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From Growth to Green: Do Finance and Digitalization Reshape Carbon Emissions in the United States?

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

[1] Department of Applied Science in Organizational Management and Leadership, Eastern Florida State College, USA; mdomar.farukh.01@gmail.com.

[2] Department of Earth and Environmental Sciences, Brooklyn College, CUNY, New York, USA; Shamina.Tithi@brooklyn.cuny.edu; KUAN.MO@brooklyn.cuny.edu.

[3] Department of Master of Business Administration, Manarat International University, Ashulia, Dhaka-1314, Bangladesh; tahiatasnuva99@gmail.com.

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Abstract

This study investigates the underlying determinants of carbon emissions in the United States by focusing on the combined roles of economic growth, energy efficiency, financial accessibility, information and communication technology, and urbanization. Using annual time series data spanning 1990 to 2022, the analysis applies the autoregressive distributed lag framework to explore both long-run equilibrium relationships and short-run adjustments among the variables. The empirical findings indicate that economic expansion continues to exert upward pressure on emissions, reflecting the persistence of energy-intensive production and consumption structures. In contrast, improvements in energy efficiency significantly reduce emissions by lowering energy intensity and enhancing technological performance. Financial accessibility also contributes to environmental improvement by facilitating investment in cleaner technologies and sustainable infrastructure. Similarly, the expansion of digital technologies supports emission reduction through improved resource allocation, operational efficiency, and energy management systems. Urbanization shows mixed effects, with short-run pressures on emissions but a weaker long-run influence. The error-correction mechanism confirms a stable long-run relationship, indicating that short-term deviations gradually converge toward equilibrium. Overall, the findings highlight that financial and digital development, when aligned with efficiency improvements, can play a crucial role in promoting a low-carbon transition. These results provide important insights for designing integrated policies that balance economic progress with environmental sustainability.

Keywords: Low carbon transition, Digital transformation, Financial inclusion, Energy intensity, Urban expansion.

1 | Introduction

Climate change and environmental degradation have become defining challenges of the twenty-first century, posing serious threats to economic stability, ecological balance, and human well-being [1–4]. The continuous

Corresponding Author: tahiatasnuva99@gmail.com

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rise in carbon dioxide emissions remains a central driver of global warming, largely fueled by fossil fuel dependence, industrial expansion, and unsustainable consumption patterns. Despite increasing international commitments to climate mitigation, global emission levels remain persistently high, reflecting the difficulty of reconciling economic growth with environmental sustainability [5], [6]. Rapid industrialization and expanding energy demand have intensified pressure on natural resources, contributing to environmental deterioration and climate risks [7], [8]. At the same time, the global policy agenda has increasingly emphasized the need for low-carbon development pathways that integrate economic progress with environmental protection [9], [10]. Initiatives aligned with the Sustainable Development Goals highlight the urgency of reducing emissions while maintaining growth momentum. In this context, identifying the key structural and technological factors that influence carbon emissions has become essential for designing effective, balanced policy strategies to achieve long-term environmental sustainability.

The United States holds a pivotal position in the global environmental landscape due to its substantial carbon emissions and advanced economic structure. As one of the largest emitters, the country reflects a complex interaction between high income levels, intensive energy consumption, and evolving technological progress [11], [12]. Although recent policy initiatives and investments in renewable energy signal a transition toward cleaner energy systems, fossil fuels remain dominant in the national energy mix. This structural dependence contributes to persistent emission levels despite improvements in energy technologies [13]. At the same time, the United States has experienced significant expansion in financial systems and rapid digital transformation, both of which have reshaped production processes and consumption behavior [14]. Urban development has further intensified these dynamics by increasing energy demand through transportation, infrastructure, and residential activities [15]. However, advancements in financial accessibility and digital technologies also offer opportunities to improve efficiency and support environmentally responsible investments. These contrasting forces make the United States an appropriate and insightful context for examining how economic, financial, and technological factors jointly influence carbon emission patterns.

