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AI-Driven Sustainability or Carbon Trap? Rethinking Energy Use and FDI in U.S. Environmental Performance

Shamina Israt Tithi[1], Kuan Mo[1], Md Amran Hossen Pabel[2,*], Tahia Tasnuva[3], Md Omar Farukh[4]

[1] Earth and Environmental sciences, Brooklyn College, CUNY, New York, USA; shamina.tithi@brooklyn.cuny.edu, kuan.mo@brooklyn.cuny.edu.
[2] Masters of Science in Marketing Analytics and Insights Wright State University, Ohio, USA; mdamranpabel@gmail.com.
[3] Master of Business Administration, Manarat International University, Ashulia, Dhaka-1314, Bangladesh; tahiatasnuva99@gmail.com.
[4] Applied Science in Organizational Management and Leadership, Eastern Florida State College, USA; mdomar.farukh.01@gmail.com.

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Abstract

This study explores the impact of Artificial Intelligence (AI) innovation, economic growth, energy consumption, Foreign Direct Investment (FDI), and urbanization on carbon emissions in the United States over the period 1990–2022. Drawing on the STIRPAT framework, the analysis employs the Autoregressive Distributed Lag (ARDL) model to investigate both short-run and long-run relationships among the variables. Unit root tests confirm a mixed order of integration, justifying the application of the ARDL bounds testing approach. The empirical findings reveal a dual pattern: AI innovation contributes to reducing carbon emissions by improving technological efficiency and promoting cleaner production processes, while economic growth, energy consumption, FDI inflows, and urbanization significantly increase environmental degradation. The results further indicate the presence of a stable long-run equilibrium relationship among the variables. In the short run, fluctuations in economic and structural factors continue to exert pressure on environmental quality. The study highlights that technological progress alone cannot ensure sustainability without effective environmental governance and energy transition strategies. Based on these findings, the study recommends promoting environmentally oriented AI development, accelerating the transition toward clean energy sources, guiding FDI toward green sectors, and implementing sustainable urban planning policies to mitigate carbon emissions and support long-term environmental sustainability in the United States.

Keywords: Artificial intelligence, CO_2 emissions, Energy consumption, Foreign direct investment, Urbanization.

1 | Introduction

Environmental degradation and climate change have become defining challenges of the twenty-first century, primarily driven by the rapid increase in greenhouse gas emissions, particularly carbon dioxide (CO_2) [1], [2].

Corresponding Author: mdamranpabel@gmail.com
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Rising global temperatures, extreme weather events, and ecological imbalances have intensified the urgency for sustainable development and environmental protection [3], [4]. In response, international initiatives such as the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement emphasize the critical need to reduce emissions while maintaining economic growth. Within this global context, the United States occupies a central position due to its status as one of the largest economies and a major contributor to global CO_2 emissions [5]. Its high level of industrialization, technological advancement, and energy consumption has historically placed significant pressure on environmental quality [6], [7]. Despite recent policy commitments aimed at reducing emissions and promoting clean energy transitions, the challenge of balancing economic expansion with environmental sustainability remains substantial [8–10]. Therefore, understanding the underlying factors that influence carbon emissions in the United States is essential for designing effective strategies that support both economic progress and ecological stability.

A growing body of research suggests that environmental outcomes are shaped by a complex interaction of economic, technological, and structural factors. Economic growth, while essential for improving living standards, is often associated with increased industrial activity and energy demand, thereby exerting upward pressure on carbon emissions [11], [12]. Energy consumption, particularly from fossil fuel sources, remains a primary driver of environmental degradation in advanced economies [2], [13]. At the same time, Foreign Direct Investment (FDI) plays a dual role, as it can stimulate economic expansion and industrialization while also facilitating the transfer of cleaner technologies and sustainable practices [14]. Urbanization further complicates this relationship by intensifying energy use, transportation demand, and infrastructure expansion, which may increase environmental stress [15]. In contrast, Artificial Intelligence (AI) has emerged as a transformative force with the potential to enhance energy efficiency, optimize production processes, and support environmental monitoring systems [16]. However, the environmental implications of AI remain ambiguous, as its development and deployment also require substantial energy resources. These contrasting dynamics create uncertainty regarding the overall impact of these factors on environmental quality, particularly in the context of a highly developed economy like the United States.

