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The Effect of Macroeconomic Factors on Carbon Emissions in the USA: A Statistical Analysis by Industry Sector

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Abstract

This study investigates how economic factors such as gross domestic product (GDP), industrial production, inflation, and the federal funds effective rate affect carbon dioxide (CO_2) emissions across nine major sectors in the United States (U.S). While previous research has primarily concentrated on aggregate national emissions, this analysis takes a sectoral approach by using linear regression analysis to quantify how each economic variable impacts specific categories of CO_2 emissions. The findings indicate that economic growth and industrial production are significant contributors to emissions, although their effects differ from one sector to another. Inflation and monetary policy appear to have the weakest and limited statistical significance and influence across sectors. The most significant decrease in CO_2 emissions is observed in coal and electric power sectors. Furthermore, we found no significant effects of the 2008 financial crisis and the COVID-19 pandemic on carbon emissions, except a significant impact of the 2008 financial crisis on carbon emissions in the transportation sector. The results highlight the complexity of the relationship between the economy and emissions, underscoring the need for sector-specific policies and technological innovation to help achieve the U.S. goal of net-zero emissions by 2050. This research provides evidence-based insights for policymakers who aim to balance economic development with environmental sustainability.

Keywords: carbon emissions; macroeconomic factors; industrial sectors; United States; regression analysis

1. Introduction

The relationship between economic growth and carbon emissions has been extensively studied in the field of environmental economics. A significant amount of research has focused on how the expansion of national economies affects environmental outcomes [1–6]. A central concept in this discussion is the Environmental Kuznets Curve (EKC) hypothesis. This hypothesis suggests that as economies develop, carbon emissions initially increase due to heightened industrial activity and energy consumption. However, emissions are expected to decline eventually as higher income levels facilitate the adoption of cleaner technologies and stricter environmental regulations [2,3,7,8]. While a fundamental study by Grossman and Krueger [7] established the theoretical basis for the EKC, empirical results within the United States have been mixed. For example, Liddle and Sadorsky [5] argued that ongoing economic growth, especially in sectors like transportation and manufacturing, continues to drive emissions upward because of a persistent reliance on energy-intensive processes. Additionally, Wang et al. [6] found a strong positive relationship between GDP

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growth and carbon emissions, highlighting significant contributions from sectors such as transportation and industrial manufacturing. In contrast, Galeotti et al. [8] showed evidence that high income levels can ultimately lead to improved environmental performance, supporting the EKC hypothesis. Aldy [9] indicated that strategic policy interventions and a shift toward clean energy could help decouple economic growth from carbon emissions in the long run. This suggests a potential transition towards a more sustainable growth model within the U.S context [9]. However, further empirical evidence is needed to determine whether this decoupling has been firmly established nationwide [9].

Energy consumption is a significant driver of carbon emissions, with the United States being one of the world's largest energy consumers. The combustion of fossil fuels represents a predominant source of anthropogenic carbon emissions [10]. Pao and Tsai [11] highlighted that increased energy consumption, often driven by strong economic growth, is a major factor behind rising emission levels. However, studies by Sadorsky [12] indicated that improvements in energy efficiency and the integration of renewable energy sources can help mitigate these emissions. Despite the growing adoption of renewable energy, Gillingham and Huang [13] observed that fossil fuels remain dominant in the U.S. energy landscape, resulting in persistently high overall emissions. Additionally, Apergis and Payne [14] emphasized the moderating role of renewable energy use and financial development, suggesting similar strategies could be employed in the U.S to transition toward a cleaner energy mix.

Besides, industrial activity is another major contributor to carbon emissions, though its impact varies significantly across different sectors. Manufacturing and heavy industries rely heavily on coal, natural gas, and petroleum, making them substantial sources of emissions [15]. In his study, Sorrell [16] pointed out that energy-intensive industrial processes continue to challenge emission reduction efforts, even with technological advancements. Johnstone et al. [17] argued that shifts toward automation and cleaner production methods have the potential to lower emissions, although sector-specific constraints may limit these improvements.

In addition, the transportation sector is also a primary source of emissions in the U.S., largely due to its reliance on gasoline and diesel. Works by Davis and Boundy [18] and Popp et al. [19] showed that while the adoption of electric vehicles and enhancements in fuel efficiency show promise, their overall impact is hindered by infrastructural challenges and slow market penetration. In the commercial and residential sectors, activities such as heating, cooling, and electricity use in buildings contribute significantly to carbon emissions. Ürge-Vorsatz et al. [20] underscored the importance of implementing stricter energy efficiency standards, providing incentives for energy-efficient systems, and developing smart grid technologies to achieve meaningful reductions in emissions.

Furthermore, the impact of trade openness on carbon emissions has garnered significant attention, particularly in the context of globalization's effects on production and transportation. Antweiler et al. [21] and Copeland and Taylor [22] argued that trade liberalization can lead to increased industrial output and, consequently, higher carbon emissions, especially when production is energy intensive. Conversely, Cole and Elliott [23] and Kalaycı and Hayaloğlu [24] suggested that globalization may also facilitate the diffusion of cleaner technologies and promote greater environmental awareness. In the U.S., Shahbaz et al. [25] found that while trade openness drives economic growth, it is also associated with increased emissions due to heightened domestic production and logistics. Liddle and Sadorsky [5] observed that trade flows can have opposing effects; for instance, exports may lower consumption-based emissions, while higher imports can increase them. Although these trends are observed globally, the specific dynamics within the U.S require further empirical validation. Aldy [9] proposed that policy measures, such as carbon border adjustments, could help mitigate the negative environmental impacts of trade by discouraging the relocation of high-emission industries to countries with less stringent regulations.

Economic policy instruments and regulatory interventions are crucial in shaping the trajectory of carbon emissions. Market-based tools, such as carbon taxes, cap-and-trade systems, and renewable energy subsidies, have been extensively studied for their effectiveness in reducing emissions without hindering economic growth [26]. Stavins [27] provided a comprehensive analysis of how these instruments, when effectively implemented, can internalize the environmental costs of emissions. For example, the Regional Greenhouse Gas Initiative (RGGI) and California's cap-and-trade program have successfully lowered emissions while supporting continued economic expansion [28]. Schmalensee and Stavins [29] noted that policies like the Clean Air Act have significantly contributed to emission reductions in the U.S, although political resistance and economic costs remain substantial barriers to further progress [30].