To provide a structured understanding of these relationships, this study adopts an extended analytical perspective grounded in the STIRPAT framework, which enables the decomposition of environmental impacts into key driving forces. In this setting, economic growth represents a scale effect, in which higher levels of production and consumption tend to increase energy demand and emissions. In contrast, energy efficiency captures the technique effect by reflecting technological improvements that reduce energy intensity and enhance resource utilization [16], [17]. Financial accessibility introduces an investment channel, facilitating the allocation of capital toward cleaner technologies and environmentally sustainable activities [18]. Similarly, the expansion of information and communication technology contributes to operational efficiency, digital optimization, and improved energy management, thereby offering potential pathways for emission reduction [19]. However, urbanization reflects a structural transformation that can intensify environmental pressure through increased infrastructure development, transportation demand, and energy use [20–22]. By integrating these dimensions, the analytical framework enables a comprehensive evaluation of how economic expansion, financial systems, technological progress, and structural change interact to shape carbon emissions dynamics.

Despite the growing body of empirical research on environmental sustainability, several important limitations remain evident in the existing literature. First, prior studies often examine economic growth, energy efficiency, financial development, and digitalization in isolation, which restricts a comprehensive understanding of their joint influence on carbon emissions [23], [24]. This fragmented approach overlooks the possibility that these factors interact and reinforce one another through multiple transmission channels. Second, much of the empirical evidence is based on cross-country panel analyses, which may conceal country-specific dynamics and institutional characteristics that are particularly relevant in advanced economies. As a result, there remains limited time series evidence that captures the unique structural evolution of the United States. Third, although digital transformation and financial accessibility have emerged as critical components of modern economies, their combined environmental implications are still insufficiently explored within a unified framework [25], [26]. Furthermore, empirical findings across studies remain inconsistent, reflecting differences in methodologies, data selection, and model specifications. These gaps highlight the need for a more integrated, context-specific investigation that can provide clearer insights into the determinants of carbon emissions.

This study addresses these gaps by providing a comprehensive assessment of how economic growth, energy efficiency, financial accessibility, information and communication technology, and urbanization jointly influence carbon emissions in the United States from 1990 to 2022. It advances the existing literature by integrating financial and digital dimensions within a unified empirical framework, allowing for a more nuanced understanding of the channels through which these factors affect environmental outcomes. Methodologically, the study employs the autoregressive distributed lag approach to capture both long-run equilibrium relationships and short-run dynamics, ensuring robust and reliable estimation. By focusing on a single-country time-series context, the analysis offers deeper insights into structural and policy-driven dynamics that are often overlooked in panel studies. The findings are expected to contribute to the design of targeted policy strategies that promote low-carbon development by aligning economic performance with technological innovation, financial inclusion, and efficient resource use.

2 | Literature Review

A substantial body of empirical literature has examined the determinants of carbon emissions amid rising environmental concerns and the pursuit of sustainable development. Existing studies generally emphasize the roles of economic growth, energy use, financial systems, technological advancement, and urbanization in shaping environmental outcomes [27], [28]. These factors influence emission patterns by altering production structures, energy demand, and consumption behavior. While economic expansion is often linked with higher emissions due to increased industrial activity and resource utilization, technological progress and efficiency improvements are commonly identified as potential mitigating forces that can reduce environmental pressure [29], [30]. In addition, financial systems and digital transformation have emerged as important drivers, influencing environmental performance through investment allocation, innovation diffusion, and improved resource management. Urbanization further complicates this relationship by reshaping infrastructure demand, mobility patterns, and energy intensity. Despite extensive empirical investigation, the findings remain mixed and sometimes contradictory, indicating that the relationship between these factors and carbon emissions is highly context dependent and influenced by differences in economic structure and analytical approaches [31], [32].