Despite the growing attention to environmental sustainability, existing empirical studies provide fragmented and often inconsistent evidence regarding the determinants of carbon emissions. A large portion of the literature has focused on traditional drivers such as economic growth, energy consumption, and urbanization, while relatively fewer studies have incorporated emerging technological factors like AI within a unified analytical framework [17], [18]. Moreover, prior research has predominantly concentrated on developing or emerging economies, leaving advanced economies such as the United States comparatively underexplored in terms of integrated environmental analysis [19], [20]. Another limitation lies in the methodological approaches, where many studies rely on static models that fail to capture the dynamic and long-run relationships among variables [21]. In addition, the simultaneous interaction of AI innovation with macroeconomic and structural factors remains insufficiently examined [22], [23]. These gaps create a lack of comprehensive understanding of how modern technological advancements, alongside economic expansion and structural transformation, jointly influence environmental outcomes. Therefore, there is a clear need for a more integrated and dynamic investigation that considers both traditional and emerging determinants of carbon emissions within a single, coherent framework.

In light of these gaps, this study aims to investigate the dynamic effects of artificial intelligence innovation, economic growth, energy consumption, FDI, and urbanization on carbon emissions in the United States over the period 1990–2022. By integrating the STIRPAT framework with the Autoregressive Distributed Lag (ARDL) approach, the study captures both short-run adjustments and long-run equilibrium relationships among the variables. This approach provides a more comprehensive understanding of how technological progress interacts with economic and structural factors in shaping environmental outcomes. The study contributes to the literature in several ways by incorporating AI as a key technological driver, focusing on a highly industrialized economy, and employing a dynamic modeling strategy suitable for mixed-order integration. The findings are expected to offer valuable insights for policymakers seeking to balance economic growth with environmental sustainability. The remainder of the paper is organized as follows: the next section reviews the relevant literature, followed by the methodology and data description, then the empirical results and discussion, and finally the conclusion and policy implications.

2 | Literature Review

The growing concern over environmental degradation has led to an expanding body of literature examining the determinants of carbon emissions and ecological sustainability. Researchers have increasingly focused on understanding how economic, technological, and structural factors interact to influence environmental outcomes [24]. Traditional studies have largely emphasized the role of economic growth, energy consumption, and urbanization as primary drivers of carbon emissions, while more recent research has begun to incorporate financial and technological dimensions such as FDI and innovation [25], [26]. In particular, the emergence of AI as a transformative technology has introduced a new dimension to the environmental discourse, raising questions about its potential to either mitigate or intensify ecological pressures [27], [28]. Despite this progress, the existing literature remains fragmented, often addressing these factors in isolation rather than within a unified analytical framework. Moreover, empirical findings are frequently inconsistent, reflecting differences in methodologies, time periods, and country contexts [29]. Therefore, a comprehensive review of the literature is essential to synthesize existing knowledge, identify areas of consensus and divergence, and establish a foundation for a more integrated analysis of environmental sustainability.

A substantial body of empirical literature has examined the relationship between economic growth and environmental degradation, often framed within the Environmental Kuznets Curve (EKC) hypothesis [19], [30]. This hypothesis suggests that environmental degradation initially increases with economic growth but eventually declines after reaching a certain income threshold. However, empirical evidence remains inconclusive. Several studies report a positive relationship between economic growth and CO_2 emissions, indicating that increased production and consumption intensify environmental pressure, particularly in industrialized and rapidly growing economies [31], [32]. Conversely, other studies support the EKC hypothesis, showing that higher income levels enable investments in cleaner technologies and environmental regulation, thereby reducing emissions over time [19]. In some cases, research even finds no significant relationship, suggesting that the growth–environment nexus may be context-specific and influenced by structural and policy factors [33], [34]. These mixed findings highlight that economic growth alone cannot guarantee environmental improvement, and its impact largely depends on energy structure, technological advancement, and regulatory frameworks.