Technological progress is widely recognized as a major factor in mitigating the environmental impact of economic activities. Jaffe et al. [31] showed that advancements in energy efficiency, carbon capture, and clean energy technologies contributed to declines in emissions intensity in developed economies, including the U.S. Nevertheless, the slow diffusion of green technologies remains a challenge [17,19]. Aghion et al. [32] emphasized that sustained investment in research and development is essential for achieving long-term reductions in emissions, especially in sectors like transportation and power generation. Recent research by Zhou et al. [33] provided evidence from both the U.S and China, demonstrating a significant inverse relationship between renewable energy consumption and carbon emissions. This suggests that regions with more advanced renewable energy transitions tend to have lower emissions. Furthermore, Rehman et al. [34] showed that increased wind and solar energy generation can substantially reduce carbon emissions, reinforcing the critical role of technological innovation in addressing environmental challenges.

In summary, the existing literature on the relationship between economic growth and carbon emissions is mainly carried out at the national level. However, based on the existing research, there is still the following question that needs to be further probed into and elucidated. Specifically, from a macroeconomic perspective, studies have observed significant effects of economic growth on carbon emissions. But, from a relatively micro-analysis perspective, how do macroeconomic factors impact carbon emissions in individual industrial sectors? Indeed, the literature underscores the complexity of the relationship between economic development and carbon emissions, highlighting the importance of sectoral analysis, the evolving role of energy sources, and the influence of trade, policy, and technological innovation. These insights provide a foundation for further empirical investigation into the detailed dynamics of economic factors and carbon emissions in the United States at industry level for better environmental policy management.

This study aims to examine how macroeconomic variables, namely gross domestic product (GDP), industrial production, inflation, and the federal funds effective rate (FER), affect sector-specific carbon dioxide (CO_2) emissions in the United States. Specifically, the objectives of the study are twofold. First, we examine how current and past economic factors, specifically inflation, GDP, industrial production, and FER, affect different types of carbon dioxide (CO_2) emissions across various sectors in the United States. Second, we compare the influence of these economic indicators on each sector to identify which factors have the most significant impact on carbon emissions.

This study makes several important contributions to the literature and policy discourse. First, it sheds light on the relationship between current and past economic factors and carbon emissions in the United States. Second, it examines the linkage between sector-specific economic activities and carbon emissions. Indeed, by disaggregating carbon emissions into nine distinct categories, it provides nuanced insights into how economic variables such as GDP, industrial production, inflation, and the federal funds effective rate differentially influence emissions across sectors, addressing limitations of previous studies that relied on aggregated data. Third, the incorporation of underexplored monetary indicators alongside traditional economic measures broadens understanding of the macroeconomic and financial determinants of emission patterns. Fourth, using a rigorous analysis based on a multiple linear regression framework with recent data, the study ensures empirical validity and relevance to current economic and regulatory contexts, including efforts toward net-zero emissions by 2050. Fifth, the findings would provide practical insights for policymakers and researchers looking to understand the connections between economic conditions and environmental outcomes to better support efforts in developing targeted strategies for reducing emissions while fostering economic growth.

The reminder of the paper is organized as follows. Section 2 presents the methodology. Section 3 describes the data and provides the results. The empirical results are discussed in Section 4. Finally, the conclusion is provided in Section 5.

2. Materials and Methods

The study focuses on sector-specific CO_2 emissions as dependent variables, capturing emissions from distinct economic activities and fuel types. Specifically, nine categories of carbon emissions are modeled as dependent variables: commercial sector emissions, electric power generation emissions, coal industrial sector emissions, residential sector emissions, transportation sector emissions, total emissions from all sectors (coal only and all fuels), aviation gasoline transportation emissions, and jet fuel transportation emissions. This disaggregated approach allows for a more precise assessment of how different sector emissions respond to economic conditions.

The independent variables selected for this analysis are four macroeconomic indicators: inflation, real gross domestic product (GDP), the industrial production index (IP), and the federal funds effective rate (FER). These variables were chosen based on their theoretical relevance and support from the existing literature. For instance, inflation reflects the general price level and may influence production costs and consumption behavior. Real GDP serves as a measure of overall economic activity, which is often associated with higher energy use and emissions. The industrial production index provides an indication of the output of the industrial sector, which tends to be energy intensive. Finally, the federal funds rate represents the stance of monetary policy and can affect both investment and household consumption, thereby indirectly influencing emissions. All data were obtained from the Federal Reserve Economic Data (FRED) database [35] of the Federal Reserve Bank of St. Louis.

The general form of the regression equation of CO_2 emissions (CO_2Emissions) is expressed as follows:

$$CO_2\text{Emissions}_{(t)} = \beta_0 + \beta_1 \times \text{Inflation}_{(t)} + \beta_2 \times \text{GDP}_{(t)} + \beta_3 \times \text{IP}_{(t)} + \beta_4 \times \text{FER}_{(t)} + \varepsilon_{(t)}. \quad (1)$$

Here, GDP is the real gross domestic product, IP is industrial production, FER is the federal funds effective rate, β_0 is the intercept, β_1 to β_4 are the estimated coefficients, ε is the error term of the estimated regression, and t is the time script.

Regression statistics are reported for each model, including the coefficients, R-squared, the F-statistic and its significance level, and both the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (BIC). These statistics enable the evaluation of the statistical significance of each predictor in explaining variations in CO_2 emissions, the regression model explanatory power, and model robustness.

Recall that the current study investigates how four contemporaneous (See Equation (1)) macroeconomic indicators—real GDP, inflation, industrial production (IP), and the federal funds effective rate (FER)—are expected to influence sectoral CO_2 emissions in the United States. Economic theory and prior empirical evidence [2,7,34] suggest that higher levels of economic activity tend to increase energy consumption and, consequently, emissions. Accordingly, real GDP and industrial production are expected to exhibit positive relationships with CO_2 emissions, particularly in energy-intensive sectors such as electric power, coal, and transportation, where increases in output typically require greater use of fossil fuels. The expected effects of inflation are less clear. On the one hand, higher inflation may reduce real incomes and dampen consumption and investment, potentially lowering energy demand and emissions. On the other hand, inflation can also coincide with periods of strong demand and overheating, which may raise production and energy use. Given this ambiguity, no strong prior hypothesis is formulated regarding the sign or magnitude of the inflation–emissions relationship. FER, an instrument of monetary policy, can influence emissions indirectly by affecting borrowing costs, investment, and overall economic activity. Tighter monetary policy (higher interest rates) is generally associated with slower growth and lower investment, which may reduce emissions, especially in sectors that depend heavily on credit-financed capital and durable goods, such as industry and transportation. Therefore, FER is expected to have a non-positive (zero or negative) effect on emissions in most sectors.

