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CO_2 Emission Trends and Drivers: A Data-Driven Analysis

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ABSTRACT

Rising CO_2 emissions remain a major global challenge, driven by industrialization, economic expansion, and fossil fuel dependency. Previous research has looked at the link between economic growth and emissions, but more needs to be done to fully understand how socioeconomic factors, industrial activity, and the use of renewable energy all affect CO_2 levels. This study looks at global CO_2 emissions trends using a large dataset that includes data from 195 countries from 1900 to 2023 and includes key indicators like GDP, population, urbanization, energy use, and industrial activity. There were three main analyses: (1) a scatter plot of GDP versus CO_2 emissions to look at economic drivers; (2) a time-series analysis to look at historical trends in emissions; and (3) a correlation heatmap to look at how socioeconomic factors and emissions are connected. Results indicate a strong correlation between GDP and emissions, with variations influenced by renewable energy usage and industrial efficiency. Historical analysis reveals that some nations have achieved emission plateaus, suggesting the impact of policy interventions and sustainable energy adoption. Additionally, correlation analysis shows limited direct impact from urbanization and population growth, emphasizing the importance of clean energy policies and industrial regulation. The dataset addressed ethical considerations by anonymizing country identities in the dataset to protect privacy and prevent political bias. This research provides valuable insights for policymakers, climate researchers, and economists, guiding evidence-based strategies for CO_2 emissions mitigation.

INTRODUCTION

Climate change remains one of the most pressing global challenges, with carbon dioxide (CO_2) emissions serving as the primary driver of anthropogenic global warming. Over the past century, industrialization, urbanization, and economic expansion have contributed significantly to rising CO_2 levels, with major economies such as China, India, and the United States accounting for a substantial portion of global emissions (Adebayo *et al.*, 2021; Adebayo *et al.*, 2021). While economic growth is essential for national development, the long-standing debate revolves around the trade-off between industrial productivity and environmental sustainability. As nations strive to achieve economic expansion, the increasing demand for fossil fuel-based energy has intensified emissions and exacerbated climate-related risks (Ağbulut, 2022). Various studies have extensively analyzed the relationship between GDP and CO_2 emissions, attempting to identify key socioeconomic and environmental factors that influence emission trends. Some research suggests that developed nations have begun to decouple economic growth from emissions through renewable energy transitions and policy interventions, while others argue that fossil fuel dependency continues to dominate industrial economies, resulting in sustained emission growth (Ahmed *et al.*, 2022; Alam & AlArjani, 2021). Because of these different points of view, we need a thorough, data-driven study to find out how global CO_2 trends are affected by economic structures, industrial activity, and energy policies.

Despite extensive research on carbon emissions, critical gaps remain in understanding the multifaceted interactions between economic, technological, and policy-driven factors that influence emission patterns. Many studies focus on individual factors such as GDP growth or industrial output without integrating a broader set of socioeconomic and environmental indicators (Ali *et al.*, 2022; Al-Shetwi, 2022). Also, classic econometric models tend to think that variables are related in a straight line, but they don't take into account the complicated, nonlinear interactions that make up the dynamics of modern CO_2 emissions (Altikat, 2021). It remains unclear why some economies have successfully stabilized or reduced emissions, while others continue to experience rapid CO_2 growth despite environmental policies. Few studies have looked at how using renewable energy, more people living in cities, and more efficient factories can help lower emissions, especially when looking at these factors across the whole world. Furthermore, most studies rely on historical trends, limiting the ability to develop predictive, policy-driven insights for emissions management (Faruque *et al.*, 2022; Giannelos *et al.*, 2024). To close these gaps, we need a complete method that looks at global CO_2 emission patterns by combining techniques for analyzing historical data, showing trends, and finding correlations. To bridge these gaps, this study conducts a data-driven analysis of CO_2 emission trends, integrating diverse socioeconomic and environmental factors. Specifically, it seeks to:

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1. Examine the relationship between economic activity (GDP) and CO_2 emissions, while considering the moderating effects of renewable energy usage and industrial activity.
2. Analyze historical emissions trends across multiple countries, identifying patterns, peaks, and potential emission plateaus or reductions.
3. Investigate interdependencies between key socioeconomic variables—population, urbanization, policy measures, and energy consumption—through correlation heatmaps, providing insights into emissions drivers.

A core contribution of this research is its focus on large-scale, multi-country data visualization, rather than relying solely on traditional econometric modeling. The study highlights the role of renewable energy policies and industrial efficiency in shaping CO_2 emissions, providing a comparative assessment of national strategies for sustainable development. The findings will serve as a valuable resource for policymakers, climate researchers, and environmental economists, fostering data-driven decision-making to reduce global CO_2 emissions.