Recent literature has increasingly explored the role of AI as a transformative force in shaping environmental outcomes [35], [36]. AI technologies can enhance energy efficiency, optimize industrial processes, and support environmental monitoring, thereby contributing to emission reduction and sustainable resource management [37]. For instance, the integration of AI in smart grids, transportation systems, and manufacturing has been shown to reduce energy waste and improve operational efficiency. However, the environmental implications of AI are not uniformly positive. The development and deployment of AI systems require substantial computational power, leading to increased electricity consumption and potential carbon emissions, particularly when powered by fossil-based energy sources [38], [39]. As a result, the net environmental impact of AI remains ambiguous and context-dependent. Although initial empirical findings suggest that AI can contribute to environmental sustainability through efficiency gains and technological innovation, this strand of literature is still in its early stages and lacks comprehensive empirical validation across different economic settings [40], [41].

Energy consumption has long been recognized as one of the most critical determinants of environmental degradation, particularly in the context of carbon emissions. A large volume of empirical studies consistently demonstrates a strong positive relationship between energy use and CO_2 emissions, primarily due to the heavy reliance on fossil fuels such as coal, oil, and natural gas [11], [42]. Increased energy demand, driven by industrial production, transportation, and household consumption, tends to intensify environmental pressure in both developed and developing economies [43]. However, the nature of this relationship may vary depending on the composition of the energy mix. While non-renewable energy sources contribute significantly to emissions, the adoption of renewable energy technologies has been shown to mitigate environmental damage and support sustainable development [44]. Some studies argue that improvements in energy efficiency and the transition toward cleaner energy sources can decouple economic growth from environmental degradation [45], [46]. Nevertheless, in economies where fossil fuels dominate the energy structure, energy consumption remains a major contributor to rising carbon emissions, reinforcing the urgency of transitioning toward sustainable energy systems.

FDI has also received considerable attention in environmental economics due to its ambiguous impact on ecological quality. The literature presents two competing hypotheses. The pollution haven hypothesis argues that multinational firms relocate pollution-intensive industries to countries with weaker environmental regulations, thereby increasing emissions. In contrast, the pollution halo hypothesis suggests that FDI can improve environmental quality through the transfer of advanced technologies, cleaner production methods, and better management practices [22], [44]. Empirical findings remain mixed. Several studies report that FDI inflows contribute to higher emissions by expanding industrial activity and energy consumption, particularly in the absence of strict environmental policies [12], [47]. On the other hand, some research indicates that FDI promotes environmental sustainability by facilitating technological innovation and improving energy efficiency [48]. These conflicting outcomes imply that the environmental effect of FDI is highly context-dependent and influenced by regulatory quality, technological capacity, and the structure of the host economy.

Urbanization constitutes another important structural factor influencing environmental quality, particularly through its impact on energy demand, infrastructure development, and consumption patterns. Rapid urban expansion is often associated with increased transportation needs, industrial concentration, and higher household energy use, all of which contribute to rising carbon emissions [49]. Empirical evidence largely supports a positive relationship between urbanization and environmental degradation, especially in economies experiencing unplanned or resource-intensive urban growth [50]. However, some studies argue that urbanization can also enhance environmental efficiency through economies of scale, improved public infrastructure, and greater adoption of green technologies in densely populated areas [51]. In developed economies, advanced urban planning and smart city initiatives may help mitigate the adverse environmental effects of urbanization. Despite these potential benefits, the overall impact remains uncertain and varies across countries depending on governance quality, technological advancement, and the nature of urban development strategies.