In summary, it is anticipated that real GDP and IP will show strong positive effects in electric power, coal, and total emissions sectors, while inflation and FER may exhibit weaker, less consistent effects across sectors. These expected signs provide an economic rationale for including the four macroeconomic variables in the regression models and offer a benchmark against which the empirical findings in Section 4 are interpreted.

3. Results

This research adopts a quantitative approach to investigate the relationship between economic variables and carbon dioxide (CO_2) emissions in the United States from 1974 to 2021. The analysis is based on annual time series data spanning 48 years. All data were obtained from the Federal Reserve Economic Data (FRED) database [35], maintained by the Federal Reserve Bank of St. Louis, which provides reliable, consistent, and publicly available macroeconomic and environmental indicators over time. In this study, nine categories of carbon emissions are separately modeled as dependent variables including commercial sector emissions, electric power generation emissions, coal industrial sector emissions, residential sector emissions, transportation sector emissions, total emissions from all sectors (coal only and all fuels), aviation gasoline transportation emissions, and jet fuel transportation emissions.

Specifically, the list of variables collected from the FRED database are electric power carbon dioxide emissions (all fuels) for the United States (EMISSCO2TOTVECTOUSA), coal industrial sector carbon dioxide emissions (EMISSCO2TOTVICCOA), residential carbon dioxide emissions (all fuels) for the United States (EMISSCO2TOTVRCTOUSA), transportation carbon dioxide emissions (all fuels) for the United States (EMISSCO2TOTVTCTOUSA), total carbon dioxide emissions from all sectors (coal) for the United States (EMISSCO2TOTVTTCOUSA), total carbon dioxide emissions from all sectors (all fuels) for the United States (EMISSCO2TOTVTTTOUSA), aviation gasoline transportation sector carbon dioxide emissions (EMISSCO2VAVACBA), jet fuel transportation sector carbon dioxide emissions (EMISSCO2VJFACBA), inflation (consumer prices) for the United States (FPCPITOTLZGUSA), gross domestic product (GDPA), industrial production total index

(IPB50001A), and federal funds effective rate (RIFSPFFNA). All variables are expressed in terms of the rate of change; for instance, first log-difference.

Table 1 provides the computed p-values from statistical tests used to check if each variable expressed in terms of rate of change is stationary. The list includes standard tests including augmented Dickey–Fuller (ADF) [36], Phillips–Perron [37], and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) [38]. Both ADF and Phillips–Perron are used to test the null hypothesis of presence of a unit root, meaning the time series is not stationary. KPSS tests the null hypothesis of stationarity (absence of unit root). Accordingly, both the ADF and Phillips–Perron tests indicate that the rate of change in all variables is stationary as the null hypothesis of the presence of a unit root is strongly rejected at the 5% significance level. Also, the KPSS test accepts the null hypothesis of a stationary rate of change of each variable at the 5% significance level. Therefore, regression equations (Equations (1) and (2)) can be estimated where the dependent and independent variables are all expressed in terms of the rate of change.

Table 1. Summary of p-values obtained from tests of stationarity: ADF, Phillips–Perron, and KPSS.

Variables	**Statistical Tests**		
	ADF	**Phillips–Perron**	**KPSS**
	***p*-Value**	***p*-Value**	***p*-Value**
Commercial Carbon Dioxide Emissions	0.001	0.001	0.100
Electric Power Carbon Dioxide Emissions	0.001	0.001	0.100
Coal Industrial Sector Carbon Dioxide Emissions	0.001	0.001	0.100
Residential Carbon Dioxide Emissions	0.001	0.001	0.100
Transportation Carbon Dioxide Emissions	0.001	0.001	0.100
Total Carbon Dioxide Emissions from All Sectors (Coal) for the United States	0.001	0.001	0.100
Total Carbon Dioxide Emissions from All Sectors (All Fuels) for the United States	0.001	0.001	0.100
Aviation Gasoline Transportation Sector Carbon Dioxide Emissions	0.001	0.001	0.100
Jet Fuel Transportation Sector Carbon Dioxide Emissions	0.001	0.001	0.100
Inflation	0.001	0.001	0.100
GDP	0.0163	0.0163	0.21
Industrial Production	0.001	0.001	0.100
Federal Funds Effective Rate	0.001	0.001	0.100

Each variable is expressed in terms of the rate of change, which is computed as the first log-difference. ADF, Phillips–Perron are used to test the null hypothesis of the presence of a unit root, meaning the time series is non-stationary. KPSS tests the null hypothesis of stationarity. All tests are performed at the 5% significance level.

Figure 1 displays an overview of the time series and linear trends in sectoral carbon dioxide emissions in the United States from 1974 to 2021. Each subplot displays both the actual annual emissions and a linear trend line, with the slope of the trend line annotated for clarity. The results reveal a varied pattern across different sectors. Notably, emissions from the electric power sector, the coal industrial sector, transportation, and total coal emissions across all sectors show negative slopes, indicating a gradual decline over time.