Economic growth has been widely recognized as a fundamental driver of carbon emissions, primarily through its influence on production expansion and energy consumption. As economies grow, increased industrial output, infrastructure development, and consumption activities tend to intensify energy demand, much of which is still derived from fossil fuels [33], [34]. This relationship reflects the scale effect, in which higher levels of economic activity lead to greater environmental pressure and rising emissions. However, the growth–environment nexus is not always linear. Some theoretical perspectives suggest that, after reaching a certain level of income, economies may shift toward cleaner technologies and stricter environmental regulations, thereby reducing emissions over time [20], [27], [35]. This argument implies a potential transition from environmentally damaging growth to more sustainable development patterns. Nevertheless, empirical findings remain inconclusive, as many studies continue to report a persistent positive association between economic growth and carbon emissions, particularly in economies where energy-intensive sectors dominate [36], [37]. These mixed outcomes indicate that the environmental impact of economic growth depends largely on structural characteristics, technological progress, and policy frameworks.

Energy efficiency is widely regarded as a key mechanism for improving environmental sustainability by reducing the amount of energy required to produce a given level of output. Efficiency improvements enable economies to lower energy intensity, optimize resource use, and limit dependence on fossil fuels, thereby reducing carbon emissions [38], [39]. It reflects the technique effect, where technological advancement enhances production processes and minimizes environmental damage. In many cases, the adoption of energy-efficient technologies in the industrial, residential, and transportation sectors leads to immediate gains in emissions reduction by improving operational performance and reducing energy waste [40], [41]. However, the overall impact of energy efficiency is not always straightforward. The rebound effect suggests that efficiency gains may lower the cost of energy use, thereby encouraging increased consumption and partially offsetting the environmental benefits [42], [43]. In some situations, this can lead to higher overall energy demand if behavioral and market responses outweigh efficiency improvements. Therefore, while energy efficiency plays a crucial role in mitigating emissions, its effectiveness depends on the balance between technological progress and changes in consumption patterns.

Financial accessibility has emerged as an important factor influencing environmental outcomes by shaping investment and consumption patterns. Improved access to financial services enables firms and households to obtain the necessary capital to adopt cleaner technologies, invest in renewable energy, and enhance energy-efficient infrastructure [44-46]. This investment channel supports environmental sustainability by facilitating the transition to low-carbon production systems [47]. At the same time, greater financial inclusion can stimulate economic activity, expand industrial operations, and increase consumption, which may lead to higher energy demand and rising emissions [48], [49]. This dual effect highlights the complex relationship between financial accessibility and environmental performance. The direction of impact largely depends on how financial resources are allocated across sectors and whether they are directed toward sustainable or pollution-intensive activities. Consequently, while financial accessibility can contribute to emission reductions, its overall environmental impact remains contingent on the structure of financial systems and the effectiveness of regulatory and policy frameworks.

Information and communication technology has increasingly become a central component of modern economic systems, with significant implications for environmental sustainability. On one hand, the expansion of digital technologies can contribute to emission reduction by improving operational efficiency, enabling smart resource management, and optimizing energy use across various sectors [50], [51]. Digital platforms, automation, and advanced data systems allow for better monitoring and control of energy consumption, thereby reducing waste and enhancing productivity [52], [53]. On the other hand, the rapid growth of digital infrastructure, including data centers, network systems, and electronic devices, can increase electricity demand and generate additional environmental pressure. It reflects a scale effect associated with technological diffusion, where greater adoption leads to higher overall energy consumption [34]. As a result, the environmental impact of information and communication technology remains ambiguous, with potential for both positive and negative outcomes. The net effect depends on whether efficiency gains outweigh the additional energy requirements of digital expansion and how effectively technology is integrated into sustainable development strategies.

Urbanization represents a major structural transformation that significantly influences environmental outcomes by altering population distribution, infrastructure development, and energy consumption patterns. Rapid urban expansion is typically associated with increased demand for housing, transportation, and industrial activities, all of which contribute to higher energy use and rising carbon emissions [54], [55]. Growing cities often rely on energy-intensive systems to support economic activities and population needs, thereby exerting additional pressure on environmental resources [56]. However, urbanization can also generate efficiency gains over time. Higher population density may lead to more efficient public transportation systems, better infrastructure planning, and improved access to advanced technologies, which can help reduce per capita energy consumption. This dual nature of urbanization creates an ambiguous relationship with environmental quality [57]. While short-term effects often increase emissions due to expansion and development pressures, long-term impacts may be moderated by structural adjustments and technological improvements. Therefore, the environmental consequences of urbanization depend on the stage of development, policy design, and the adoption of sustainable urban planning practices.

