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Beyond Traditional Drivers: Artificial Intelligence and the Evolving Structure of Carbon Emissions in the United States

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Abstract


This study examines the determinants of carbon emissions in the United States over the period 1990–2022, with particular attention to the role of Artificial Intelligence (AI) within a broader macroeconomic setting. While traditional literature has primarily emphasized economic growth and energy consumption as the main drivers of environmental degradation, this paper extends the analysis by incorporating technological change alongside Foreign Direct Investment (FDI) and urbanization in a unified time-series framework. The empirical results indicate that economic growth and energy use continue to exert upward pressure on carbon emissions, reflecting the U.S. economy's continued reliance on energy-intensive production and consumption patterns. FDI and urban expansion also contribute to higher emissions, although their effects vary across time and may depend on structural conditions within the economy. These findings confirm that conventional development pathways remain closely associated with environmental stress.


In contrast, AI is found to have a mitigating association with carbon emissions. This relationship likely reflects improvements in production efficiency, energy-use optimization, and better allocation of economic resources, driven by technological progress. However, the results also suggest that the environmental effects of AI are not independent, as they interact with existing economic and energy structures to shape overall emission outcomes.

Keywords: Artificial intelligence, Carbon emissions, Energy consumption, Foreign direct investment, urbanization.

1 | Introduction

Carbon emissions remain one of the most persistent environmental challenges facing modern economies, particularly in highly industrialized countries such as the United States. Despite decades of policy efforts to reduce greenhouse gas emissions, the scale of economic activity, energy demand, and consumption patterns

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continues to exert considerable pressure on the environment [1], [2]. The United States, as one of the largest global economies, plays a central role in shaping both current emission levels and future climate trajectories due to its high levels of production, transportation activity, and energy-intensive industrial structure [3]. Although there have been gradual improvements in energy efficiency and the expansion of cleaner energy sources, fossil fuels still account for a significant share of total energy consumption, which continues to put upward pressure on carbon emissions. At the same time, structural changes such as urban expansion, global investment flows, and technological transformation are continuously reshaping the drivers of environmental degradation [4]. Within this evolving context, understanding the key forces that influence emission patterns has become essential for designing effective long-term sustainability strategies.

A large body of environmental economics literature explains carbon emissions through a set of core macroeconomic and structural factors. Economic growth is often viewed as a central driver [5–7], as increases in production and income levels tend to raise energy demand and expand industrial output, thereby intensifying environmental pressure [8], [9]. Closely linked to this is energy consumption, particularly when economies remain dependent on fossil-fuel-based energy systems, which directly contribute to higher emissions [10]. Foreign Direct Investment (FDI) has also received significant attention, with contrasting arguments in the literature. While some studies suggest that FDI facilitates the transfer of cleaner technologies and improves environmental performance [11], others argue that it may encourage the relocation of pollution-intensive industries to host countries with relatively weaker environmental regulations [12–14]. Urbanization represents another important dimension, as rapid population concentration in cities increases transportation needs, infrastructure development, and resource consumption [15], [16]. Together, these factors form the traditional framework for explaining variations in carbon emissions over time and across economies. However, this framework increasingly faces limitations in capturing the influence of newer technological forces that are reshaping production and consumption systems.

In recent years, attention has increasingly shifted toward the role of technological change in shaping environmental outcomes. Digital transformation has altered the way economic systems operate by improving efficiency, reducing transaction costs, and enabling more precise resource allocation [17]. Within this broader transformation, Artificial Intelligence (AI) has emerged as a particularly influential development due to its ability to process large-scale data, optimize complex systems, and support decision-making across industries. Unlike earlier forms of technological progress, AI is not limited to a single sector but operates across production, transportation, energy management, and services, thereby broadening its potential environmental implications [18]. From an environmental perspective, AI may contribute to lower emissions by improving energy efficiency, reducing waste, and enabling smarter industrial processes [19]. At the same time, its expansion may also increase energy demand through higher computational requirements, suggesting that its overall impact is not straightforward. This dual nature makes AI an important but still underexplored factor in explaining long-term emission dynamics, particularly at the macroeconomic level in advanced economies such as the United States.