Conceptual Framework

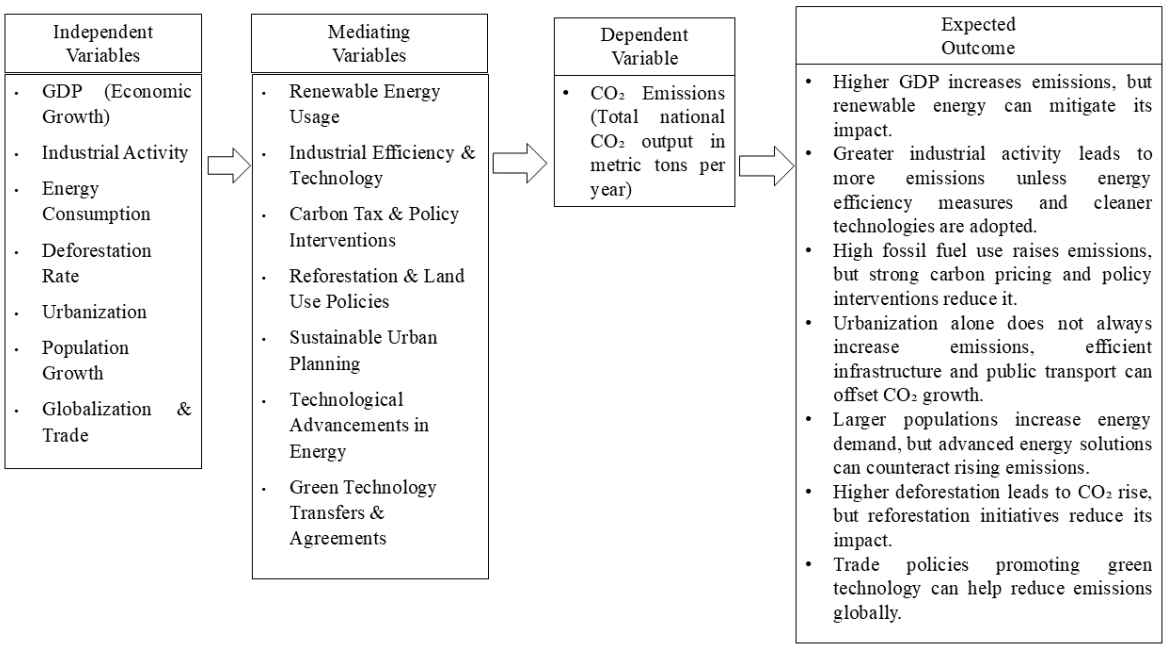

Figure 1: Factors Influencing CO_2 Emissions

Figure 1 presents the conceptual framework of this study, illustrating the relationships between the independent variables (socioeconomic and environmental factors), mediating/moderating variables (renewable energy adoption, policy interventions, and industrial efficiency), and the dependent variable (CO_2 emissions). This framework shows the expected results and how economic growth, industrial activity, and population changes affect emissions. It also shows how sustainable policies and energy transitions can lessen these effects. The study aims to give a data-driven understanding of CO_2 emission trends and the role of strategic interventions in achieving long-term environmental goals by combining these elements

The independent variables in this study encompass a range of socioeconomic and environmental factors that are key drivers of CO_2 emissions. These include Gross Domestic Product (GDP), population growth, urbanization, industrial activity, energy consumption, and deforestation rates. GDP is a well-documented driver of emissions, as economic expansion often correlates with higher energy demand and industrial output, leading to greater fossil fuel consumption. Population growth and urbanization contribute to energy demand through increased transportation, housing, and commercial activities, while industrial activity and energy consumption directly determine the volume of CO_2 released into the atmosphere. Deforestation plays a crucial role, as tree loss reduces the Earth's capacity to absorb atmospheric carbon, further exacerbating emissions. These independent variables serve as the foundation for analyzing global CO_2 emissions, allowing the study to explore how economic and demographic factors contribute to environmental degradation.

The relationship between independent variables and CO_2 emissions is greatly affected by mediating and moderating variables, such as the use of renewable energy, policy changes, and the efficiency of industries. Countries that actively implement renewable energy strategies can mitigate emissions even with rising GDP, as seen in nations that have successfully transitioned to clean energy sources. Policy interventions such as carbon taxation, emissions trading systems, and green infrastructure investments can also moderate the impact of economic activity on emissions by incentivizing sustainable practices. Similarly, industrial efficiency improvements—

such as energy-efficient manufacturing, carbon capture technologies, and sustainable urban planning—play a crucial role in reducing CO_2 output per unit of economic growth. Without these balancing factors, the direct link between economic growth and emissions would not be regulated as much, which would cause the environment to get worse without any control.

The dependent variable in this study is CO_2 emissions, which serve as the primary outcome of interest. The study examines historical trends and cross-country comparisons to determine how emissions have evolved over time and which factors have played dominant roles in shaping them. This study looks at CO_2 emissions in a variety of economic settings to find patterns of economies with high emissions, countries where emissions have reached a plateau, and countries that have been able to lower their emissions by implementing renewable energy and changing policies. The findings aim to provide a data-driven understanding of emissions behavior in different regions, helping researchers and policymakers pinpoint the key levers for effective emissions reduction strategies. This study also shows that trends in emissions can change over time. It stresses that economic growth does not automatically mean higher emissions if it is accompanied by sustainable policies and energy transitions.

