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Carbon Footprints and Income Inequality: A Panel Data Analysis of the 66 Largest Carbon-Emitting Nations

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Abstract. *In this study, we delved into the complex interaction between carbon emissions and critical economic and environmental factors using Two-step Sys-GMM Dynamic Panel Data Estimation. Our comprehensive dataset encompassed 66 major carbon-emitting nations spanning 1990-2020, providing a robust analytical foundation. Our key findings revealed a noteworthy positive relationship between income inequality, as measured by the Gini index, and carbon emissions across all models. This implies that higher income inequality is linked to increased carbon emissions, possibly due to consumption disparities and resource utilization. Furthermore, the relationship between income and emissions displayed intriguing dynamics. While income per capita exhibited a positive association with emissions, suggesting that growing economies tend to emit more, the squared income per capita variable showcased an inverted U-shaped pattern. This suggests that emissions increase at a diminishing rate as income levels reach a certain threshold, aligning with the Environmental Kuznets Curve hypothesis. Surprisingly, we observed that rising income inequality contributed to long-term carbon reduction, hinting at potential shifts in consumption behavior driven by environmental policies as nations develop. Our analysis also highlighted the roles of energy consumption and urbanization in elevating emissions, emphasizing the need for energy efficiency and sustainable urban planning. Conversely, a higher share of renewable energy was linked to reduced emissions, underscoring the urgency of transitioning to cleaner energy sources. Furthermore, net foreign direct investment and international trade exhibited positive associations with carbon emissions, emphasizing the environmental consequences of globalization. Our research underscores the potential of targeted policies addressing income inequality to promote social equity while reducing emissions. Striking a balance between economic growth and environmental sustainability remains crucial, given the intricate dynamics between income and emissions.*

Keywords: Carbon footprint, CO2 emission, income inequality, Sys-GMM .

JEL Codes: C33, Q56, Q52, O15.

1. Introduction

The first industrial revolution, which started in England in the 18th century and soon had its effects all over the world, pushed countries into economic growth models that included more production and consumption. By the end of the 19th century, mass production became widespread, and with the developments in technology, production became mechanized in many countries and production levels increased greatly. Although economic models based on production and consumption have increased welfare in many countries, these welfare levels have created environmental side effects that the world cannot overcome. Carbon emissions, the most basic indicator of environmental damage, reached around 20 billion cubic meters in the late 1980s, from 4.85 billion cubic meters in 1940 (Statista, 2023). These side effects, which could no longer be tolerated after many years of unconscious production around the world, finally attracted the attention of policy makers in 1987, and it was emphasized in Our Common Future that the resources to be left to future

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generations were at great risk. With the Rio Conference held in 1992, the concept of "sustainable development" began to be accepted by all countries and international organizations as a common language. After this period, the concept of sustainable development went far beyond environmental factors and drew a new development model that included economic, social and institutional issues.

Although the dimensions of sustainable development mentioned above may seem like separate issues at first glance, it is very difficult to say that a sustainable world model that does not achieve success in all its dimensions can be successful. Based on this understanding, the United Nations put forward 17 Sustainable Development Goals in 2015. These targets, signed by 191 member countries, are aimed to be achieved by 2030. One of these goals, which includes the three dimensions of sustainable development, economic, social and corporate sustainability, is to reduce carbon emissions to zero all over the world. Aligned with this objective, the United Nations has extended invitations not only to government officials but also to companies and individuals, urging collective action toward this shared goal. A global consensus is evident as stakeholders universally acknowledge the imperative of reducing carbon emissions. The imposition of additional taxes on carbon emissions and government support for sustainable energy resources are instrumental in motivating companies to curtail their carbon footprint. The European Green Deal, a recent commitment by the European Union, stands as a significant initiative geared towards achieving zero carbon emissions by 2050. Noteworthy global companies, including Disney, General Motors, Delta Airlines, Alphabet, Cemex, and Microsoft, have made substantial investments in recent years to mitigate their carbon footprint (Hope, 2022). Despite a seemingly shared awareness and concerted efforts towards sustainable development and carbon reduction, it remains challenging to observe a corresponding decline in emission rates. Notably, global carbon emissions were 35.56 billion metric tons in 2015, when the United Nations set the zero-emission target, and this figure climbed to 37.49 billion metric tons in 2022 (Statista, 2023). The most significant declines in carbon emissions occurred in 2009 and 2020. Consequently, there is a hesitancy to assert a transformative shift towards more sustainable global production models. Emission rates tend to rise during periods of increased economic activity and decrease during economic contractions.