Empirical research on the relationship between economic activity and environmental outcomes has produced a wide range of findings, reflecting differences in data, methods, and country contexts. Many studies confirm that economic growth and energy consumption remain closely associated with rising carbon emissions, especially in economies where fossil fuels dominate the energy mix [20], [21]. The role of FDI and urbanization is less consistent, with results often depending on regulatory conditions, technological capacity, and the structure of local industries [14], [22–24]. While this body of work has improved understanding of traditional emission drivers, it has paid relatively limited attention to how newer forms of technological change interact with these factors. Existing studies that consider digitalization or AI tend to focus on specific sectors or cross-country comparisons, which makes it difficult to draw clear conclusions about their broader macroeconomic effects [25]. As a result, there is still limited time-series evidence on how AI fits into the established growth–energy–investment framework, particularly in the United States, where both technological development and energy use remain high.

Against this background, an important gap remains in understanding how AI interacts with established macroeconomic drivers of carbon emissions within a single, coherent framework. Most existing studies examine these factors in isolation or rely on cross-country datasets, which may mask country-specific dynamics and long-term structural relationships. In the United States, where technological advancement and energy consumption have evolved simultaneously, there is a need for a focused time-series analysis that captures both persistence and change over time. It is still unclear whether technological progress, particularly AI, can offset the environmental pressures generated by economic growth, energy use, investment inflows, and urban expansion. Moreover, limited attention has been given to how these relationships unfold in both the long run and short run within the same empirical setting. Addressing this issue requires an integrated approach that allows for dynamic interactions among variables while preserving the country-specific context of the U.S. economy.

This study examines how carbon emissions in the United States are shaped by the joint influence of economic growth, energy consumption, FDI, urbanization, and AI over the period 1990–2022. The analysis focuses on whether a stable, long-term relationship exists among these variables and how short-term adjustments occur when deviations occur. Particular attention is given to the role of AI to understand whether it contributes to reducing environmental pressure or simply interacts with existing drivers without altering overall emission trends. By considering both conventional and emerging factors within the same empirical framework, the study seeks to provide a clearer picture of how technological change fits into the broader economic structure. The approach also allows for a comparison between the effects of traditional growth-related variables and those associated with technological progress, offering a more balanced view of the forces influencing carbon emissions over time.

The contribution of this study lies in bringing together technological change and conventional macroeconomic factors within a single time-series framework for the United States. By incorporating AI alongside economic growth, energy consumption, FDI, and urbanization, the analysis offers a more integrated view of the forces shaping carbon emissions over a long historical period. The use of annual data from 1990 to 2022 allows the study to capture both earlier structural patterns and more recent technological developments. In addition, the empirical approach accounts for both long-run relationships and short-run adjustments, enabling observation of how these factors evolve rather than relying on static associations. This setup provides a clearer understanding of whether technological progress is beginning to alter the established link between economic activity and environmental pressure. It also helps to distinguish between the roles of traditional drivers and emerging influences, offering a more grounded basis for interpreting changes in emission patterns within the U.S. economy.

2 | Literature Review

The relationship between economic growth and environmental degradation has been widely examined in the literature, with carbon emissions often used as a key indicator of environmental pressure. A common view is that rising income levels lead to higher emissions through increased production, consumption, and energy demand, reflecting what is often described as the scale effect [24], [26]. This perspective suggests that as economies expand, environmental stress intensifies, particularly when energy-intensive industries support growth. At the same time, an alternative line of reasoning suggests that economic development may eventually support environmental improvement through technological progress, structural transformation, and stricter regulatory frameworks [27], [28]. This idea is often discussed in the context of nonlinear patterns in the growth–environment relationship. Empirical findings, however, remain mixed. While many studies report a positive association between growth and emissions, others indicate that the effect weakens or changes over time depending on the composition of the economy and the level of technological advancement [29]. These variations suggest that economic growth alone does not determine environmental outcomes; rather, it operates through multiple channels that interact with energy use and technological change.

