hungary reached peak emissions of about 0.65 Mt at a GDP per capita of roughly USD 4500, while Slovakia's emissions began to decline after reaching a GDP per capita of approximately USD 5000 and 0.15 Mt of CO_2 emissions. These results suggest that economic growth and environmental sustainability are not inherently contradictory and that tailored policies promoting sustainable development are crucial. However, these findings strongly support Hypothesis 1 (H1). The inverted U-shaped curves observed for all V4 countries demonstrate that CO_2 emissions initially rise with economic growth and then decline after reaching a specific income threshold. This pattern is consistent with the EKC hypothesis for the Visegrád region.

The sectoral analysis (Figure 3) identified the power industry as the predominant source of CO_2 emissions across the V4 nations, contributing an average of 88.09% of total emissions. The transport and industrial combustion sectors also play significant roles, with transport accounting for an average of 2.12% and industrial combustion 1.28% of annual emissions. These findings highlight the substantial impact of the energy sector on national emission profiles and point to critical areas for intervention and policy development.

Our analysis (Figure 5) unveiled distinct patterns in the correlation between GDP and CO_2 emissions within the V4 region. Czechia displayed a positive correlation (0.35), indicating that as GDP increases, CO_2 emissions tend to rise. In contrast, Hungary (−0.37), Poland (−0.21), and Slovakia (−0.11) exhibited negative correlations, suggesting that higher GDP levels may be associated with reduced emissions. This variability underscores the importance of considering country-specific economic structures and environmental policies when addressing climate change and economic development.

Moreover, examining the link between the nation's economic output and its transport-related emissions (Figure 6) reveals that Poland has experienced a substantial increase in carbon dioxide emissions. This increase is evident in both road vehicles and air travel. This trend underscores a close connection between the country's GDP growth and rising CO_2 emissions in these areas of transportation. In contrast, Slovakia did not show a strong correlation between air traffic emissions and GDP. This suggests that other factors, such as specific policy strategies, could be influencing these emissions.

Furthermore, the EKC hypothesis suggests that as countries become wealthier, their emissions initially increase but then moderate or decline. This pattern seems reasonable because economically challenged nations rely on more environmentally polluting industries to grow, whereas wealthier countries can invest in cleaner technologies. Poland, with the highest GDP per capita among the V4, faces challenges due to increasing emissions and a growing economy. Czechia, with the second-highest income and highest pollution levels, is still in the early stages of growth, with fossil fuel CO_2 emissions being a major concern. Hungary, in a similar economic position to Poland and Czechia, shows a slower increase in emissions, indicating potential progress in adopting eco-friendly practices even as its economy expands. Slovakia, the least wealthy of the group, has the lowest pollution levels but follows a similar trend to Czechia, with emissions rising quickly, suggesting it is in the early development stage of the EKC. These results partially support Hypothesis 2 (H2). Poland has significantly higher CO_2 emissions compared to Hungary and Slovakia. Czechia's emissions are also higher than Hungary and Slovakia, though not as high as Poland's. This aligns with the expectation that Poland and Czechia would have higher emissions due to greater industrialization and fossil fuel reliance.

Interestingly, Poland has emerged as the top emitter in power generation, transportation, and agriculture, followed by Czechia, Slovakia, and Hungary (Figure 2). While overall emissions decreased across all nations from 2010 to 2020, Poland experienced a notable 20.8% reduction in the power industry. However, the transport sector saw declines in all countries except Poland, which experienced a 30.3% increase. Other sectors, including agriculture, buildings, and industry, also showed decreasing trends, albeit more slowly. These findings provide limited support for Hypothesis 3 (H3) that economic growth eventually leads to reduced emissions. The initial steep rise in Poland's emissions with GDP growth suggests a strong positive correlation in the early stages of development.

The declining portions of the MEKC curves for all four countries support Hypothesis 4 (H4), suggesting that factors such as technological innovation and effective environmental regulations play a crucial role in reducing emissions as economies develop. This result indicates that as countries transition to higher income levels, the implementation of advanced technologies and stringent environmental policies becomes increasingly effective in mitigating CO_2 emissions. Poland's ongoing growth and the subsequent adoption of cleaner technologies and regulations highlight this trend, reinforcing the notion that technological advancements and robust regulatory frameworks are essential for achieving sustainable development goals.

To address these issues, researchers propose several strategies. Governments and policymakers in the V4 countries can encourage the use of public transportation, invest in electric cars and other fuel-efficient options, and make it easier for people to walk and use bicycles. By implementing these measures, Hungary, Slovakia, and other countries in the region can develop transportation systems that are efficient, clean, and capable of supporting their growing economies.

Overall, this study underscores the complexity of the relationship between economic growth and environmental impact. The observed inverted U-shaped relationship and varying turning points across the countries indicate that economic development can eventually lead to reduced environmental harm, provided that appropriate sustainable development policies are implemented. The sectoral contributions emphasize the need for targeted strategies in the energy and transport sectors to mitigate CO_2 emissions effectively. Tailoring effective policies that harmonize economic growth and environmental sustainability requires a deep understanding of each country's distinct economic and ecological landscapes. In light of this, the present study has uncovered several key findings:

1. Inverted U-shape relationship: An inverted U-shaped relationship exists between GDP per capita and CO_2 emissions, suggesting environmental impact initially increases with economic growth but eventually declines.
2. Turning points: In Czechia, peak emissions of approximately 1.15 Mt were observed at a GDP per capita of around USD 5000. In Hungary, peak emissions of roughly 0.65 Mt were reached at a GDP per capita of about USD 4500. In Slovakia, emissions began to decline after reaching a GDP per capita of approximately USD 5000 and 0.15 Mt of CO_2 emissions. These findings suggest that economic growth and environmental

sustainability may not necessarily be mutually exclusive and that policies aimed at promoting sustainable development should consider country-specific contexts.