Despite the extensive body of research on environmental degradation, several critical gaps remain in the existing literature. First, most studies examine the effects of economic growth, energy consumption, FDI, and urbanization in isolation, with limited attention given to their combined and interactive influence on environmental outcomes [52], [53]. Second, although AI has emerged as a key technological driver, its integration into environmental analysis alongside traditional macroeconomic variables is still underexplored [54]. Third, a significant portion of empirical work focuses on developing and emerging economies, while comprehensive and updated evidence for advanced economies, particularly the United States, remains relatively scarce [27], [40]. Finally, many prior studies rely on static modeling techniques that fail to capture the dynamic adjustments and long-run equilibrium relationships among variables. Addressing these gaps, the present study adopts an integrated framework to jointly examine the roles of AI innovation, economic growth, energy consumption, FDI, and urbanization in shaping carbon emissions, thereby offering a more comprehensive and context-specific understanding of environmental sustainability in the United States.

3 | Methodology

This study examines the relationship between environmental degradation and its key determinants by employing annual time series data for the United States over the period 1990–2022. Carbon dioxide emissions are used as the proxy for environmental degradation and serve as the dependent variable. The selection of explanatory variables is guided by the STIRPAT framework, incorporating economic, technological, and structural factors. Economic growth is measured by gross domestic product per capita, while artificial intelligence innovation is proxied through investment-related indicators. Energy consumption is included to capture the effect of resource use on environmental pressure. FDI reflects external capital inflows and their potential environmental implications, and urbanization is measured by total population or urban population dynamics. All variables are transformed into natural logarithmic form to stabilize variance and ensure comparability of coefficients. Data are primarily sourced from the World Development Indicators and other reliable international databases, ensuring consistency and accuracy for empirical analysis.

This study adopts a rigorous empirical strategy to examine both the short-run and long-run dynamics between carbon emissions and its determinants within a time-series framework. Initially, unit root tests, including Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Dickey–Fuller Generalized Least Squares (DF-GLS), are applied to determine the order of integration of the variables. The presence of mixed integration levels justifies the use of the ARDL approach, which is suitable for variables integrated at I(0) and I(1) [47], [17]. Subsequently, the ARDL bounds testing procedure is employed to investigate the existence of a long-run cointegration relationship among the variables. Once cointegration is confirmed, both long-run coefficients and short-run dynamics are estimated within the ARDL framework. The short-run adjustments are captured through the Error Correction Term (ECT), which reflects the speed at which deviations from long-run equilibrium are corrected. Furthermore, the study applies the Pairwise Granger causality test to explore the direction of causal relationships among variables. This comprehensive approach enables a deeper understanding of both equilibrium relationships and dynamic interactions among economic, technological, and environmental factors.

4 | Results and Discussion

The descriptive statistics provide an overview of the distributional properties of the variables used in the analysis, covering the period 1990–2022. The results, reported in *Table 1*, indicate that all variables exhibit relatively stable behavior, with moderate variations over time. Carbon emissions (LCO2) show a high mean value with a low standard deviation, suggesting limited volatility and a consistent upward trend over the sample period. Economic growth (LGDP) also demonstrates steady progression, reflecting the stable expansion of the U.S. economy. Artificial intelligence investment (LAI) displays comparatively higher variability, indicating rapid growth and fluctuations associated with technological development. Energy consumption (LENU) remains relatively stable, though its variation reflects changes in energy demand and efficiency over time. Similarly, foreign direct investment (LFDI) shows moderate dispersion, capturing fluctuations in international capital inflows. Urbanization (LURB) exhibits minimal variation, consistent with the already high and mature urban structure of the United States. Overall, the distributional characteristics suggest no extreme outliers, supporting the suitability of the dataset for time-series econometric analysis.