Energy consumption is widely recognized as one of the most direct and consistent drivers of carbon emissions. In economies where energy systems are largely dependent on fossil fuels, increases in energy use translate almost immediately into higher emission levels [30]. This relationship reflects the central role of energy in supporting industrial production, transportation, and household activities. A large number of empirical studies report a strong, positive link between energy consumption and environmental degradation, particularly in countries with carbon-intensive energy systems [31], [32]. At the same time, the composition of energy use has become an important consideration. While non-renewable energy sources continue to contribute significantly to emissions, the expansion of renewable energy has been associated with improvements in environmental quality. However, the overall impact often depends on the pace of energy transition and the extent to which cleaner sources can replace fossil fuels [33], [34]. In advanced economies, improvements in energy efficiency have helped moderate emissions growth, but rising demand continues to offset some of these gains. It highlights the need to consider both the level and structure of energy consumption when assessing its environmental impact.

The environmental effects of FDI have been widely debated, with no clear consensus across the literature. One line of argument suggests that FDI can improve environmental quality by facilitating the transfer of advanced technologies, better management practices, and more efficient production processes [16]. This perspective, often referred to as the pollution-halo hypothesis, assumes that multinational firms introduce cleaner technologies that can reduce emissions in host economies. In contrast, the pollution haven hypothesis argues that firms may relocate pollution-intensive activities to countries with less stringent environmental regulations, thereby increasing local emissions. Empirical findings reflect both possibilities [35], [36].

In some cases, FDI is associated with higher carbon emissions due to industrial expansion and increased resource use, particularly when investments are directed toward energy-intensive sectors. In other cases, the effect appears neutral or even negative, depending on the technological content of investment and the regulatory environment [37]. These mixed outcomes suggest that the environmental impact of FDI is not uniform but is shaped by structural conditions such as institutional quality, industrial composition, and technological development.

Urbanization has become a defining feature of economic development, with important implications for environmental outcomes. The concentration of population and economic activity in urban areas tends to increase demand for energy, transportation, housing, and infrastructure, all of which contribute to higher carbon emissions [38]. Rapid urban growth is often associated with expanded construction, greater reliance on private transport, and increased consumption, creating additional pressure on natural resources [39]. At the same time, urbanization can also generate efficiency gains through better infrastructure planning, improved public transportation systems, and more compact living arrangements [40]. In some contexts, these factors may help reduce per capita emissions, especially when supported by effective policy and technological integration [41]. Empirical evidence reflects this dual nature, with many studies finding a positive relationship between urbanization and emissions, while others report weaker or context-dependent effects [42], [43]. The overall impact appears to depend on how urban growth is managed, including the quality of planning, energy sources, and the adoption of efficient technologies within cities.

AI has recently emerged as an important area of inquiry in discussions of environmental sustainability, although its role remains less established than that of traditional macroeconomic drivers. From one perspective, AI is associated with improvements in efficiency across production systems, logistics, and energy management [44]. By enabling more accurate forecasting, automation, and real-time optimization, AI-based systems can reduce waste and support more efficient resource use, which may contribute to lower emissions intensity [45]. In industrial settings, these improvements can translate into cleaner production processes and better coordination of energy demand. However, the environmental implications of AI are not entirely straightforward. The increasing use of high-performance computing, data storage, and digital infrastructure also requires substantial energy input, which may offset some of the potential environmental gains [38], [46]. As a result, the overall effect of AI on emissions and environmental quality is likely to depend on how it is

implemented within the broader economic and energy structure. Despite growing interest in this area, most existing studies remain focused on sectoral applications or specific technologies, leaving limited evidence on its aggregate macroeconomic impact, particularly in advanced economies such as the United States.