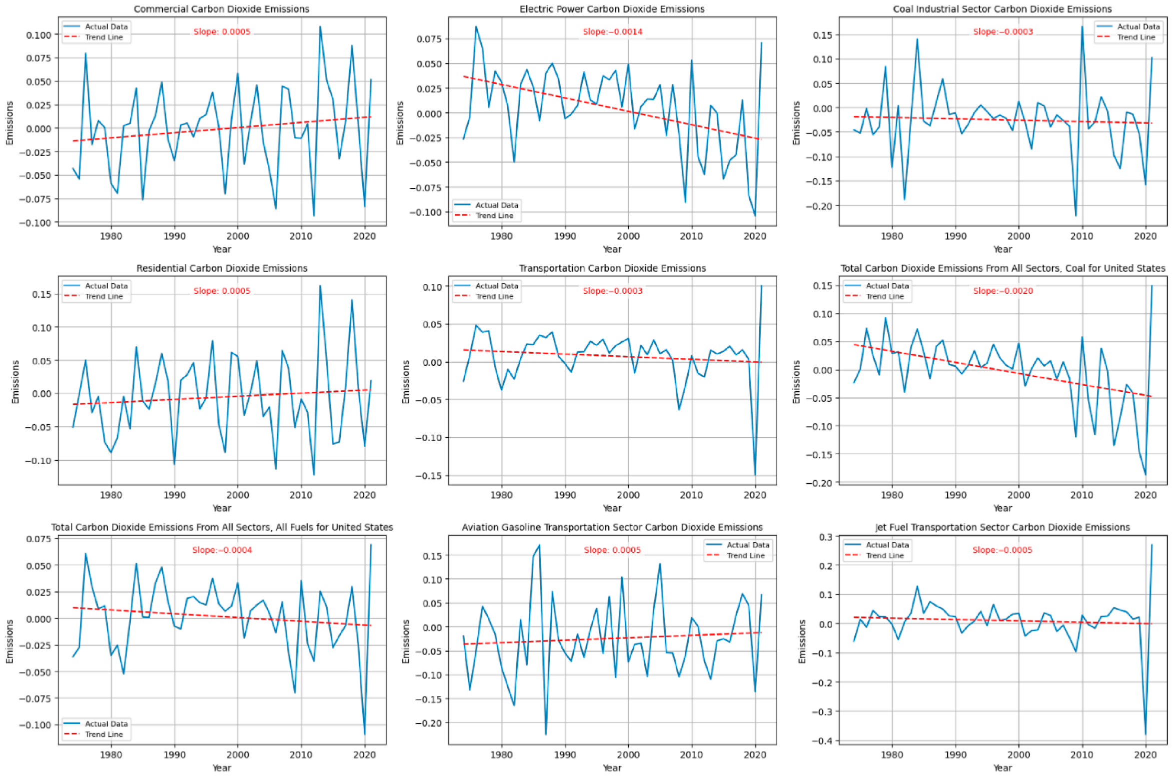

Figure 1. Time series of CO_2 emissions from various sectors.

For example, electric power emissions and total coal emissions from all sectors have slopes of −0.0014 and −0.0020, respectively, reflecting the nation's shift away from coal and improvements in electricity generation efficiency. Additionally, transportation emissions demonstrate a modest downward trend (slope: −0.0003), likely due to advances in vehicle efficiency and the use of alternative fuels.

In contrast, commercial and residential carbon dioxide emissions exhibit slight positive slopes (0.0005 for both), suggesting that emissions in these sectors have remained relatively stable or have experienced a marginal increase. Aviation gasoline emissions also show a small positive trend (slope = 0.0005), while jet fuel emissions display a slight decrease (slope = −0.0005). Overall, total carbon dioxide emissions from all fuels across all sectors present a small negative slope (−0.0004), indicating a slow overall reduction in emissions, despite the mixed trends at the sectoral level. A particularly striking feature across all sectors is the sharp drop in CO_2 emissions in 2020, which marked the lowest point in the time series for most sectors. This significant decline can be directly attributed to the widespread economic disruptions caused by the COVID-19 pandemic. Indeed, the pandemic led to substantial reductions in industrial activity, transportation, air travel, and energy demand due to lockdowns, travel restrictions, and changes in consumer behavior. Consequently, CO_2 emissions in 2020 fell to levels not seen in decades, highlighting the sensitivity of emissions to large-scale societal and economic changes.

Overall, these trends indicate that while significant progress has been made in reducing emissions from coal and electric power, sectors such as commercial, residential, and aviation gasoline have not experienced notable declines. The year-to-year variability in emissions across all sectors suggests that they are influenced by a combination of economic, technological, and policy factors. These findings emphasize the need for targeted policy interventions, particularly in sectors where emissions remain stable or are increasing, to achieve broader climate goals.

Figure 2 displays a heatmap that shows the Pearson correlation coefficients between sectoral carbon dioxide emissions (the dependent variables) and economic indicators (the independent variables: inflation, GDP, industrial production, and the federal funds effective rate). The color gradient ranges from blue, indicating a negative correlation, to red, indicating a positive correlation, with specific correlation values annotated in each cell. A closer look at the heatmap reveals several important patterns. For instance, industrial production is the economic variable which is most strongly and consistently correlated with emissions across multiple sectors. Indeed, it shows a very strong positive correlation with total CO_2 emissions from all fuels (0.80), electric power emissions (0.70), and coal sector emissions (0.70). This suggests that increases in industrial activity are closely linked to higher emissions, particularly in energy-intensive industries.