Table 1. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
T	33	2006.1	9.845	1990	2022
LCO2	33	15.482	0.072	15.301	15.612
LGDP	33	10.712	0.338	10.094	11.241
LAI	33	7.843	1.125	6.214	9.982
LENU	33	4.692	0.287	3.982	5.188
LFDI	33	2.714	0.156	2.301	2.982
LURB	33	19.563	0.064	19.402	19.672

The stationarity properties of the variables are examined using ADF, PP, and DF-GLS unit root tests. The results, reported in *Table 2*, reveal a mixed order of integration among the variables. Specifically, carbon emissions (LCO2), economic growth (LGDP), artificial intelligence (LAI), energy consumption (LENU), and foreign direct investment (LFDI) are found to be non-stationary at level but become stationary after first differencing, indicating integration of order I(1). In contrast, urbanization (LURB) is stationary at level, implying integration of order I(0). The consistency of results across all three-unit root tests strengthens the reliability of these findings. The presence of both I(0) and I(1) variables confirms that the dataset does not follow a uniform integration order. Therefore, the application of the ARDL model is appropriate, as it accommodates variables with mixed integration properties. These results ensure that further cointegration analysis can be conducted without the risk of spurious regression outcomes.

Table 2. Unit Root Test Results.

Variable	ADF		PP		DF-GLS	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
LCO2	-0.412	-4.125***	-0.398	-4.231***	-0.405	-4.188***
LGDP	-0.953	-4.342***	-0.874	-4.621***	-0.912	-4.287***
LAI	-0.682	-5.284***	-0.731	-5.417***	-0.705	-5.362***
LENU	-0.215	-5.142***	-0.204	-5.198***	-0.856	-2.342***
LFDI	-0.104	-4.256***	-0.118	-4.193***	-0.072	-4.389***
LURB	-5.231***	-7.412***	-5.804***	-7.832***	-5.762***	-7.521***

Note: *** indicates statistical significance at the 1% level.

The ARDL bounds testing approach is employed to examine the existence of a long-run equilibrium relationship among carbon emissions and its determinants. According to the results presented in *Table 3*, the computed F-statistic is found to be higher than the upper critical bound at conventional significance levels, indicating strong evidence against the null hypothesis of no cointegration. This result confirms that a stable long-run relationship exists among economic growth, AI, energy consumption, FDI, urbanization, and carbon emissions in the United States. The rejection of the null hypothesis implies that these variables move together over time and are interconnected in the long run. This finding is consistent with the theoretical expectation of the STIRPAT framework, which suggests that environmental pressure is influenced by economic, technological, and structural factors. Establishing cointegration is a crucial step, as it validates the estimation of long-run coefficients and short-run dynamics within the ARDL framework. Therefore, the study proceeds to estimate both long-run and short-run effects to better understand the nature and magnitude of these relationships.

Table 3. ARDL Bounds Test.

Test Statistic	Value	Significance	I(0)	I(1)
F-statistic	5.876	10%	2.12	3.05
k	5	5%	2.45	3.38
		2.5%	2.87	3.92
		1%	3.21	4.37

The ARDL estimation results, presented in *Table 4*, provide important insights into both the long-run equilibrium relationships and short-run dynamics between carbon emissions and its determinants in the United States. In the long run, economic growth (LGDP) exhibits a positive and statistically significant effect on CO_2 emissions ($\beta = 0.312$, $p < 0.01$), indicating that a 1% increase in economic output leads to a 0.312% rise in carbon emissions. This finding suggests that the scale effect of growth dominates any potential efficiency gains, thereby contributing to environmental degradation. In contrast, artificial intelligence innovation (LAI) demonstrates a negative and statistically significant relationship with CO_2 emissions ($\beta = -0.184$, $p < 0.01$), implying that technological advancement plays a crucial role in enhancing energy efficiency and promoting cleaner production processes. This result supports the argument that AI-driven innovations contribute meaningfully to environmental sustainability by improving resource productivity and reducing emissions intensity.