3. Sectoral contributions: The power industry was found to be the largest contributor to CO_2 emissions in all four countries, accounting for an average of 88.09% of total emissions. In addition, transport and industrial combustion sectors were the significant contributors, with transport averaging 2.12% and industrial combustion 1.28% of annual emissions.
4. GDP and CO_2 emission correlation: The study found varying correlations between GDP and CO_2 emissions across the V4 countries. Czechia showed a positive correlation (0.35), while Hungary (−0.37), Poland (−0.21), and Slovakia (−0.11) showed negative correlations.
5. Transport emissions: Analysis of the relationship between GDP and transport emissions revealed that Poland had the strongest growth in CO_2 emissions from both road transport and air traffic.

The findings of this research align with previous studies, further confirming the complex relationship between economic growth and CO_2 emissions across different countries. Lazăr et al. [66] explored the connection between economic growth and CO_2 emissions in Central and Eastern European countries, confirming an inverted U-shaped relationship between GDP per capita and CO_2 emissions in most of the region. They highlighted the impact of technological advances and structural economic changes in reducing emissions over time, which is consistent with our findings. Similarly, Ayad et al. [67] focused on V4 countries and underscored the influence of policy measures on these dynamics, aligning with our consideration of different CO_2 emission scenarios. He pointed out that improvements in energy efficiency and shifts in economic structure play crucial roles in decreasing emissions, supporting our MEKC framework. Additionally, in alignment with the findings of Saud et al. [68], our analysis reveals substantial inter-country disparities in emissions attributable to divergent economic structures and energy policies. The pronounced emission levels of Poland compared to its neighbors exemplify this phenomenon.

6. Conclusions

The MEKC provides a comprehensive analysis of the relationship between economic development, as quantified by GDP, and environmental quality, as measured by $FFCO_2$ emissions, within the V4 countries. This study indicates that while CO_2 emissions initially rise with economic growth, they may stabilize as these nations advance, underscoring the critical need for integrating sustainability into economic development policies.

The diverse impacts of various sectors on climate change and environmental quality within the V4 region offer valuable information for policymakers aiming to develop effective mitigation strategies and promote sustainable growth. However, putting these findings into practice emphasizes the importance of crafting sustainable development policies that are tailored to each country's unique context.

1. Policymakers in V4 countries should focus on decoupling economic growth from CO_2 emissions, particularly in the power industry sector.
2. To achieve significant carbon reductions, policymakers must leverage existing research to develop targeted strategies for the transport and industrial sectors, which collectively account for 88.09% of total emissions. Previous studies have shown that promoting compact urban forms [69], improving public transit supply [70], constraining urban expansion [71], and expanding green spaces [72] can effectively lower emissions resulting from anthropogenic activities. By implementing these strategies, policymakers can create more sustainable urban environments and significantly reduce the carbon footprint in key sectors.
3. Poland may need to implement more aggressive environmental policies to curb its continuously increasing emissions, even as its economy grows.
4. Czechia should focus on transitioning to cleaner energy sources and improving energy efficiency to reverse the positive correlation between GDP and emissions.

5. Hungary's negative correlation between GDP and emissions could serve as a model for other V4 countries, highlighting the potential for economic growth alongside reduced emissions.
6. Investment in sustainable transportation solutions is crucial, especially for Poland, to mitigate the increasing emissions from the transport sector.
7. Policymakers should consider the unique economic and environmental contexts of each V4 country when designing and implementing emission reduction strategies.

To effectively integrate environmental sustainability with economic growth, it is crucial that policies account for the unique circumstances and challenges faced by each nation.

However, a significant limitation of the study is that it does not fully capture the impact of national and EU-level environmental policies, regulations, and incentives, despite their crucial role in influencing emission patterns and economic activities. Variations in institutional frameworks, governance quality, and enforcement mechanisms across the Visegrád countries also affect the relationship between economic growth and CO_2 emissions. The EKC hypothesis suggests that economic growth initially leads to increased environmental degradation, which later improves after reaching a certain income level. However, this assumption may not hold universally across all pollutants or contexts, with the turning point varying significantly.

Moreover, the study simplifies the complex relationships between economic activity, environmental policy, and social factors influencing emissions, potentially overlooking the overall process of environmental improvement. The analysis primarily focuses on fossil fuel CO_2 emissions and may not capture the full extent of environmental pollution generated by economic growth. Factors like population growth, technological advancements, and government policies also play significant roles in influencing economic growth and emissions.

Considering the limitations of this research, future research should adopt a comprehensive framework for examining the direct and indirect impacts of specific policies on CO_2 emissions and economic performance within the Visegrád region. A comparative study of institutional frameworks, governance quality, and enforcement mechanisms could provide deeper insights into how these factors influence the relationship between economic growth and CO_2 emissions. Additionally, incorporating other environmental measures and social and economic factors will help obtain an in-depth picture of the impact of GDP growth on the environment. By addressing these aspects, future studies can significantly enhance the understanding of the intricate relationship between economic growth and environmental sustainability in the Visegrád Region and beyond.

Ultimately, it is crucial for governments and policymakers in the Visegrád countries to promote sustainable solutions that align economic growth with environmental sustainability, ensuring prosperity for the present, and for future generations.

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