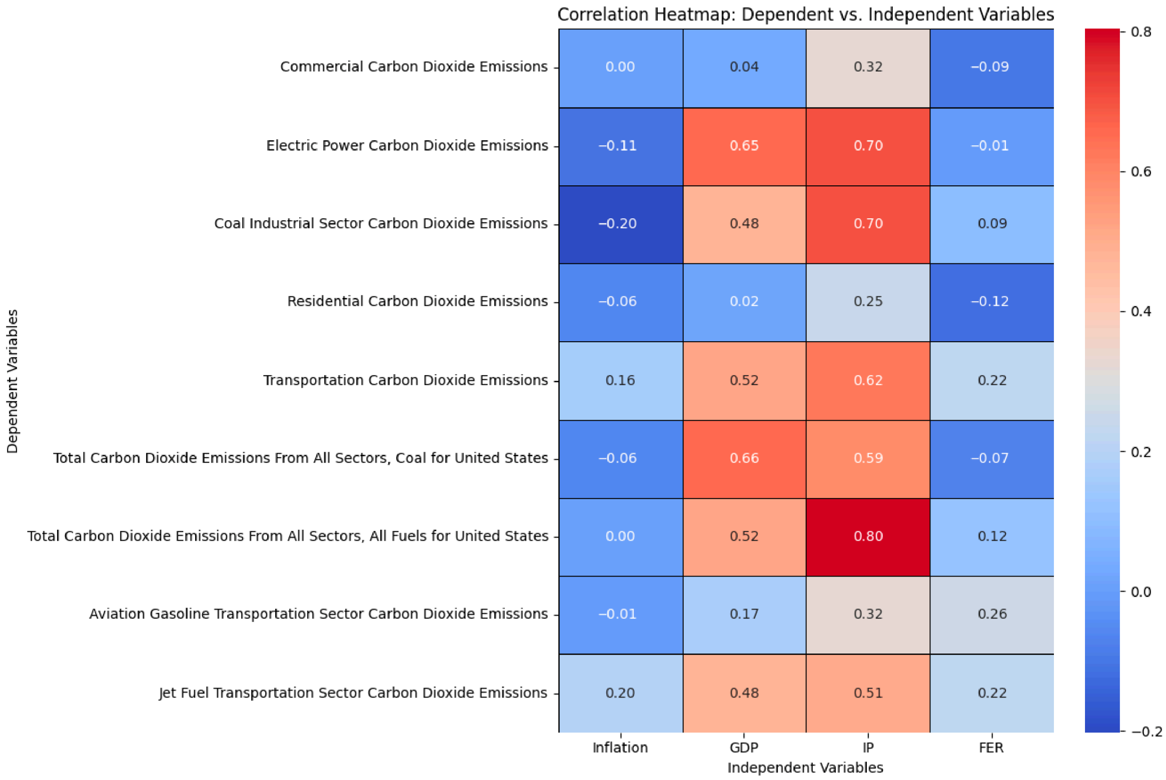

Figure 2. Cross correlation between dependent and independent variables.

GDP also exhibits moderate to strong positive correlations with several emissions categories, especially with total coal sector emissions (0.66), electric power emissions (0.65), and transportation emissions (0.52). This relationship reflects the general trend that economic growth leads to increased energy use, although the correlation is weaker in the residential and aviation gasoline sectors. Inflation generally shows weak correlations with emissions, with most values close to zero or slightly negative. The exceptions are transportation (0.16) and jet fuel emissions (0.20), where the correlations are positive but still modest. This finding indicates that changes in price levels have a limited direct impact on sectoral emissions. FER, which is a proxy for monetary policy, displays mostly weak correlations, with the highest positive values found in aviation gasoline (0.26), transportation (0.22), and jet fuel emissions (0.22). This finding suggests that changes in interest rates may influence emissions in transportation-related sectors, possibly by affecting investment and consumption patterns, although the overall effect is not strong.

In sum, the heatmap illustrates that industrial production and GDP are the primary economic drivers of carbon emissions in the U.S., particularly in the electric power, coal, and transportation sectors. In contrast, inflation and monetary policy appear to have a much smaller direct impact. Indeed, these insights can assist policymakers in prioritizing interventions in the sectors most sensitive to emissions and enhance their understanding of the macroeconomic factors most closely linked to environmental outcomes.

Table 2 shows the regression analysis used to examine the contemporaneous effects (Equation (1)) of inflation, industrial production, GDP, and the federal funds effective rate on nine categories of CO_2 emissions (Y_1–Y_9) across U.S economic sectors. The models revealed considerable variation in explanatory power, with *R*-squared values reaching as high as 0.67 for total CO_2 emissions from all fuels (Y_7). The electric power sector (Y_2) and total CO_2 from coal (Y_6) also exhibited strong model fits, with *R*-squared values of 0.64 and 0.57, respectively. In contrast, the residential (Y_4) and aviation gasoline (Y_8) models demonstrated very low explanatory power, suggesting that the selected economic variables explain only a small portion of emissions variability in these sectors.

Table 2. Summary of regression results when carbon emissions (Y) of each sector are regressed on current macroeconomic factors.

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9
Variables									
Intercept	0.01	−0.04 *	−0.06 *	0	−0.02	−0.07 *	−0.02 *	−0.04	−0.05 *
Inflation	0	0	−0.01	0	0	0	0	0	0.01
GDP	−0.29	0.54 *	0.38	−0.32	0.26	0.96 *	0.12	0.01	0.7
IP	0.56 *	0.56 *	1.01 *	0.60 *	0.43 *	0.60 *	0.63 *	0.49	0.70 *
FER	−0.02	−0.02	0.00 *	−0.02 *	0.00 *	−0.03 *	−0.01	0.03	0
Regression statistics									
R-Squared	0.18	0.64	0.54	0.12	0.47	0.57	0.67	0.14	0.36
F-Statistic	2.3	19.22	12.49	1.47	9.56	14.33	22.24	1.77	6.13
Akaike Criterion	−294.99	−342.77	−283.96	−263.68	−343.91	−298.34	−371.02	−239.32	−256.73
Schwartz Criterion	−285.64	−333.42	−274.6	−254.33	−334.56	−288.98	−361.66	−229.96	−247.38
Durbin–Watson	2.06	2.11	2.14	2.15	2.24	1.79	1.85	2.45	2.48
White Test Statistic	12.01	16.37	34.37 *	12.33	27.88 *	20.77	21.5	11.86	23.4

Y1: Commercial Carbon Dioxide Emissions, Y2: Electric Power Carbon Dioxide Emissions, Y3: Coal Industrial Sector Carbon Dioxide Emissions, Y4: Residential Carbon Dioxide Emissions, Y5: Transportation Carbon Dioxide Emissions, Y6: Total Carbon Dioxide Emissions from All Sectors (Coal) for the United States, Y7: Total Carbon Dioxide Emissions from All Sectors (All Fuels) for the United States, Y8: Aviation Gasoline Transportation Sector Carbon Dioxide Emissions, Y9: Jet Fuel Transportation Sector Carbon Dioxide Emissions. * indicates significance at the 5% level.

Among the independent variables, industrial production consistently emerged as the most influential and statistically significant predictor of CO_2 emissions across nearly all models. The regression coefficients were positive and substantial, ranging from 0.38 in the residential sector (Y_4) to 1.01 in the industrial sector (Y_3), with similarly high values in total CO_2 emissions (Y_7, 0.63) and jet fuel (Y_9, 0.70). These results indicate that increases in industrial activity are closely linked to higher emissions, reinforcing its role as an economic driver of environmental impact. GDP also exhibited significant effects in several sectors. It was particularly influential in the electric power (Y_2, coefficient = 0.54) and coal-based (Y_6, 0.96) sectors, and showed moderate effects in transportation (Y_5, 0.26) and jet fuel (Y_9, 0.70). However, its influence was less consistent across other categories, where coefficients were smaller and statistically insignificant.