In economic literature, the correlation between economic growth and environmental degradation was initially introduced through the Environmental Kuznet Curve hypothesis. This hypothesis posits that during the initial phases of economic development, economic growth has an adverse impact on the environment; however, as income levels rise, this effect is reversed. The empirical evidence supporting this hypothesis, tested across numerous countries over many years, exhibits significant variations. For instance, Narayan et al.'s (2016) analysis of 181 countries confirmed the hypothesis in only 21 nations. Significantly, the inclusion of high-income nations such as the USA, Japan, and Germany among those with the highest carbon emissions questions the assumption that a rise in income necessarily leads to a reduction in carbon emissions (Worldometers, 2023). Contradictory findings in empirical studies have prompted skepticism about the validity of the inverted U-shaped curve. According to some researchers, the hypothesis has recently lost its relevance, with environmental impacts now being influenced more by variations in income distribution than by the overall income levels of countries. In other words, as income inequality increases, the reducing effect of economic growth on carbon emissions has begun to disappear (Wang et al., 2023).

Considering the elimination of both domestic and intercountry income inequalities, which is among the sustainable development goals of the United Nations, understanding the complex relationship between carbon emissions and income inequality, which is among the environmental goals, will be an element that will reshape social and environmental policies that will ensure income equality. Although there is a consensus in the literature that economic growth will cause environmental degradation by increasing carbon emissions, there is no consensus yet on how income distribution affects carbon emissions. Ravallion et al. (2000) were among the first to empirically analyze the relationship between carbon emissions and income inequality and showed that

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income inequalities both within and between countries will lead to significant differences in carbon emissions. However, Borghesi (2006) and Jorgenson et al. (2017) obtained different results. The main motivation of this study, which attempts to reveal the intricate relationship between income inequality and carbon emissions for 66 countries, stems from the lack of consensus on the relationship between the two variables in the literature. The fact that the world's natural resources are not distributed fairly to all countries is a fact that economists and policy makers cannot find a solution to. However, consuming these resources fairly can reduce environmental damage and also has the potential to distribute income fairly. In this context, the study aims to provide important clues to policy makers for both designing environmental policies and creating a more just society.

2. Review of Literature

The idea put forth by Simon Kuznet in 1955 forms the basis of the theoretical relationship between environmental deterioration and income inequality. Based on the relationship between economic growth and income inequality, Kuznet argued that there will be deteriorations in income inequality in the early stages of economic growth, but as the later stages of economic growth progress, income inequality will be positively affected by this situation. In the early 1990s, when economic growth accelerated in all countries due to globalization, Grossman and Krueger (1993) brought a new perspective to this hypothesis. Researchers who observed that rapid increases in economic growth rates lead to environmental degradation have associated Kuznet's hypothesis with the environmental dimension. According to this model, which entered the literature as the Environmental Kuznets Curve (EKC), there is a U-shaped relationship between environmental degradation and income inequality. In other words, according to this hypothesis, carbon emissions will increase in the early stages of economic growth, deteriorating environmental quality, but this situation will reverse as per capita income increases. Therefore, continued economic growth at high-income levels will have an improving effect on environmental factors. Selden and Song (1994) delineated this process as one in which environmental pollution initially surges but subsequently declines. The adoption of more advanced techniques in agriculture and industrial growth is initially linked to an uptick in environmental pollution. However, factors such as positive income elasticities related to environmental quality, shifts in production and consumption patterns, heightened education levels, and increased environmental awareness are expected to contribute to a reduction in environmental pollution over time. Empirical studies in the literature primarily focus on testing the EKC hypothesis to explore the relationship between environmental factors and income inequality.

Carrying out one of the pioneering empirical studies in the literature, Ravallion et al. (2000) analyzed data from 42 countries for the period 1975-1992 with the pooled OLS method and revealed that there is a static balance between reducing carbon emissions and reducing income inequality. The results of Borghesi (2006), who analyzed the period 1988-1995 for 37 countries, gave different results depending on the methods. While the analysis results did not reveal a significant result between income inequality and carbon emissions according to the fixed effects estimator, the pooled OLS estimator revealed a statistically significant and negative relationship between income inequality and carbon emissions.