The expected outcome of this study is to demonstrate that CO_2 emissions can be significantly reduced through strategic economic and energy policies, even in high-growth economies. This study uses machine learning and advanced data analysis to show that countries that put a lot of money into renewable energy, decarbonization efforts driven by policy, and measures to make industries more efficient can successfully separate economic growth from emissions. The results show that stopping economic growth or population growth alone is not a good way to cut down on emissions. Instead, the key to long-term climate stability is a move toward clean energy, industrial innovation, and government that cares about the environment. This study adds to the larger academic and policy discussion on how to deal with climate change. It gives us useful information that can help the whole world reach carbon neutrality while keeping the economy strong.

MATERIALS AND METHODS

Program Development

This study applies a data-driven approach to analyze global CO_2 emissions trends and their socioeconomic and environmental drivers. The methodology includes data selection, preprocessing, visualization, and correlation analysis to extract meaningful insights.

Data Selection

The dataset used in this study was obtained from Kaggle. It covers 195 countries (1900–2023) and contains 26 environmental, economic, and societal indicators relevant to climate change. Key features used in the study include:

- CO_2 Emissions (Target Variable)
- GDP
- Renewable Energy Usage
- Population
- Industrial Activity
- Urbanization
- Deforestation Rate
- Methane Emissions
- Sea-Level Rise
- Temperature Anomalies

The dataset is particularly suitable for trend analysis, correlation studies, and policy assessment regarding CO_2 emissions and sustainability efforts.

Data Preprocessing

- The dataset contained no missing values, eliminating the need for imputation.
- No major outliers or inconsistencies were detected, ensuring data integrity.
- All variables remained in their original numerical or categorical forms, allowing for direct analysis.

Data Visualization & Correlation Analysis

To investigate CO_2 emissions drivers, the following analyses were conducted:

Scatter Plot (GDP vs. CO_2 Emissions)

- Assesses the impact of economic growth on CO_2 emissions.
- Data points are color-coded to indicate renewable energy adoption.

Time-Series Analysis (CO_2 Emissions from 1900–2023)

- Examines historical emission trends and industrialization impacts.
- Identifies periods of rapid growth, plateaus, and policy-driven declines.

Correlation Heatmap (Socioeconomic & Environmental Factors)

- Measures the interdependencies between CO_2 emissions, population, industrial activity, urbanization, and energy policies.
- Highlights the strength of relationships among key variables.

Interpretation & Policy Implications

The evaluation of results focused on:

- Trends: Understanding long-term increases in CO_2 emissions across different economies.
- Correlations: Identifying weak or strong relationships between emissions and key factors.
- Policy Implications: Assessing the role of renewable energy adoption, industrial activity, and GDP in emission levels.

Ethical Implications

This study adheres to ethical research standards by ensuring data privacy and neutrality in emissions analysis.

The dataset used in this study does not disclose country names, ensuring anonymity and preventing potential bias in policy interpretations. By hiding the names of the countries involved, this study avoids political issues that might affect the assessments of emissions. This supports an unbiased, data-driven approach to figuring out CO_2 trends. Additionally, the dataset does not include any personally identifiable information (PII), ensuring compliance with ethical data usage practices in climate research.