Despite extensive research on the determinants of carbon emissions, several important gaps remain in the existing literature. Most studies have focused on conventional macroeconomic drivers such as economic growth, energy consumption, FDI, and urbanization, often treating them as separate influences rather than examining their joint dynamics within a unified framework [47], [48]. In addition, while a growing number of studies have begun to explore the environmental implications of technological change, the role of AI remains poorly integrated into macro-level empirical models [49–51]. Existing evidence is largely fragmented, with a stronger emphasis on cross-country comparisons or sector-specific analyses, which limits the understanding of country-specific long-term relationships. In the United States, where both technological advancement and energy consumption are highly developed, there is limited time-series evidence on how AI interacts with traditional drivers of emissions over time. Furthermore, little attention has been given to both long-run equilibrium relationships and short-run dynamics within a single coherent framework. These gaps highlight the need for an integrated empirical approach that jointly examines technological and structural factors in explaining carbon emissions.

3 | Methodology

This study uses annual time-series data for the United States covering the period 1990–2022. The dependent variable is Carbon Dioxide (CO₂) emissions, measured in kilotons. The key explanatory variables include economic growth, proxied by Gross Domestic Product (GDP) per capita; energy consumption, measured as energy use per capita; FDI, captured by net inflows; urbanization, represented by total population; and AI, measured using AI-related investment data as a proxy for technological advancement. All macroeconomic variables are obtained from the World Development Indicators, while AI data are sourced from Our World in Data. All variables are transformed into natural logarithms to ensure consistency and interpretability.

The relationship among the selected variables is grounded in the idea that carbon emissions result from the interaction of economic, structural, and technological forces. Economic growth is expected to influence emissions through scale effects, as higher income levels typically lead to expanded production, consumption, and energy demand [24]. Energy consumption acts as a direct channel through which economic activity translates into environmental pressure, particularly when energy systems rely heavily on fossil fuels [52]

. FDI can affect emissions in two opposing ways: it may increase environmental degradation if investment flows are directed toward pollution-intensive industries, or it may reduce emissions if it facilitates the transfer of cleaner technologies and more efficient production methods [53]. Urbanization represents a structural transformation of the economy, in which population concentration and infrastructure expansion tend to increase energy use and emissions. However, efficiency gains in urban systems may partially offset this effect [54], [55]. AI is introduced as a technological factor that can reshape these relationships by improving efficiency, optimizing resource allocation, and supporting cleaner production processes [17], [22]. At the same time, its energy requirements may generate additional demand pressures. Together, these variables capture the combined influence of economic development, structural change, and technological progress on environmental outcomes.

The empirical framework of this study is designed to capture both the long-run relationship and short-run dynamics among carbon emissions and their determinants in the United States. Given the time-series nature of the data, the first step is to examine the stationarity of all variables to minimize the risk of spurious regression. Once the order of integration is confirmed, the Autoregressive Distributed Lag (ARDL) approach is employed, as it is suitable for variables integrated of mixed orders, provided none is integrated beyond order one [56]. The ARDL framework allows the estimation of both long-run equilibrium relationships and short-run adjustments within a single unified model. In addition, the error correction representation derived from the ARDL model is used to assess the speed at which deviations from long-run equilibrium are corrected

over time. Appropriate lag lengths are selected using standard information criteria to ensure model stability and reliability. The framework also enables the simultaneous inclusion of multiple explanatory variables, enabling a comprehensive assessment of economic, structural, and technological influences on emissions. This approach provides a flexible, robust framework for analyzing dynamic relationships and is particularly well-suited for capturing gradual adjustments in environmental and economic systems over time.

4 | Results and Discussion

The table presents descriptive statistics for the variables used in the study for the United States over the period 1990–2022. The results show that all variables exhibit relatively stable behavior across time with no extreme volatility. Carbon emissions display low dispersion, indicating gradual changes in environmental pressure over the sample period. Economic growth and energy consumption show moderate variation, reflecting steady macroeconomic expansion and energy demand patterns. AI records the highest variability, suggesting rapid technological advancement in recent years. FDI and urbanization appear comparatively stable, indicating slower structural changes.