The issue of sustainability has become more prevalent in government and company agendas since the late 2000s, which has led to further research on the subject in academia. It is seen that most of the single-country analyzes in the literature focus on the USA and China, which produce the most emissions. Jorgenson et al. (2017), who conducted a state-level analysis for the USA, examined the carbon emission- income inequality nexus, taking into account the 10% group with the largest share of income and the Gini coefficient. In the study using longitudinal analysis for the period 1997-2012, it was observed that while there was a positive relationship between the 10% segment receiving the highest share of income and emissions, this relationship did not appear in the Gini coefficient. The result of the study showed that a more equitable income distribution

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resulting from the shift of the poor to the middle class will not trigger the consumption of carbon-intensive products. In another study conducted at the state level in the USA, Liu et al. (2019) used ARDL and quantile regression models to show that high-income inequality initially increases carbon emissions, but this effect is reversed in the long run. Notably, states with higher per capita emissions experienced a more pronounced reduction in carbon emissions with increased income inequality. Sager (2019), who examined the income inequality-emission nexus for US households using input-output analysis and Environmental Engel Curves (EEC), found that income was a significant driver of carbon emissions during the 1996-2009 period. The researcher predicted that emissions could increase by 2.3% in case of a complete redistribution of income distribution and emphasized this situation as the "equal-pollution dilemma". On the other hand, Uzar and Eyüboğlu (2023), who analyzed the period 1965-2017 for the USA using Fourier ARDL and Fourier ADL methods, showed that income inequality improves environmental quality. Yang et al. (2023), who recently conducted research in the USA and France, revealed interesting results utilizing wavelet decomposition and Quantile-on-Quantile techniques. In France, income inequality negatively affected carbon emissions in periods of low-income inequality, while this effect turned positive in periods when income inequality increased. Similarly, in the USA, the emission-increasing effect of deepening income inequality has gradually reversed.

Liu et al (2020), one of the first to investigate the relationship between income inequality and household carbon emissions in China, found a strong positive relationship between the two variables using nationwide micropanel data. According to the findings, household carbon emissions are higher in counties with greater income inequality. Liao et al. (2023), studying 17 provinces in China, showed that carbon emissions per capita decreased with the improvement of income inequality in the period from 2015 to 2017. The study by Liang et al. (2023), in which they investigated the effects of different income groups and consumption categories on per capita carbon footprint in China, concluded that high-income households should reduce their consumption expenditures in order to reduce carbon emissions.

Idress and Majeed (2022), who conducted research on Pakistan, investigated the complex interaction between income distribution, environmental quality and financial development by examining the period 1972-2018. In the study questioning the validity of the Extended Environmental Kuznet Curve (EKC), it was revealed that income inequality and financial development increase environmental pollution. Based on the findings, The EKC hypothesis was not confirmed for Pakistan.

When recent studies in the literature are examined, it is seen that multi-country analyzes are also increasing. Grunewald et al. (2017)'s analysis covering 158 countries aimed to reveal the relationship between income inequality and carbon dioxide emissions per capita. The study, covering the period 1980-2008, concluded that high-income inequality reduces carbon emissions in low- and middle-income countries, while increased income inequality triggers carbon emissions in upper-middle and high-income economies. Mittmann and De Mattos (2020), who conducted research on Latin America, similarly claimed that income levels would be decisive in the impact of income inequality on per capita carbon emissions. Analyzing data from 2006 to 2017 across 18 developing economies in Asia, Khan and Yahong (2021) established a causal connection between income inequality and environmental vulnerability. Belaïd et al. (2022) investigated the driving forces influencing short- and long-term CO_2 emissions patterns in 11 Mediterranean economies from 1990 to 2012. In the analysis employing a dynamic ARDL model, it was observed that while the connection between income inequality and emissions appeared positive in the short term, this association reversed to a negative trend over the long term. Ehigiamusoe et al. (2022) investigated 70 countries with different income levels. The empirical results revealed that both carbon emissions and ecological footprint increased with higher levels of income inequality and poverty across the entire dataset. Considering income groups separately, income inequality alleviated environmental impact in high-income countries but exacerbated it in middle-income countries. Testing the Environmental Kuznets Curve (EKC) hypothesis for 56 countries, Wang et al. (2023) investigated