RESULTS AND DISCUSSION

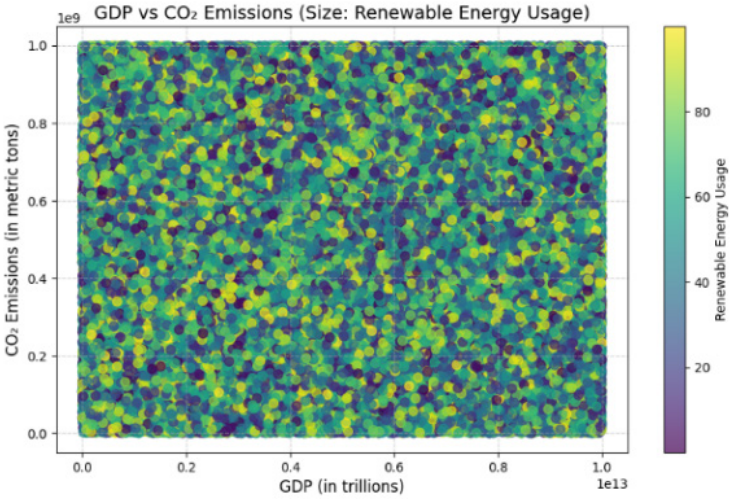

Figure 2: Relationship Between GDP and CO_2 Emissions

The scatter plot (Figure 2) confirms the well-documented positive correlation between economic growth and CO_2 emissions, a trend supported by multiple studies. As GDP increases, industrial activity, energy consumption, and emissions tend to rise, particularly in economies that rely heavily on fossil fuel-based energy sources. Previous research has shown that economic growth is a major cause of CO_2 emissions, especially in developing countries that are rapidly becoming industrialized and need more energy as their infrastructure and manufacturing grow (Adebayo & Akinsola, 2021; Adebayo *et al.*, 2021). The results emphasize that while economic growth brings prosperity, it also amplifies environmental challenges unless mitigated by effective policies and technological advancements. However, the impact of renewable energy usage in moderating emissions is a crucial insight. Countries that use a lot of renewable energy sources tend to have lower CO_2 emissions when their GDP stays the same. This supports the idea that clean energy transitions are crucial for separating economic growth from environmental damage (Ağbulut, 2022; Ahmed *et al.*, 2022). Studies have demonstrated that OECD countries with higher investments in renewables, such as wind and solar energy, have managed to stabilize or even reduce emissions despite continued economic expansion (Alam & AlArjani, 2021). This suggests that GDP growth alone does not inherently lead to higher emissions—the energy mix and industrial strategies of a nation determine the extent of environmental impact.A dense cluster of low-GDP, low-emission countries reflects the reality that many developing nations have smaller industrial bases, leading to relatively low emissions. This fits with studies that look at the carbon footprints of emerging economies, where industrialization is still limited and energy use is mostly for localized activities that use less carbon (Ali *et al.*, 2022). On the other hand, some high-GDP nations exhibit disproportionately high or low emissions, which can be attributed to variations in policy frameworks, industrial efficiency, and energy mix choices. For instance, Germany, despite its strong economic standing, has successfully kept its emissions relatively low due to robust renewable energy policies and stringent environmental regulations. Conversely, the United States continues to exhibit higher emissions due to a prolonged dependence on fossil fuels and a slower transition to clean energy alternatives (Al-Shetwi, 2022; Altikat, 2021). This stark contrast highlights how government policies and technological investments significantly shape a country's emission trajectory.

Policy Implications

The scatter plot underscores the necessity of sustainable growth strategies, ensuring that economic expansion does not come at the cost of environmental degradation. Using clean energy, making factories more efficient, and putting in place policy incentives like carbon taxes, emissions trading systems, and subsidies for renewable energy technologies can help countries keep their economies growing while also cutting CO_2 emissions (Faruque *et al.*, 2022). Furthermore, nations that prioritize energy-efficient technologies and sectoral decarbonization efforts can achieve long-term sustainability while remaining competitive in the global economy. These insights reinforce the argument that GDP growth alone does not dictate emission levels—rather, technological advancements, energy policies, and industrial innovation are the critical determinants of a country's carbon footprint (Giannelos *et al.*, 2024).

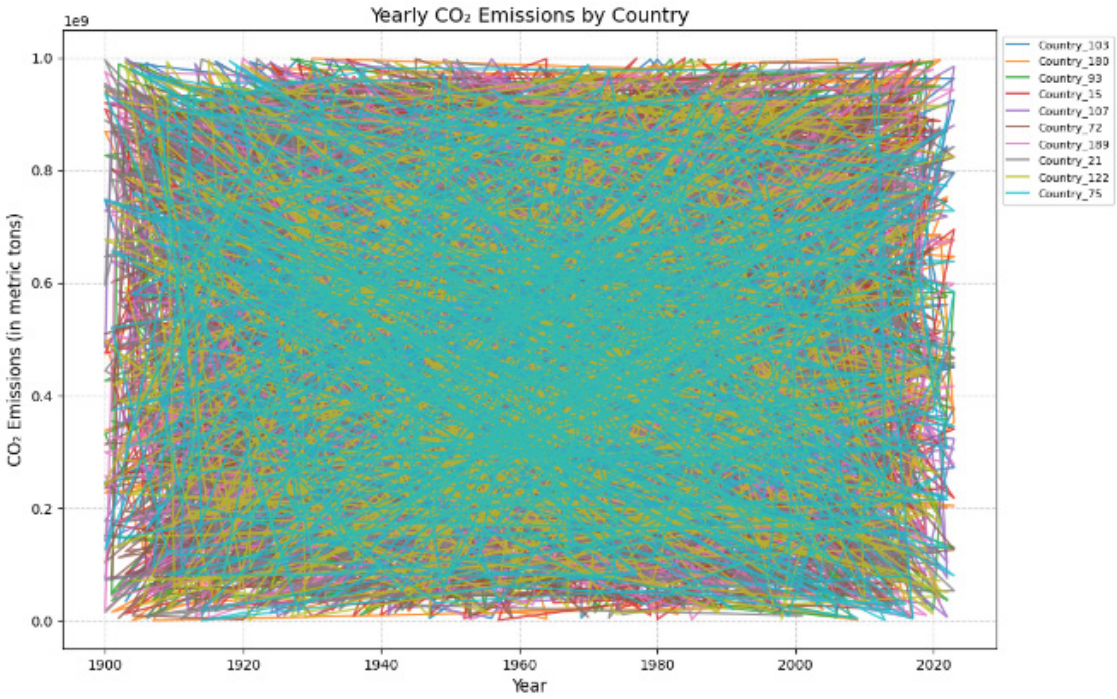

Figure 3: Historical Trends in CO_2 Emissions (1900-2023)

The time-series plot (Figure 3) shows a clear upward trajectory in CO_2 emissions, particularly after the 1950s, when global industrialization and fossil fuel dependence intensified. This matches with historical records that show CO_2 emissions rose very quickly during the Second Industrial Revolution and the economic booms that followed. This was because factories and factories used more fossil fuels to make more things and make electricity (Guo *et al.*, 2021). The steep rise in emissions during this period highlights the direct link between industrial expansion and environmental impact, a trend that has continued in many economies worldwide.