Table 1. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
T	32	2005.0	9.50	1990	2021
LCO2	32	15.530	0.092	15.300	15.720
LGDP	32	10.720	0.345	10.120	11.250
LAI	32	7.610	1.120	6.410	9.950
LENU	32	4.820	0.350	3.980	5.420
LFDI	32	2.690	0.155	2.300	2.960
LURBA	32	19.540	0.105	19.340	19.720

The unit root test results based on the Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Dickey–Fuller Generalized Least Squares (DF-GLS) tests indicate that the variables exhibit mixed integration orders. Specifically, most variables, such as Log of Carbon Dioxide emissions (LCO2), Log of Gross Domestic Product (LGDP), and Log of Energy Use (LENU), are non-stationary at levels but become stationary after first differencing, confirming an integration of order one. In contrast, Log of Agricultural Input (LAI) and Log of Foreign Direct Investment (LFDI) show borderline stationarity at the level in some tests, suggesting a combination of I(0) and I(1) properties. Log of Urbanization (LURBA) appears strongly stationary in level form across all tests. Importantly, no variable is integrated beyond order one, which validates the applicability of the ARDL bounds testing approach for further analysis.

Table 2. Unit root test results.

Variable	ADF		PP		DF-GLS		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LCO2	-0.318	-4.226***	-0.401	-4.512***	-0.287	-4.103***	I(1)
LGDP	-1.042	-5.118***	-0.998	-5.274***	-1.115	-4.982***	I(1)
LAI	-2.864*	-5.632***	-2.941*	-5.781***	-2.712*	-5.402***	I(0)
LENU	-0.521	-4.897***	-0.613	-5.034***	-0.487	-4.765***	I(1)
LFDI	-2.711*	-4.403***	-2.803*	-4.589***	-2.655*	-4.321***	I(0)
LURBA	-3.912***	-6.215***	-4.084***	-6.338***	-3.776***	-6.102***	I(0)

The ARDL bounds test results indicate a stable long-run relationship among the variables in the model. The computed F-statistic (6.2148) is higher than the upper bound critical values at all conventional significance levels, including the 1% level. This argument supports rejecting the null hypothesis of no cointegration. In other words, carbon emissions, economic growth, energy consumption, AI, FDI, and urbanization move

together over the long run in the United States. The result supports the existence of equilibrium relationships among the variables, justifying the use of the ARDL approach for further long-run and short-run estimations.

Table 3. ARDL bound test.

Test Statistic	Value	Significance	I(0) Bound	I(1) Bound
F-statistic	6.2148	10%	2.08	3
		5%	2.39	3.38
		2.50%	2.7	3.73
		1%	3.06	4.15

The long-run results indicate a stable relationship between carbon emissions and the selected macroeconomic and technological variables in the United States over the study period. Economic growth shows a positive, statistically significant effect on emissions, suggesting that output expansion continues to rely on energy-intensive activities that put pressure on environmental quality. Similarly, energy consumption is positively associated with emissions, confirming its role as a primary transmission channel through which economic activity affects the environment. FDI also exhibits a positive coefficient, implying that investment inflows may be linked with increased industrial activity and energy use, particularly in sectors that are not fully decarbonized. Urbanization is found to have a significant positive impact on emissions, reflecting higher demand for infrastructure, transportation, and residential energy use as population concentration increases.

In contrast, AI displays a negative and statistically significant relationship with carbon emissions. It suggests that technological advancement may contribute to improved efficiency, better resource allocation, and reduced energy wastage in the long run. However, the magnitude of this effect is smaller than that of traditional economic drivers, indicating that while AI has a mitigating influence, it does not fully offset the environmental pressures created by growth, energy use, and structural expansion in the economy.

Table 4. ARDL long-run estimation.

Variable	Coefficient	Std. Error	t-Statistic	Probability
LGDP	0.4182	0.1024	4.08	0.0003***
LENU	0.3567	0.0891	4	0.0004***
LAI	-0.2154	0.0768	-2.8	0.0091***
LFDI	0.1183	0.0552	2.14	0.0415**
LURBA	0.2749	0.0987	2.78	0.0096***

The short-run results from the error-correction model show that changes in the explanatory variables immediately affect carbon emissions before long-run adjustments occur. Economic growth continues to exert a positive and statistically significant effect in the short run, indicating that increases in output quickly translate into higher energy demand and emissions. Similarly, energy consumption shows a strong positive impact, confirming that short-term fluctuations in energy use are closely tied to changes in environmental pressure. FDI has a positive but relatively weaker effect in the short run, suggesting that its environmental impact depends on the timing and nature of investment inflows, with adjustment effects occurring gradually over time. Urbanization also contributes to rising emissions in the short run, reflecting immediate increases in transportation needs, construction activity, and household energy consumption associated with population concentration.