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how income inequality affects economic growth and carbon emissions, especially during the COVID-19 period. Empirical results have shown that the inverted U-shaped Environmental Kuznets Curve has transformed into an N-shaped curve. According to the findings, economic growth in periods of low income inequality worsens carbon emissions, while growth accompanying high income inequality suppresses carbon emissions. It has been determined that this effect is especially evident in countries belonging to high income groups. In a recent study, Hou et al. (2024) employed a Multi-Regional Input-Output model to investigate the dynamic interplay between economic growth, income inequality, and carbon footprint across 43 major economies from 1995 to 2019. The research assessed consumption-based carbon footprints and explored the moderating role of income inequality, measured by the Gini coefficient, on the relationship between GDP per capita and CO2 per capita. The findings revealed that a more equitable income distribution, reflected in a lower Gini coefficient, significantly facilitated the decoupling of economic growth from carbon footprint.

3. Empirical Analysis

In this section, we describe the empirical framework and methodological approach employed in our study. The objective of this research is to systematically investigate the relationship between carbon emissions and income inequality across a panel of 66 countries that renowned for their substantial carbon emissions. We selected 66 countries based on their significant contribution to global carbon emissions. These countries collectively account for approximately 80% of the world's total emissions. This selection ensures that our analysis captures the majority of global carbon emissions. It provides a comprehensive understanding of the factors influencing these emissions. The chosen countries vary in economic development, industrial activities, and income levels. This makes them representative of different profiles relevant for studying the impact of income inequality on carbon emissions. We included developed nations with high GDP per capita, significant industrial activities, and well-documented environmental policies. Emerging economies experiencing rapid growth and industrialization are also included. Additionally, developing countries with notable contributions to global emissions due to specific sectors or population size are part of the study. This diversity allows us to examine the interaction between income inequality and carbon emissions across different economic contexts.

The analysis spans from 1990 to 2020. This allows us to examine the temporal dynamics of carbon emissions and income inequality. The dataset covers 66 major carbon-emitting nations during this period. Extending the dataset to 2023 is not feasible due to several constraints. Data for these years are not yet fully available or verified. Ensuring their reliability is crucial. Additionally, our balanced panel data structure requires complete data across all years and countries; incomplete data for 2021-2023 would compromise this.

The COVID-19 pandemic significantly impacted these years, causing disruptions in economic activity and emissions patterns, which could introduce anomalies and biases. The period from 1990 to 2020 provides a comprehensive view of long-term trends, including critical phases of economic growth, technological advancements, and policy changes. We acknowledge the limitation of not including the most recent years and suggest that future research extend the analysis as more data becomes available.

Our analysis incorporates a set of key variables, each meticulously chosen to capture critical dimensions of the carbon emissions and income inequality nexus. These variables include CO2 emissions in kilotons (kt) as a vital indicator of a nation's environmental impact, the Gini index to quantify income inequality within each nation, GDP per capita in constant 2015 US dollars as a proxy for economic growth, energy consumption per GDP (in 1000 Btu/2015$ GDP PPP) to gauge energy efficiency, renewable energy share as the proportion of modern renewables in total final energy consumption, urban population figures to provide demographic insights, FDI net inflows as a percentage of GDP to illuminate economic globalization, and international trade in goods and services in constant local currency units to emphasize economic dynamics. FDI can lead to

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increased industrial activities and economic growth, potentially elevating emissions. However, it can also bring cleaner technologies and practices, reducing emissions. The relevance of FDI is twofold: it promotes technology transfer, improved industrial practices, and economic growth, but it can also lead to increased emissions due to higher production levels.

3.1. Methodology

The study utilizes a methodology based on advanced econometric techniques to examine the relationship between carbon emissions and income inequality. The System Generalized Method of Moments (Sys-GMM) estimation is employed in order to effectively handle endogeneity concerns, incorporate unobservable heterogeneity, and minimize potential biases. This approach ensures the integrity and validity of our empirical results. This enables us to discover enduring patterns and reveal relationships that may not be apparent through traditional cross-sectional or time-series analyses.

Before conducting the Dynamic Panel-Data Two-Step Sys-GMM estimations, a series of preliminary tests were conducted to ensure the robustness and reliability of the empirical model. The analysis commenced with a correlation analysis in order to ascertain the relationships between the key variables. This allowed us to gain an understanding of the basic associations and identify any potential issues related to multicollinearity. Descriptive statistics were calculated to summarize the central tendencies, dispersion, and overall distribution of the data, with the purpose of identifying any anomalies that could potentially impact the analysis.