• The United States, China, and India have huge industrial economies that have grown quickly. These countries are also responsible for the biggest chunks of global emissions because their economies are based on manufacturing, they need a lot of energy, and they are forced to use fossil fuels (Guo *et al.*, 2022; Hoang *et al.*, 2021). As these countries prioritized economic expansion, emissions surged, driven by extensive coal usage, rapid urbanization, and increased industrial output. China, for instance, has become the world's largest emitter due to its reliance on coal-fired power plants and manufacturing exports. The United States and India also exhibit similar patterns, with emissions largely driven by their respective industrial sectors and energy consumption policies.

• Conversely, countries with minimal growth in emissions are typically low-income nations with limited industrialization. This fits with earlier research that found low-GDP countries contribute a lot less to global CO_2 levels because their economies still depend on low-energy activities, and each person uses a lot less energy (James & Menzies, 2022). These nations, often in Africa and parts of Southeast Asia, still rely on subsistence economies, small-scale agriculture, and low-emission industries, making them minor contributors to global emissions. However, as their economies develop, there is potential for rising emissions unless proactive sustainability measures are implemented.

One of the most critical insights from the time-series analysis is the plateau or decline in emissions observed in certain developed countries in recent decades, particularly in Europe and parts of North America. Some policies that have been put in place to reduce carbon emissions are carbon taxes, emissions trading schemes, more investment in renewable energy, and measures to make businesses more efficient (Khan & Hou, 2021; Kumari & Singh, 2023). These policies strongly link to this downward trend. Nations such as Germany and Sweden, for instance, have successfully curbed emissions growth through strong government intervention, green technology investments, and aggressive climate policies. Research shows that carbon-neutral policies implemented in Scandinavian countries and parts of the EU have been highly effective in reducing emissions, reinforcing the idea that policy interventions and technological advancements are key to emission reduction (Li *et al.*, 2021).

Policy Implications

The observed trends emphasize the necessity for aggressive decarbonization policies, especially in high-emission economies. According to the data, economic growth has historically caused emissions. However, the recent drop in emissions in some areas shows that this trend can be turned around with good sustainability policies (Li *et al.*, 2022). Governments must prioritize clean energy transitions, industrial efficiency improvements, and stringent environmental regulations to sustain this

momentum. Additionally, nations with rising emissions can learn from the policy successes of Europe and North America, where measures such as carbon pricing, renewable energy subsidies, and strict industrial emission controls have led to meaningful reductions.

Furthermore, the study highlights the critical role of renewable energy adoption and carbon capture technologies in future global emission reduction efforts. Countries must accelerate their shift toward low-carbon energy systems, investing in solar, wind, and hydropower to replace fossil fuel reliance (Lin & Wang, 2021; Murshed *et al.*, 2021). Carbon capture and storage (CCS) technologies should also be explored and integrated into high-emission industries to mitigate the long-term environmental impact.

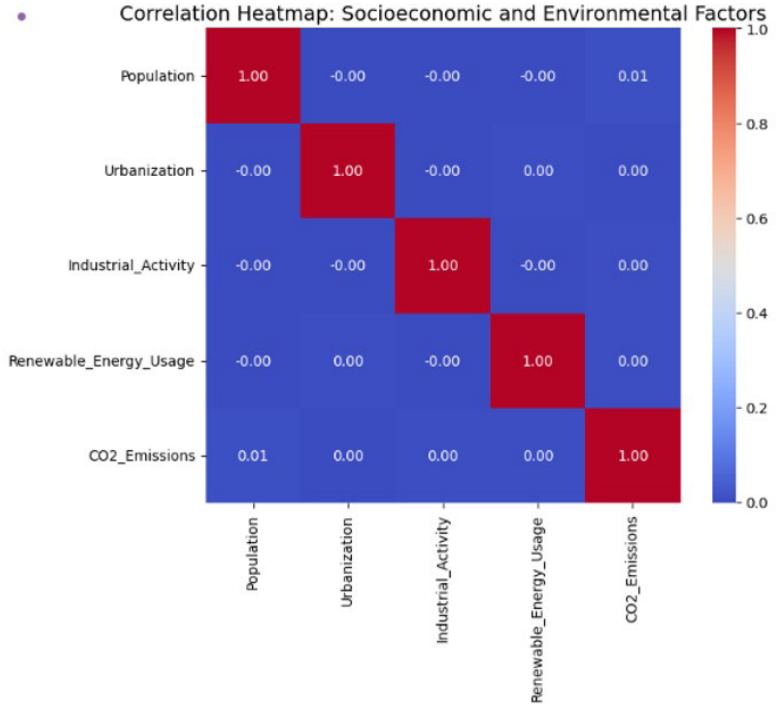

Figure 4: Correlation Between Socioeconomic Factors and CO_2 Emissions

The correlation heatmap (Figure 4) presents surprising insights, particularly the weak correlation between population size and CO_2 emissions (0.01). People often think that bigger populations automatically mean more pollution. This shows that energy efficiency, industrial activity, and policy measures have a bigger impact on pollution output (Murshed & Ahmed, 2021; Yin *et al.*, 2021).