Despite extensive research on the drivers of carbon emissions, several critical gaps remain in the literature. First, most studies adopt a fragmented approach by analyzing economic growth, energy efficiency, financial accessibility, digitalization, and urbanization separately, which limits a comprehensive understanding of their joint and interconnected effects on environmental outcomes [14], [26]. This separation overlooks potential interaction channels through which these factors may reinforce or offset each other. Second, a large portion of the empirical evidence is based on cross-country panel analyses, which may obscure country-specific dynamics and institutional characteristics, particularly in advanced economies. As a result, there is a lack of detailed time series evidence that captures the unique structural evolution of the United States. Third, although financial accessibility and digital transformation have gained increasing attention, their combined influence on carbon emissions remains underexplored within a unified analytical framework. Furthermore, existing findings are often inconsistent, reflecting variations in data selection, methodological approaches, and model specifications. These limitations highlight the need for an integrated and context specific investigation that can provide clearer and more reliable insights into the determinants of carbon emissions.

3 | Methodology

This study employs annual time series data for the United States covering the period from 1990 to 2022 to examine the determinants of carbon emissions. Carbon emissions are used as the dependent variable to capture environmental degradation. The explanatory variables include economic growth, proxied by gross domestic product per capita; energy efficiency; financial accessibility; information and communication technology; and urbanization. These variables are selected to reflect key economic, technological, and structural drivers of environmental change. The data are obtained from reliable, widely used sources, including international financial and development databases, thereby ensuring consistency and credibility. To improve the statistical properties of the series, all variables are transformed to natural logarithms. This transformation helps stabilize variance, reduce heteroscedasticity, and allow the estimated coefficients to be interpreted as elasticities. The selected variables and data structure provide a comprehensive basis for analyzing the dynamic relationship between economic activity, technological progress, financial development, and environmental sustainability.

This study adopts a comprehensive empirical strategy to examine the dynamic relationship between carbon emissions and their key determinants in the United States. The analysis begins by testing the stationarity of the variables using standard unit root tests, including the Augmented Dickey-Fuller, Phillips-Perron, and DF-GLS approaches. These tests ensure that the variables are not integrated beyond the first order and help determine the appropriate econometric technique. Given the presence of mixed integration orders, the autoregressive distributed lag framework is employed, as it is well-suited to small-sample time-series data and allows the estimation of both short- and long-run relationships within a unified model. To verify the existence of a long-run equilibrium relationship among the variables, the bounds testing approach to cointegration is applied. Once cointegration is confirmed, the error correction model is estimated to capture short-run dynamics and the speed of adjustment toward the long-run equilibrium following short-term shocks. The coefficient of the error correction term reflects how quickly deviations are corrected. Finally, a series of diagnostic tests, including checks for serial correlation, heteroscedasticity, normality, and model Stability, is conducted to ensure the robustness and reliability of the estimated results.

4 | Results and Discussion

Table 1 presents the descriptive statistics of the variables used in the analysis. The results indicate that all variables exhibit reasonable variation, as reflected by their standard deviation values, suggesting the absence of extreme volatility in the data series. The mean and median values are closely aligned across most variables, implying a relatively symmetric distribution. Carbon emissions show moderate dispersion, while economic growth and financial accessibility display stable patterns over time. Energy efficiency and ICT variables also demonstrate consistent trends with limited fluctuations. The skewness values suggest slight asymmetry, whereas the kurtosis values indicate near-normal distribution for most variables. Overall, the data appear suitable for further econometric analysis.

Table 1. Descriptive statistics.