We also conducted tests for slope homogeneity and cross-sectional independence to assess if the regression slopes were consistent across different cross-sections and to check for cross-sectional dependence in the panel data. Additionally, Pesaran (2003) CADF, Pesaran (2007) CIPS, and Karavias and Tzavalis (2014) unit root tests were performed to verify the stationarity of the variables in order to ensure the suitability of our panel data series.

Identifying the presence of individual and time effects within the models was crucial for selecting an appropriate panel data model. We employed tests to assess the validity of these effects. This informed our choice of model and confirmed the presence of individual effects. These findings guided our decision to use Sys-GMM.

In order to validate the fundamental assumptions of our model, a series of tests were performed to assess heteroskedasticity, autocorrelation, and endogeneity. The test results revealed the existence of heteroskedasticity, autocorrelation, and endogeneity among the variables, which provides a rationale for employing the System Generalized Method of Moments (Sys-GMM) technique.

The preliminary tests were conducted to ensure the robustness and suitability of our dataset and chosen methodology for analyzing the dynamics between carbon emissions and income inequality. By addressing the fundamental econometric concerns, we have established a strong foundation for the subsequent analysis of dynamic panel-data. This approach has significantly improved the reliability and validity of our empirical findings.

3.2. Model Specification

Within the model framework, Table 1 provides a full compilation of the variables used in the model, along with their corresponding abbreviations and representations.

Table 1. Variables

Variable	Notation	Proxy
Carbon Emissions	CO2	CO_2 emissions (kt)

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Income Inequality	GINI	Gini index
Income per Capita	GDP	GDP per capita (constant 2015 US$)
Energy Consumption	ENC	Energy consumption per GDP (1000 Btu/2015$ GDP PPP)
Renewable Energy Share	RES	Share of modern renewables in total final energy consumption (%)
Population	POP	Urban population
Foreign Direct Investment	FDI	Foreign direct investment, net inflows (% of GDP)
International Trade	TRD	Trade of goods and services (constant LCU)

Source: World Bank, International Energy Agency

The data set of "renewable energy share" has been extracted from the database of the International Energy Agency, while data pertaining to other series has been compiled from the database of the World Bank. The dataset spans from 1990 to 2020.

Before delving into the empirical findings, it's essential to understand the structural framework of our analysis. The main goal of our study is to investigate the complex links between carbon emissions (CO2) and a specific group of socio-economic and environmental factors. The basis of this investigation is the understanding that these factors collectively impact carbon emissions. In order to examine this hypothesis, the functional equation is formulated as follows:

$$CO2 = f(GINI, \quad GDP, \quad ENC, \quad RES, \quad POP, \quad FDI, \quad TRD) \qquad (Eq.1)$$

Equation 1 illustrates the complex relationship between carbon emissions (CO2), income inequality (GINI), per capita income (GDP), energy consumption per GDP (ENC), renewable energy share (RES), urban population (POP), foreign direct investment (FDI), and international trade (TRD). Our objective is to explore intricate observations on the relationship between income inequality, economic growth, energy consumption, environmental sustainability, and population dynamics in relation to carbon emissions.

The functional expression of the model in Equation 1 may be converted into the empirical model specification, as seen in Equation 2. We will now start the analysis of this equation, which serves as the fundamental basis for our empirical investigation.

$$LnCO2_{it} = \varphi LnCO2_{it-1} + \beta_1 lnGDP_{it} + \beta_2 (lnGDP)^2_{it} + \gamma Z'_{it} + \theta X'_{it} + \mu_i + \phi_t + e_{it} \qquad (Eq.2)$$

t (year): 1990…2020; i(country): 1…66

Equation 2 represents a dynamic panel data model that investigates the relationship between carbon emissions and several explanatory variables, including income per capita and its squared term, control variables, and time-varying covariates. It accounts for both country-specific fixed effects and time-specific effects to better capture the underlying dynamics of carbon emissions across countries and over time. The system GMM estimation technique is used to address potential endogeneity and measurement error issues commonly encountered in panel data analysis.