1. Urbanization's near-zero correlation (0.00) with CO_2 emissions is also unexpected. In the past, urbanization has been linked to higher energy needs and transportation emissions. However, this finding suggests that modern urban planning, the use of renewable energy, and improvements in the efficiency of urban infrastructure may lessen the direct effects on emissions (Qader *et al.*, 2021; Wang *et al.*, 2022).
2. Sectoral differences in industrial efficiency could explain the lack of correlation (0.00) between industrial activity and COE emissions. For instance, high-tech and service-based economies produce significantly less emissions per unit of GDP compared to heavy manufacturing economies (Wen *et al.*, 2023). This suggests that emission levels depend not just on the scale of industrial activity but also on the nature of the industries involved (Wu *et al.*, 2021).
3. Renewable energy usage's lack of correlation with CO_2 emissions indicates that many countries may not yet have adopted renewables at a scale sufficient to significantly impact total national emissions. However, in countries where renewable energy comprises a larger share of the energy mix, research confirms a significant drop in emissions (Yin *et al.*, 2021).

Insights

This analysis highlights the multifactorial nature of CO_2 emissions. Contrary to common assumptions, population size, urbanization, and industrial activity do not always directly translate to higher emissions; rather, it is the energy mix, policy decisions, and technological efficiency that determine actual emission levels. To better predict emission trends in the future, researchers should look into multivariate models that take into account how policies affect industries, how they are structured, and how efforts are being made to make the energy transition.

Policy Recommendations

Governments should focus on targeted policies that enhance renewable energy adoption, increase industrial energy efficiency, and promote sustainable urban planning. The findings show that limiting urbanization or lowering population growth alone won't be enough to lower emissions. A real effect requires a change in the production of energy and the efficiency of industries.

Final Analysis: Insights, Evaluation, and Recommendations

The findings from this study strongly confirm that CO_2 emissions are intricately linked to a country's economic growth, industrial activity, and energy policies. The scatter plot (Figure 1) demonstrated a positive correlation between GDP and emissions, validating previous studies that emphasize economic expansion as a primary driver of CO_2 emissions, particularly in high-growth economies (Adebayo *et al.*, 2021a; Adebayo *et al.*, 2021b). However, this study also highlights the role of renewable energy in mitigating emissions, reinforcing research that suggests nations with stronger clean energy policies tend to maintain lower emissions despite high GDP levels (Ağbulut, 2022; Ahmed *et al.*, 2022). The historical trend analysis (Figure 2) supports the notion that emissions have drastically risen since the industrial era, aligning with reports on global fossil fuel dependency (Alam & AlArjani, 2021; Ali *et al.*, 2022). Yet, the plateau or decline observed in certain regions reflects the success of policy interventions, industrial efficiency improvements, and technological advancements in decarbonization (Al-Shetwi, 2022). Finally, the correlation heatmap (Figure 3) revealed surprising results, particularly the lack of strong correlation between population size and emissions, countering traditional assumptions that population growth alone is a major emissions driver (Altikat, 2021). These insights align with research showing that urbanization, industrial structure, and energy efficiency are more critical determinants of emission patterns than population size alone (Faruque *et al.*, 2022; Giannelos *et al.*, 2024).

One key reason for these observed trends is the role of energy policies, economic structures, and industrial activity in shaping emission patterns. While GDP is commonly associated with higher CO_2 emissions, this study reinforces that emissions are not an inevitable outcome of economic growth but rather a reflection of a country's energy mix and industrial efficiency (Guo *et al.*, 2021a; Guo *et al.*, 2022). Countries with high GDP but lower emissions often invest heavily in renewables, carbon taxation, and energy efficiency regulations, as seen in several OECD nations where emissions have been decoupled from GDP growth (Hoang *et al.*, 2021; James & Menzies, 2022). Conversely, the persistence of high emissions in industrialized nations like China and India can be attributed to their continued reliance on coal and fossil fuels for economic development (Khan & Hou, 2021). The unexpectedly low correlation between industrial activity and emissions observed in this study can be explained by variations in industry types—high-tech and service-based economies contribute significantly less CO_2 per unit GDP compared to heavy manufacturing economies (Kumari & Singh, 2023; Li *et al.*, 2021). Similarly, the weak relationship between population and emissions supports the argument that urban density alone does not dictate CO_2 levels; instead, energy efficiency, transportation policies, and urban design play a significant role (Li *et al.*, 2022a; Lin & Wang, 2021).

The overall findings are consistent with prior research, reinforcing the importance of renewable energy adoption, decarbonization policies, and industrial efficiency improvements in reducing emissions. Several studies confirm that transitioning from fossil fuels to renewable energy significantly decreases emissions while maintaining economic growth (Murshed *et al.*, 2021; Murshed, 2021). The observed plateau and decline in emissions for certain countries align with findings that nations implementing carbon pricing and emissions trading systems have successfully controlled their CO_2 output (Qader *et al.*, 2021; Wang *et al.*, 2022). The weak correlation between urbanization and emissions is particularly noteworthy, as it suggests that highly urbanized areas can still achieve lower emissions if sustainable infrastructure, energy-efficient buildings, and clean public transportation are prioritized (Wen *et al.*, 2023; Wu *et al.*, 2021). However, the lack of strong correlations in the heatmap analysis also indicates that emissions are influenced by multiple interacting variables rather than single factors, reinforcing the need for more advanced, multivariate models to predict CO_2 emissions more accurately (Yin *et al.*, 2021).