In contrast, inflation had a negligible impact across all models, as reflected in coefficients near zero (ranging from −0.01 to 0.01) and consistently not significant. The federal funds effective rate similarly showed limited effects, except for coal-based emissions (Y_6, coefficient = −0.03), where its influence was modest but statistically significant. The coefficients for the federal funds effective rate remained small and statistically insignificant except for coal industrial sector carbon dioxide emissions (3), residential carbon dioxide emissions (Y4), transportation carbon dioxide emissions (Y5), and total carbon dioxide emissions from all sectors (Y6). The overall fit and significance of the models were assessed using *F*-statistics showing the significance of all estimated regression models.

Diagnostic indicators support the validity of the regression estimates. As shown in Table 3, variance inflation factors (VIFs) were consistently low (≈1.4 to 1.6), confirming the absence of multicollinearity among regressors. In addition, Durbin–Watson statistics ranged between 1.96 and 2.43, suggesting no autocorrelation in the residuals. Furthermore, White test results show the presence of homoskedasticity (as indicated by asterisks) across all models, except for coal industrial sector carbon dioxide emissions (Y_3) and transportation carbon dioxide emissions (Y_5).

Table 3. Computed VIF when carbon emissions (Y) of each sector are regressed on current macroeconomic factors.

Variables	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9
Inflation	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27
GDP	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44
IP	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
FER	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35

Y1: Commercial Carbon Dioxide Emissions, Y2: Electric Power Carbon Dioxide Emissions, Y3: Coal Industrial Sector Carbon Dioxide Emissions, Y4: Residential Carbon Dioxide Emissions, Y5: Transportation Carbon Dioxide Emissions, Y6: Total Carbon Dioxide Emissions from All Sectors (Coal) for the United States, Y7: Total Carbon Dioxide Emissions from All Sectors (All Fuels) for the United States, Y8: Aviation Gasoline Transportation Sector Carbon Dioxide Emissions, Y9: Jet Fuel Transportation Sector Carbon Dioxide Emissions. All values of VIFs are less than ten, which indicates an absence of multicollinearity.

In short, the empirical results highlight industrial production as the primary economic driver of CO_2 emissions across most U.S. sectors. GDP also plays an important, though more sector-specific, role. In contrast, inflation and the federal funds effective rate show minimal influence. The explanatory power of the models varies considerably by sector, being strongest in electric power, coal, and total emissions, and weakest in residential and aviation gasoline.

Table 4 provides the results from a regression model used to examine the lagged effects of inflation, industrial production, GDP, and the federal funds effective rate on nine categories of carbon dioxide emissions (Y_1–Y_9) across major U.S. economic sectors. Specifically, the estimated regression is expressed as follows:

$$CO_2Emissions_{(t)} = \alpha_0 + \alpha_1 \times Inflation_{(t-1)} + \alpha_2 \times GDP_{(t-1)} + \alpha_3 \times IP_{(t-1)} + \alpha_4 \times FER_{(t-1)} + \varsigma_{(t)}. \quad (2)$$

Here, the α variables are the regression coefficients and ς is the error term. According to Table 4, the overall explanatory power of the models remained relatively weak, with *R*-squared values mostly very low, indicating that the past values of the selected macroeconomic indicators explain only a small fraction of the observed variations in CO_2 emissions. The electric power sector (Y_2) displayed the highest explanatory strength (R^2 = 0.15), while jet fuel transportation (Y_9) emissions recorded the lowest (R^2 = 0.03). The *F*-statistics across all models were statistically insignificant, confirming that the relationships between the dependent and independent variables lack overall significance. Among the explanatory variables, GDP lagged by one period and showed the most notable yet inconsistent effects. Positive coefficients appeared in the electric power (Y_2, 0.43) and total coal-based (Y_6, 0.64) sectors, suggesting that increases in economic activity may modestly raise emissions in these areas. However, the influence was not statistically robust across the remaining categories.

Table 4. Summary of regression results when carbon emissions (Y) of each sector are regressed on lagged macroeconomic factors.

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9
Intercept	0.02	−0.02	−0.01	0.02	0.01	−0.03	0.01	0	0.02
Lagged Inflation	0	0	0	0	0	0	0	0.01	0.01
Lagged GDP	−0.33	0.43	−0.3	−0.46	−0.04	0.64	−0.05	−0.51	−0.12
Lagged IP	−0.04	−0.07	0.02	0.13	0.08	−0.25	0.05	0.51	0.21
Lagged FER	0	−0.03	−0.02	0.01	−0.02	−0.04	−0.01	0	−0.03
Regression statistics									
R-Squared	0.06	0.15	0.04	0.04	0.04	0.14	0.04	0.06	0.03
F-Statistic	0.62	1.81	0.49	0.44	0.44	1.66	0.44	0.62	0.35
Akaike Criterion	−148.68	−160.89	−109.44	−120.06	−175.14	−124.74	−179.25	−95.26	−97.98
Schwartz Criterion	−139.43	−151.64	−100.19	−110.81	−165.89	−115.49	−170	−86.01	−88.72
Durbin-Watson	2.23	1.96	2.43	2.18	2.05	1.98	1.97	2.34	2.38
White Test Statistic	20.45	21.95	20.35	21.3	7.5	21.58	14.13	5.02	9.42

Y1: Commercial Carbon Dioxide Emissions, Y2: Electric Power Carbon Dioxide Emissions, Y3: Coal Industrial Sector Carbon Dioxide Emissions, Y4: Residential Carbon Dioxide Emissions, Y5: Transportation Carbon Dioxide Emissions, Y6: Total Carbon Dioxide Emissions from All Sectors (Coal) for the United States, Y7: Total Carbon Dioxide Emissions from All Sectors (All Fuels) for the United States, Y8: Aviation Gasoline Transportation Sector Carbon Dioxide Emissions, Y9: Jet Fuel Transportation Sector Carbon Dioxide Emissions. None of the estimated coefficients is significative at 5%. Also, *F*-statistic and White Test Statistic are not significant at 5%.