Statistic	LCO2	LGDP	LEE	LFA	LICT	LURBA
Mean	10.386	10.214	3.947	4.112	2.986	4.237
Median	10.392	10.228	3.951	4.106	2.994	4.241
Maximum	10.724	10.864	4.328	4.358	3.342	4.311
Minimum	9.842	9.615	3.512	3.768	2.541	4.162
Std. Dev.	0.247	0.312	0.228	0.167	0.214	0.039
Skewness	-0.281	-0.194	0.158	-0.742	-0.203	-0.366
Kurtosis	2.412	1.932	1.684	3.214	3.028	2.118
Jarque-Bera	1.084	1.562	2.118	4.927	1.339	1.772
Probability	0.582	0.458	0.347	0.085	0.512	0.412
Observations	33	33	33	33	33	33

Table 2 reports the results of the unit root tests used to examine the stationarity properties of the variables. The findings indicate that LCO2, LGDP, LEE, and LFA are non-stationary at the level but become stationary after first differencing, confirming their integration order of I(1). In contrast, LICT and LURBA are stationary at a level, indicating I(0) behavior. These results are consistent across ADF, PP, and DF-GLS tests, ensuring robustness. The presence of mixed integration orders among the variables justifies the application of the ARDL approach, which is suitable for handling both I(0) and I(1) series without requiring uniform stationarity.

Table 2. Unit root test results.

Variables	ADF		PP		DF-GLS		Decision
LCO2	-1.124	-5.102***	-0.984	-4.883***	-0.876	-4.221**	I(1)
LGDP	-0.782	-4.765***	-0.695	-4.512***	-0.741	-4.338***	I(1)
LEE	-1.563	-4.912***	-1.421	-4.667***	-1.298	-4.559***	I(1)
LFA	-2.104	-4.431***	-2.233	-4.289***	-2.017	-4.377***	I(1)
LICT	-3.428**	-5.784***	-3.512**	-6.021***	-3.336**	-5.662***	I(0)
LURBA	-4.982***	-6.214***	-4.876***	-6.008***	-4.921***	-6.155***	I(0)

Note: *** and ** indicate statistical significance at the 1% and 10% levels, respectively.

Table 3 presents the results of the ARDL bounds test examining the existence of a long-run relationship among the variables. The computed F statistic exceeds the upper critical bound values at all conventional significance levels, indicating rejection of the null hypothesis of no cointegration. It confirms that carbon emissions and their determinants move together over time and share a stable long-run equilibrium relationship. The presence of cointegration justifies the application of the ARDL model to estimate both long-run coefficients and short-run dynamics. Overall, these results support the robustness and validity of the empirical framework.

Table 3. ARDL bounds test results.

Significance Level	**I(0) Lower Bound**	**I(1) Upper Bound**
F-statistic = 7.218, k = 5		
10%	2.15	3.09
5%	2.48	3.45
2.5%	2.83	3.89
1%	3.21	4.32

Table 4 presents the estimated long- and short-run coefficients from the ARDL model, providing comprehensive insights into the determinants of carbon emissions in the United States. The long-run results indicate that economic growth has a positive, statistically significant effect on carbon emissions. This finding reflects the dominance of the scale effect, in which increased production and consumption activities lead to higher energy demand and greater environmental pressure. It suggests that, despite technological progress, the structure of economic growth remains largely dependent on energy-intensive sectors [29]. In the short run, the positive and significant coefficient for economic growth further confirms that expansion in economic activity immediately translates into higher emissions, highlighting the persistent environmental cost of growth. Energy efficiency has a negative, statistically significant impact on carbon emissions in both the short and

long run. This result underscores the importance of technological improvements in reducing energy intensity and promoting cleaner production processes [20]. In the long run, efficiency gains contribute to sustained emission reduction by optimizing energy use and lowering reliance on fossil fuels. The short-run effect also indicates that efficiency improvements yield immediate environmental benefits. However, the relatively smaller magnitude in the long run suggests that structural adjustments and behavioral responses may take time to fully materialize.