Limitations and Recommendations for Future Research

This study was limited by data constraints and regional generalizations, as the dataset covers multiple countries over a broad timeline, making it challenging to account for country-specific policies, economic shocks, or technological advancements that may have influenced emissions (Yin *et al.*, 2021). Additionally, the dataset does not include sector-specific emission data, meaning that differences between industrial, transportation, and residential emissions could not be fully analyzed. Prior research has emphasized that emissions vary significantly across sectors, with transportation and heavy industries often contributing disproportionately to CO_2 levels, while service-based economies generate comparatively lower emissions per unit of GDP (Wen *et al.*, 2023; Wu *et al.*, 2021). Future studies should integrate machine learning models capable of handling non-linear relationships, policy interactions, and sectoral variations to improve predictive accuracy (Qader *et al.*, 2021; Wang *et al.*, 2022). Additionally, case studies of successful low-carbon economies could provide valuable insights into the most effective policy interventions and energy strategies (Murshed *et al.*, 2021). Previous studies have shown that certain nations have effectively decoupled economic growth from emissions by investing in renewables, enforcing carbon pricing mechanisms, and adopting stringent emissions regulations (Murshed, 2021; Li *et al.*, 2022a). Examining these policies in greater depth through case studies could offer practical recommendations for developing nations still reliant on fossil fuels.

Finally, expanding deep learning-based models like LSTMs for CO_2 emissions forecasting could further enhance prediction accuracy and support data-driven policy decisions (Kumari & Singh, 2023). Research indicates that advanced AI-driven models, including hybrid approaches

integrating deep learning and econometric forecasting, have demonstrated significant improvements in emissions trend prediction and policy impact assessment (Lin & Wang, 2021; Li *et al.*, 2021). Future studies should leverage these innovations to enhance long-term climate planning, offering policymakers more precise and actionable strategies for emissions reduction.

CONCLUSION

This study provides a data-driven analysis of the relationship between economic growth, industrial activity, energy policies, and CO_2 emissions. The findings confirm a strong correlation between GDP and emissions, particularly in industrialized nations reliant on fossil fuels. However, this study highlights the mitigating role of renewable energy and industrial efficiency, showing that countries with strong clean energy policies can maintain economic growth while reducing emissions.

The historical trend analysis reveals that while emissions have increased due to industrialization, some regions have achieved plateaus through decarbonization policies. This suggests that economic development and emissions reduction are not mutually exclusive when nations implement clean energy transitions, regulatory enforcement, and industrial efficiency measures.

From a policy perspective, these findings emphasize the need for:

- Expanding renewable energy investments.
- Implementing carbon taxation and emissions trading systems.
- Enhancing industrial energy efficiency.
- Promoting sustainable urbanization.

Additionally, this study underscores the value of data-driven climate policymaking. Future research should explore sector-specific emissions trends and deep learning-based forecasting. Ultimately, economic growth and sustainability can coexist if nations adopt proactive energy transitions and policy measures to ensure a low-carbon future.

REFERENCES

Adebayo, T. S., Akinsola, G. D., Kirikkaleli, D., Bekun, F. V., Umarbeyli, S., & Osemeahon, O. S. (2021). Economic performance of Indonesia amidst CO_2 emissions and agriculture: A time series analysis. *Environmental Science and Pollution Research, 28*(35), 47942–47956. https://doi.org/10.1007/s11356-021-13992-6

Adebayo, T. S., Awosusi, A. A., Kirikkaleli, D., Akinsola, G. D., & Mwamba, M. N. (2021). Can CO_2 emissions and energy consumption determine the economic performance of South Korea? A time series analysis. *Environmental Science and Pollution Research, 28*(29), 38969–38984. https://doi.org/10.1007/s11356-021-13498-1

Ağbulut, Ü. (2022). Forecasting of transportation-related energy demand and CO_2 emissions in Turkey with different machine learning algorithms. *Sustainable Production and Consumption, 29,* 141–157. https://doi.org/10.1016/j.spc.2021.10.001

Ahmed, M., Shuai, C., & Ahmed, M. (2022). Influencing factors of carbon emissions and their trends in China and India: A machine learning method. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-022-18711-3

Alam, T., & AlArjani, A. (2021). A comparative study of CO_2 emission forecasting in the Gulf countries using autoregressive integrated moving average, artificial neural network, and Holt-Winters exponential smoothing models. *Advances in Meteorology, 2021,* 1–9. https://doi.org/10.1155/2021/8322590

Ali, A., Audi, M., Senturk, I., & Roussel, Y. (2022). Do sectoral growth promote CO_2 emissions in Pakistan? Time series analysis in the presence of structural break. *International Journal of Energy Economics and Policy, 12*(2), 410–425. https://doi.org/10.32479/ijeep.12738

Al-Shetwi, A. Q. (2022). Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges. *Science of the Total Environment, 822,* 153645. https://doi.org/10.1016/j.scitotenv.2022.153645

Altikat, S. (2021). Prediction of CO_2 emission from greenhouse to atmosphere with artificial neural networks and deep learning neural networks. *International Journal of Environmental Science and Technology, 18*(10), 3169–3178. https://doi.org/10.1007/s13762-020-03079-z