In contrast, AI exhibits a negative and significant effect, implying that even in the short term, technological tools may help improve efficiency and reduce waste in production and energy systems. The error correction term is negative and statistically significant, confirming that deviations from the long-run equilibrium are corrected over time. Its magnitude indicates a relatively fast speed of adjustment, suggesting that the system returns to equilibrium within a reasonable period after short-term shocks.

Table 5. ARDL short-run estimation.

Variable	Coefficient	Std. Error	t-Statistic	Probability
Δ LGDP	0.3015	0.0882	3.42	0.0021***
Δ LENU	0.2641	0.0735	3.59	0.0014***
Δ LAI	-0.1428	0.061	-2.34	0.0267**
Δ LFDI	0.0912	0.0448	2.03	0.0521*
Δ LURBA	0.1876	0.0694	2.7	0.0112**
ECT(-1)	-0.6423	0.1215	-5.28	0.0000***

5 | Conclusion

This study examined the relationship between carbon emissions and key macroeconomic and technological factors in the United States over the period 1990–2022. By integrating AI alongside traditional determinants such as economic growth, energy consumption, FDI, and urbanization, the analysis provides a broader view of the forces shaping environmental outcomes. The findings show that economic activity and energy use remain the dominant drivers of emissions in both the short- and long-run. At the same time, urbanization and foreign investment also contribute to environmental pressure, though with varying intensity across time. In contrast, AI appears to play a mitigating role, suggesting that technological progress can support efficiency improvements and help reduce emissions, even if its impact remains limited compared to conventional drivers. Overall, the results indicate that while technological advancement is becoming increasingly relevant, it has not yet fully offset the environmental impacts of economic growth and structural expansion. This argument highlights the continued importance of balancing economic development with sustainable energy use and targeted policy interventions to reduce carbon intensity.

The findings of this study offer several policy implications for managing carbon emissions in the United States. First, the strong role of economic growth and energy consumption in driving emissions suggests that policies should focus on improving energy efficiency and accelerating the transition from fossil fuels to cleaner energy sources. Strengthening renewable energy infrastructure and encouraging low-carbon production systems can help reduce the environmental cost of economic expansion. Second, the positive impact of urbanization and FDI underscores the need for stronger regulatory frameworks to guide urban development and channel investment toward environmentally sustainable sectors. Environmental standards and green investment incentives can play an important role in this regard. Third, the negative relationship between AI and emissions highlights the potential of technological innovation as a supporting tool for environmental improvement. Policymakers should encourage the adoption of AI-based systems in energy management, industrial optimization, and transportation efficiency. However, attention should also be given to the energy demand of digital infrastructure to ensure that technological progress does not create new environmental burdens.

Despite its contributions, this study has several limitations that should be acknowledged. First, the analysis is based on annual time-series data for a single country, which may limit the generalizability of the findings to other economies with different structural characteristics. Second, the proxy used for AI may not fully capture the multidimensional nature of technological progress. Third, the study does not explicitly account for structural breaks or policy regime shifts that may influence long-run relationships. Future research could extend this work by using cross-country panel data to compare heterogeneous effects across regions. In addition, incorporating more refined measures of digital transformation and exploring nonlinear or threshold effects could provide deeper insights into the evolving relationship between technology and environmental outcomes.

Authors' Contributions

K. M: writing-original draft, methodology, data curation, conceptualization, software, and visualization, and validation. T. T: writing-review and editing, formal analysis, and investigation. M. O. F: writing-review and editing, formal analysis, and investigation. S. I. T: validation, writing-review and editing, and formal analysis. The authors have read and agreed to the published version of the manuscript.

Data Availability

The data is available on request from the corresponding author.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The authors have given consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

The authors confirm that this research did not involve human participants or animal subjects.

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