Overall, the results reveal that lagged traditional macroeconomic indicators exert limited influence on CO_2 emissions at the sectoral level in the United States. Lagged GDP shows the most notable but inconsistent association, while inflation, industrial production, and the federal funds effective rate appear largely irrelevant within this framework. A comparison between the two regression specifications where the dependent variables were regressed first on current and then on lagged independent variables reveals only limited dynamic effects in the relationship between macroeconomic indicators and sectoral CO_2 emissions. In the contemporaneous model (Equation (1)), the explanatory power was relatively high for electric power sector (Y2) and fuels (Y7). Moderate explanatory power was observed in transportation (Y5) and coal (Y6) sectors. This suggests that contemporaneous changes in economic activity were more immediately associated with variations in emissions levels in major industrial sectors.

In summary, empirical results from Tables 2 and 4 suggest that the relationship between macroeconomic conditions and carbon emissions in the U.S. is largely contemporaneous, with minimal lagged effects. In other words, changes in GDP or industrial output tend to impact emissions within the same period rather than carrying over to future periods. The weak dynamic component highlights the need for models that incorporate structural or sector-specific variables such as energy consumption patterns, fuel substitution, or policy interventions to better capture the temporal behavior of emissions across industries.

4. Discussion

Sustainability is receiving a growing academic attention, including studies related to environmental pollution [39–41], climate change [42–44], waste disposal [45–47], natural resource depletion [48–50], green finance [51–53], and the green economy [54–56]. The primary goal of this study was to evaluate how macroeconomic indicators, specifically inflation, GDP, industrial production, and the federal funds effective rate, affect carbon dioxide (CO_2) emissions across nine major sectors in the United States. By employing multiple linear regression analysis, two models were estimated: one based on current independent variables and another incorporating lagged (past) values. This dual approach allowed for examining both immediate and delayed effects of economic activity on emissions. The sectoral focus provides a more granular understanding of how economic dynamics shape environmental outcomes, which is critical for designing targeted policy responses.

The empirical results from the current-variable model indicate that industrial production is the most consistent and significant driver of CO_2 emissions across nearly all sectors. Its positive and statistically significant coefficients underscore the environmental costs of industrial growth, especially in energy-intensive sectors such as manufacturing, electric power, and fuel-based categories. GDP also exerts a positive influence, particularly in the electric power and coal-based sectors, confirming that higher economic output generally corresponds with higher emissions. In contrast, inflation and the federal funds effective rate show weak and inconsistent effects, suggesting that short-term monetary or price-level changes do not directly influence emission levels.

The most significant decrease in CO_2 emissions, from coal and electric power, can be explained by US environmental protection procedures and measures to eco-modernize the energy sector. In addition, the noteworthy reduction in CO_2 emissions from coal and electric power compared to sectors such as commercial, residential, and aviation gasoline could be due to sector and industry specificities. Moreover, CO_2 emissions in these sectors may increase due to a rise in the production of electricity, which is generated from traditional energy resources.

In addition, in terms of the magnitude of the estimated coefficients in Table 2, the empirical results show that industrial production has the strongest impact on carbon emissions in all sectors, whilst inflation and interest rates exhibit extremely low impacts. This could be explained by the environmental protection measures that have been taken in the USA along with eco-modernization of the energy sector. Indeed, industrial production tends to be energy intensive; therefore, environmental protection measures related to heavy industrial and energy sectors would cause reductions in carbon emissions from these sectors. The small level of impacts of inflation and the federal funds effective rate can be explained by limited influence on production costs and consumption behavior.

Table 2 indicates that R^2 from residential and aviation sectors is low compared to the other industrial sectors. Hence, macroeconomic factors are not able to explain variations in carbon emissions in these two sectors. This could be explained by the fact that macroeconomic variables considered in this study are not determinants of carbon emissions in these industrial sectors, and industry specific factors would be the main determinants. For instance, natural gas used for heating and kerosine could be the main driver of carbon emissions in residential and aviation sectors.

When considering the lagged-variable model, the results reveal that the influence of past economic conditions on current emissions is relatively limited. The explanatory power of the lagged model declines, and most lagged coefficients lose statistical significance. Only lagged GDP retains a weak positive association in a few sectors, particularly in electric power and coal, implying that the impact of economic activity on emissions occurs primarily within the same period rather than carrying over to subsequent periods.

Overall, the comparison between the two models suggests that the relationship between macroeconomic indicators and emissions is largely contemporaneous, with industrial activity exerting an immediate and dominant effect. This finding underscores the short-term responsiveness of emissions to economic fluctuations and highlights the challenge of decoupling industrial growth from environmental degradation in the near term.

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An interesting question to examine would be the effect of the 2008 financial crisis and the COVID-19 pandemic on carbon emissions in each individual sector. To address this question, Equation (3) is estimated using ordinary least squares.

$$CO_2Emissions_{(t)} = \beta_0 + \beta_1 \times Crisis_{(t)} + \beta_2 \times Pandemic_{(t)} + \varepsilon_{(t)}. \quad (3)$$

where Crisis and Pandemic are dummy variables used to indicate the financial crisis in 2008 and the COVID-19 pandemic in 2020–2021, respectively. The results of these estimations are provided in Table 5. We found no significant effect of these major events on carbon emissions, except a significant effect of the 2008 financial crisis on carbon emissions in the transportation sector (Y5). In addition, the empirical results indicate the effect of COVID-19 on carbon emissions in all sectors was negative, yet not significant. Similarly, the effect of the 2008 financial crisis was negative on carbon emissions in all sectors, except on carbon emissions in the commercial and residential sectors. Furthermore, the explanatory power (R^2) of all the regressions models in Table 5 is weak, confirming that the 2008 financial crisis and the COVID-19 pandemic do not explain carbon emissions.

Table 5. Summary of results when carbon emissions are regressed on dummy variables related to the 2008 financial crisis and the COVID-19 pandemic.