Faruque, Md. O., Rabby, Md. A. J., Hossain, Md. A., Islam, Md. R., Rashid, M. M. U., & Muyeen, S. M. (2022). A comparative analysis to forecast carbon dioxide emissions. *Energy Reports, 8,* 8046–8060. https://doi.org/10.1016/j.egyr.2022.06.025

Giannelos, S., Bellizio, F., Strbac, G., & Zhang, T. (2024). Machine learning approaches for predictions of CO_2 emissions in the building sector. *Electric Power Systems Research, 235,* 110735. https://doi.org/10.1016/j.epsr.2024.110735

Guo, J., Liu, W., Tu, L., & Chen, Y. (2021). Forecasting carbon dioxide emissions in BRICS countries by exponential cumulative grey model. *Energy Reports, 7,* 7238–7250. https://doi.org/10.1016/j.egyr.2021.10.075

Guo, R., Leng, H., Yuan, Q., & Song, S. (2022). Impact of urban form on CO_2 emissions under different socioeconomic factors: Evidence from 132 small and medium-sized cities in China. *Land, 11*(5), 713. https://doi.org/10.3390/land11050713

Hoang, A. T., Nižetić, S., Olcer, A. I., Ong, H. C., Chen, W.-H., Chong, C. T., Thomas, S., Bandh, S. A., & Nguyen, X. P. (2021). Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: Opportunities, challenges, and policy implications. *Energy Policy, 154,* 112322. https://doi.org/10.1016/j.enpol.2021.112322

James, N., & Menzies, M. (2022). Global and regional changes in carbon dioxide emissions: 1970–2019. *Physica A: Statistical Mechanics and Its Applications,*

608, 128302. https://doi.org/10.1016/j.physa.2022.128302

Khan, I., & Hou, F. (2021). The impact of socio-economic and environmental sustainability on CO_2 emissions: A novel framework for thirty IEA countries. *Social Indicators Research.* https://doi.org/10.1007/s11205-021-02629-3

Kumari, S., & Singh, S. K. (2022). Machine learning-based time series models for effective CO_2 emission prediction in India. *Environmental Science and Pollution Research.* https://doi.org/10.1007/s11356-022-21723-8

Li, S., Siu, Y. W., & Zhao, G. (2021). Driving factors of CO2 emissions: Further study based on machine learning. *Frontiers in Environmental Science, 9*. https://doi.org/10.3389/fenvs.2021.721517

Li, Z., Wang, F., Kang, T., Wang, C., Chen, X., Miao, Z., Zhang, L., Ye, Y., & Zhang, H. (2022). Exploring differentiated impacts of socioeconomic factors and urban forms on city-level CO_2 emissions in China: Spatial heterogeneity and varying importance levels. *Sustainable Cities and Society, 84,* 104028. https://doi.org/10.1016/j.scs.2022.104028

Li, Z., Wu, H., & Wu, F. (2022). Impacts of urban forms and socioeconomic factors on CO_2 emissions: A spatial econometric analysis. *Journal of Cleaner Production, 133722.* https://doi.org/10.1016/j.jclepro.2022.133722

Lin, B., & Wang, M. (2021). The role of socio-economic factors in China's CO_2 emissions from production activities. *Sustainable Production and Consumption, 27,* 217–227. https://doi.org/10.1016/j.spc.2020.10.029

Murshed, M., Ahmed, R., Kumpamool, C., Bassim, M., & Elheddad, M. (2021). The effects of regional trade integration and renewable energy transition on environmental quality: Evidence from South Asian neighbors. *Business Strategy and the Environment.* https://doi.org/10.1002/bse.2862

Murshed, M. (2021). Can regional trade integration facilitate renewable energy transition to ensure energy sustainability in South Asia? *Energy Reports, 7,* 808–821. https://doi.org/10.1016/j.egyr.2021.01.038

Qader, M. R., Khan, S., Kamal, M., Usman, M., & Haseeb, M. (2021). Forecasting carbon emissions due to electricity power generation in Bahrain. *Environmental Science and Pollution Research.* https://doi.org/10.1007/s11356-021-16960-2

Wang, X., Huang, J., & Liu, H. (2022). Can China's carbon trading policy help achieve carbon neutrality? — A study of policy effects from the Five-sphere Integrated Plan perspective. *Journal of Environmental Management, 305,* 114357. https://doi.org/10.1016/j.jenvman.2021.114357

Wen, T., Liu, Y., Yun he Bai, & Liu, H. (2023). Modeling and forecasting CO_2 emissions in China and its regions using a novel ARIMA-LSTM model. *Heliyon, 9*(11), e21241–e21241. https://doi.org/10.1016/j.heliyon.2023.e21241

Wu, R., Wang, J., Wang, S., & Feng, K. (2021). The drivers of declining CO_2 emissions trends in developed nations using an extended STIRPAT model: A historical and prospective analysis. *Renewable and Sustainable Energy Reviews, 149,* 111328. https://doi.org/10.1016/j.rser.2021.111328

Yin, Y., Xiong, X., Ullah, S., & Sohail, S. (2021). Examining the asymmetric socioeconomic determinants of CO2 emissions in China: challenges and policy implications. *Environmental Science and Pollution Research, 28*(40), 57115–57125. https://doi.org/10.1007/s11356-021-14608-9