Energy consumption (LENU) exhibits the largest positive impact on carbon emissions in the long run ($\beta = 0.526$, $p < 0.01$), confirming that continued reliance on fossil fuel-based energy remains the dominant driver of environmental degradation in the United States. Similarly, foreign direct investment (LFDI) is found to exert a positive and significant effect on emissions ($\beta = 0.097$, $p < 0.05$), suggesting that investment inflows may be channeled toward pollution-intensive activities in the absence of stringent environmental regulations. Urbanization (LURB) also contributes positively and significantly to carbon emissions ($\beta = 0.218$, $p < 0.05$), reflecting that expanding urban infrastructure and rising energy demand associated with urban growth intensify environmental stress. In the short run, the results remain broadly consistent with the long-run findings, although the magnitude of the coefficients is relatively smaller across all variables. The Error Correction Term ($ECT = -0.461$, $p < 0.01$) is negative and statistically significant, confirming the existence of a stable long-run equilibrium relationship among the variables. The coefficient implies that approximately 46.1 percent of any short-term disequilibrium is corrected within each period, indicating a moderately fast adjustment speed and reinforcing the robustness of the long-run estimates. The overall model fit is strong, with an R-squared value of 0.923, suggesting that the selected variables explain approximately 92.3% of the variation in carbon emissions.

Table 4. ARDL Long-run and Short-run Results.

Variables	Long-Run Coefficient	Short-Run Coefficient
LGDP	0.312*** (0.104)	0.274*** (0.089)
LAI	−0.184*** (0.061)	−0.143** (0.053)
LENU	0.526*** (0.118)	0.389*** (0.094)
LFDI	0.097** (0.042)	0.073** (0.031)
LURB	0.218** (0.093)	0.162** (0.074)
ECT(−1)	—	−0.461*** (0.034)
Constant	8.631***	—
R-squared	0.923	

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors in parentheses. ECT = error correction term.

5 | Conclusion and Policy Implications

This study investigates the dynamic relationship between artificial intelligence innovation, economic growth, energy consumption, FDI, and urbanization on carbon emissions in the United States over the period 1990–2022. Using the ARDL framework within the STIRPAT model, the findings confirm the existence of a stable long-run relationship among the variables. The results reveal a contrasting pattern in environmental outcomes. AI emerges as a key factor in reducing carbon emissions by enhancing efficiency and promoting cleaner production processes. In contrast, economic growth, energy consumption, FDI, and urbanization contribute significantly to environmental degradation, indicating that traditional growth and structural expansion continue to exert pressure on ecological systems. The short-run dynamics further support these findings, showing that deviations from equilibrium are corrected over time through a stable adjustment mechanism. The results highlight that technological advancement alone cannot ensure environmental sustainability without complementary policy support. In particular, the dominance of fossil fuel-based energy and the nature of investment flows play a crucial role in shaping environmental outcomes.

The empirical findings suggest several targeted policy measures to achieve environmental sustainability in the United States. First, the government should actively promote the development and diffusion of environmentally friendly AI. Public support for research and development, tax incentives for green innovation, and the integration of AI in energy management systems can enhance efficiency and reduce emissions. Second, energy policy must prioritize a rapid transition toward renewable sources. Expanding investments in solar, wind, and other clean technologies, along with strengthening energy efficiency standards, can significantly lower carbon intensity. Third, FDI should be carefully regulated to ensure environmental compliance. Policymakers should encourage green FDI by offering incentives for clean and sustainable projects while imposing strict environmental standards on pollution-intensive investments. This approach can transform FDI into a channel for technology transfer and environmental improvement. Fourth, sustainable urbanization policies are essential. Promoting smart city development, improving public transportation networks, and adopting energy-efficient infrastructure can mitigate the environmental impact of urban growth. Finally, a coordinated policy framework that aligns economic growth with environmental objectives is crucial. Strengthening institutional quality, enforcing environmental regulations, and fostering collaboration between government, industry, and research sectors will support a balanced and sustainable low-carbon transition.

Author Contribution

S. I. T.: writing-original draft, methodology, data curation, conceptualization, and validation. K. M.: writing-review and editing, software, formal analysis, and investigation. M. A. H. P.: writing-review and editing, formal analysis, and investigation. T. T.: validation, writing-review and editing, visualization. M. O. F.: 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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