	Y1	**Y2**	**Y3**	**Y4**	**Y5**	**Y6**	**Y7**	**Y8**	**Y9**
Intercept	−0.0012	0.0062	−0.0247	−0.0057	0.010414	−0.0009	0.0031	−0.0222	0.0139
Crisis	0.0425	−0.0276	−0.0137	0.0435	−0.0746 *	−0.0147	−0.0352	−0.0825	−0.0630
Pandemic	−0.0149	−0.023158	−0.0033	−0.0245	−0.0350	−0.0182	−0.0234	−0.0124	−0.0698
Regression statistics									
R-Squared	0.0222	0.02	0.0008	0.017	0.133	0.00456	0.0419	0.0222	0.0443
F-Statistic	0.511	0.459	0.02	0.39	3.47 *	0.103	0.984	0.511	1.04

Y1: Commercial Carbon Dioxide Emissions, Y2: Electric Power Carbon Dioxide Emissions, Y3: Coal Industrial Sector Carbon Dioxide Emissions, Y4: Residential Carbon Dioxide Emissions, Y5: Transportation Carbon Dioxide Emissions, Y6: Total Carbon Dioxide Emissions from All Sectors (Coal) for the United States, Y7: Total Carbon Dioxide Emissions from All Sectors (All Fuels) for the United States, Y8: Aviation Gasoline Transportation Sector Carbon Dioxide Emissions, Y9: Jet Fuel Transportation Sector Carbon Dioxide Emissions. None of the estimated coefficients is significative at 5%. R^2 is weak in all regressions and *F*-statistic is not significant at 5% except for the transportation sector. The * indicates significance at 5% level.

From a policy and managerial perspective, these results suggest that efforts to reduce emissions should prioritize industrial decarbonization and cleaner production technologies. The strong influence of industrial production implies that emission-reduction strategies should target structural changes in how goods are manufactured, and energy is consumed. For instance, promoting energy efficiency, carbon-capture technologies, and renewable energy use within the industrial sector could significantly curb emissions without compromising output. Furthermore, the sector-specific role of GDP points to the need for differentiated policies that recognize the varying sensitivity of emission categories to economic expansion. Sectors where GDP has a strong impact, such as electric power and transportation, may benefit from growth-oriented green investment, while those with weaker links may require regulatory or behavioral interventions.

Despite its contributions, this study has several limitations. The analysis is based solely on macroeconomic indicators and does not account for the full range of factors that influence emissions, such as technological innovation, regulatory changes, energy prices, or behavioral shifts. The sectoral models, while robust for energy-intensive industries, have limited explanatory power for sectors like residential and aviation gasoline, indicating the need for a broader set of explanatory variables. Additionally, the study relies on annual data and a limited set of macroeconomic variables and does not account for all possible determinants of emissions. Future research should consider longer records, incorporating additional factors, higher-frequency data, and alternative/non-linear modeling approaches to further enhance our understanding of the complex dynamics driving sectoral emissions.

5. Conclusions

This research work set out to quantitatively investigate the relationship between macroeconomic indicators and carbon dioxide (CO_2) emissions across major U.S. economic sectors from 1974 to 2021. Using sector-specific multiple regression models based on long-term data from the Federal Reserve Economic Data (FRED) database, the study explored both contemporaneous (current) and dynamic (lagged) relationships between inflation, real GDP, industrial production, and the federal funds effective rate and their influence on CO_2 emissions. This dual-model approach provided a more comprehensive understanding of how economic conditions shape environmental outcomes over time.

The results indicate that the effects of macroeconomic variables on CO_2 emissions are largely sector-dependent and predominantly contemporaneous. Industrial production consistently emerged as the strongest and most statistically significant determinant of emissions across nearly all sectors, particularly in the industrial, electric power, and total emissions categories. GDP also played a notable role, especially in the electric power and coal-based sectors, although its influence varied across categories. In contrast, inflation and the federal funds effective rate showed weak or statistically insignificant effects in most cases, suggesting that short-term monetary conditions have minimal direct impact on emissions.

When lagged variables were used, the explanatory power of the models generally declined, and most coefficients lost statistical significance. This finding suggests limited dynamic persistence in the relationship between economic activity and emissions, implying that changes in production or output influence emissions primarily within the same period rather than across time. The variation in R^2 values across sectors further highlights that past economic activity alone cannot fully explain emissions trends; other factors such as current economic factors, technological innovation, environmental regulations, and behavioral changes likely play an important complementary role.

In summary, this thesis contributes to the growing body of evidence highlighting the heterogeneous and short-term nature of the economic determinants of CO_2 emissions. It emphasizes that sustainable emission reductions require a combination of economic, technological, and policy-driven measures that reflect the distinct characteristics of each sector.

From a policy and managerial perspective, these findings underscore the need for targeted, sector-specific strategies to reduce emissions effectively. Sectors with strong economic–emissions linkages, such as industry and electric power, may benefit most from production-side interventions including carbon pricing, cleaner technologies, and efficiency incentives. For instance, to reduce carbon emissions in such energy-intensive sectors, industrial companies may choose to design and implement carbon reduction projects or cooperate with energy service companies. Also, energy-intensive companies in the industrial sector may start planification of energy structure optimization and investing in new technologies. Besides, sectors where economic variables have limited explanatory power, such as commercial, residential, and aviation gasoline, may require behavioral or technological approaches, such as consumer incentives for green choices or stricter efficiency standards. For instance, for commercial and residential sectors, policymakers should focus on developing green internet-based infrastructures, strategizing plans to promote clean natural resources (solar energy), and facilitating domestic greening. For the aviation sector, policymakers should introduce incentives to improve energy efficiency and strong legal environment rules.

This study provides valuable insights but also underscores several potential avenues for future research. First, expanding the analytical framework to include policy variables such as environmental regulations and carbon pricing along with factors related to technological innovation, like renewable energy adoption and improvements in industrial efficiency, as well as behavioral aspects, such as shifts in consumer preferences, could enhance the explanatory power of emissions models. This is particularly important for sectors where macroeconomic variables alone are insufficient. Second, future studies could utilize nonlinear or dynamic modeling approaches to better capture the evolving relationship between economic activity and emissions, especially in contexts marked by rapid technological change or external shocks. Third, incorporating higher-frequency or more granular data such as emissions data at the regional or firm level could expose additional sources of variability and facilitate more targeted policy interventions. Finally, conducting comparative studies across different countries or regions could help identify best practices and assess the applicability of findings in various economic and regulatory contexts.

By broadening the scope of analysis and integrating a wider range of variables, future research can provide a more comprehensive and accurate understanding of the drivers of carbon emissions. This, in turn, will support the development of more effective climate and economic policies aimed at achieving net-zero goals.

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Abbreviations

The following abbreviations are used in this manuscript:

ADF	Augmented Dickey–Fuller test
CO_2	Carbon dioxide
FER	Federal funds effective rate
GDP	Gross domestic product
KPSS	Kwiatkowski–Phillips–Schmidt–Shin
IP	Industrial production
VIF	Variance inflation factor

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