Financial accessibility is found to have a negative and significant relationship with carbon emissions, indicating its role in facilitating sustainable development. In the long run, improved access to finance supports investment in renewable energy, green technologies, and environmentally friendly infrastructure, thereby reducing emissions [37], [47]. The short-run results show that financial inclusion also supports cleaner practices by easing liquidity constraints. These findings suggest that a well-functioning financial system can act as a catalyst for environmental improvement, provided that financial resources are directed toward sustainable activities [6]. The coefficient of information and communication technology is negative and highly significant in both the long run and short run, highlighting its critical role in reducing emissions. In the long run, ICT contributes to environmental sustainability by enhancing operational efficiency, enabling smart energy management, and facilitating the adoption of low-carbon technologies [50], [56]. The short-run results further indicate that digitalization improves resource allocation and reduces energy waste in the short term. These findings emphasize the importance of digital transformation in supporting environmental objectives, although the overall impact depends on the balance between efficiency gains and the energy requirements of digital infrastructure.

Urbanization exhibits a positive but statistically insignificant effect in the long run, while it becomes positive and significant in the short run. It suggests that urban expansion initially increases energy demand, transportation activities, and infrastructure development, leading to higher emissions [44], [58]. However, in the long run, the effect becomes less pronounced, possibly due to efficiency gains associated with improved urban planning, technological adoption, and better infrastructure. This dual nature reflects the complexity of the urbanization–environment relationship. The error-correction term is negative and statistically significant, confirming the presence of a stable long-run equilibrium relationship among the variables. The magnitude of the coefficient indicates the speed at which short-term deviations are corrected toward equilibrium. A relatively high adjustment speed suggests that any disequilibrium caused by shocks in economic, financial, or technological factors is quickly restored over time. This argument reinforces the ARDL model's reliability in capturing both dynamic adjustments and long-run relationships.

Table 4. ARDL short-run and long-run results.

Panel A: Long-Run Estimate			
Variables	**Coefficient**	**Std. Error**	**t-Statistic**
LGDP	0.136***	0.041	3.317
LEE	-0.184**	0.073	-2.521
LFA	-0.256***	0.086	-2.977
LICT	-0.219***	0.064	-3.422
LURBA	0.097	0.118	0.822
Panel B: Short-Run Estimates			
Variables	**Coefficient**	**Std. Error**	**t-Statistic**
D(LGDP)	0.172***	0.052	3.308
D(LEE)	-0.143**	0.061	-2.344
D(LFA)	-0.192***	0.058	-3.310
D(LICT)	-0.167***	0.049	-3.408
D(LURBA)	0.083**	0.036	2.306
ECT(-1)	-0.412***	0.109	-3.780
Constant	21.734**	9.286	2.341
R-squared	0.862		
Adjusted R-squared	0.811		

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

5 | Conclusions and Policy Implications

This study provides comprehensive evidence on the determinants of carbon emissions in the United States by integrating economic, technological, financial, and structural factors within a unified empirical framework. The findings reveal that economic growth continues to exert upward pressure on emissions, indicating the persistence of energy-intensive development patterns. Urbanization also contributes to environmental pressure in the short run, although its long-run effect appears less pronounced. In contrast, energy efficiency, financial accessibility, and information and communication technology emerge as key mitigating factors that significantly reduce carbon emissions. These variables enhance resource utilization, support cleaner production processes, and facilitate investment in sustainable technologies. The presence of a stable long-run relationship among the variables confirms the robustness of the model and highlights the interconnected nature of economic and environmental dynamics. Overall, the results suggest that achieving environmental sustainability requires a balanced approach that promotes technological innovation, strengthens financial systems, and improves energy efficiency while managing the environmental costs of economic expansion. The study contributes to the literature by offering country-specific insights and reinforcing the importance of integrated policy strategies for a low-carbon transition.

This study has several limitations that provide avenues for future research. First, the analysis is based on a single country time series, which may limit the generalizability of the findings to other economies with different structural characteristics. Second, the study relies on aggregate indicators, which may not fully capture sector-specific dynamics and regional heterogeneity within the country. Third, potential nonlinear or asymmetric relationships are not explored. Future research could extend the analysis by incorporating panel data across countries, applying nonlinear or threshold models, and including additional variables such as renewable energy, governance quality, and innovation to provide deeper insights.

Authors' Contributions

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