The model considers CO2 as the dependent variable, whereas s represents the natural logarithm of CO2 at time 't' for country i. It's a measure of carbon emissions in a given year for a specific country. "$\varphi LnCO2_{it-1}$" is the lagged value of CO2 in the previous time period (it-1). Lagged variables are often used in dynamic panel models to capture the effect of past values on the current outcome. "$\beta_1 lnGDP_t$" represents the linear effect of the natural logarithm of GDP per capita at time 't' on CO2. It measures how changes in income per capita influence carbon emissions. "$\beta_2 (lnGDP)^2$" represents the squared effect of the natural logarithm of GDP per capita at time 't' on CO2. The inclusion of the squared term allows for a nonlinear relationship between income per capita and carbon emissions, potentially capturing the Environmental Kuznets Curve (EKC) effect. "$\gamma Z'_{it}$" Are control variables represented by the vector Z'_{it}. These variables can include factors that are expected to influence CO2 but are not the primary focus of the analysis. The vector "γ" represents the coefficients

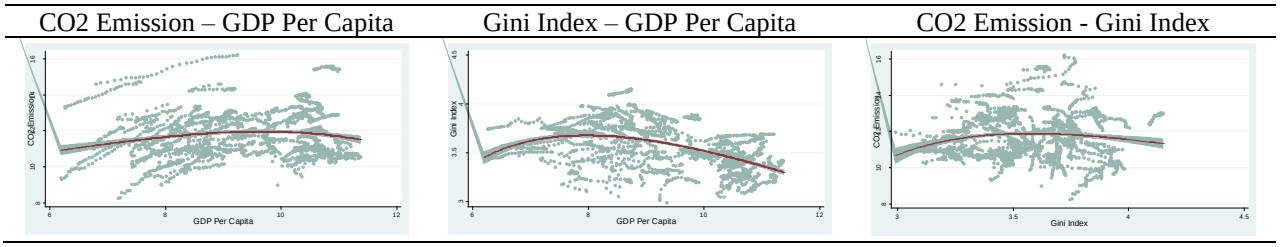
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associated with these control variables. "$\theta X'_{it}$" are time-varying covariates represented by the vector X'_{it}. These variables are assumed to vary across time periods and countries. The vector "θ" represents the coefficients associated with these covariates. "μ_i" are individual (country) fixed effects. They capture unobservable country-specific characteristics that are constant over time but may influence carbon emissions.

"ϕ_t" are time effects or time fixed effects. They capture unobservable time-specific factors that affect carbon emissions but are common to all countries. Time effects account for changes in carbon emissions over time that are consistent across all countries. "e_{it}" is the error term or residual. It represents unexplained variation in carbon emissions that is not accounted for by the model's independent variables, fixed effects, or time effects.

Prior to conducting the empirical analysis, it is essential to visually inspect the relationships between the key variables that are the focal point of our research. Figure 1 depicts the potential correlations between CO2 emissions and GDP per capita, Gini Index and GDP per capita, and CO2 emissions and Gini Index. The initial visualizations offer valuable insights into potential relationships, trends, and variations within our dataset.

Figure 1. Graph of selected major variables



Upon a first analysis of the graph illustrating the correlation between CO2 Emission – GDP Per Capita, it becomes apparent that there exists a positive association between income levels and CO2 emissions up to a certain threshold. Nevertheless, once income above this threshold, there is a subsequent decline in CO2 emissions. The observed association between CO2 Emission – GDP Per Capita, which exhibits an inverted U-shaped pattern, aligns with the theoretical framework of the Environmental Kuznets Curve. Upon analysis of the graph depicting the relationship between the Gini Index and GDP Per Capita, it becomes evident that a comparable pattern is discernible. Within a specific threshold, the augmentation of income has a tendency to exacerbate income inequality. However, once income surpasses this threshold, further increases in income have a favourable effect on the fairness of income distribution. The CO2 Emission - Gini Index graph likewise exhibits the same tendency. Although visual interpretations may not provide conclusive solutions, they serve to illuminate our uncertainties and guide our focus towards key components in the following analysis.

Table 2. Correlation Matrix

Variable	CEM	GINI	GDP	GDP2	ENC	POP	RES	FDI	TRD
CO2	1								
GINI	0.035	1							
GDP	0.085	-0.434	1						
GDP2	0.078	-0.449	0.998	1					
ENC	0.295	-0.276	0.186	0.173	1				
POP	0.813	0.298	-0.310	-0.310	-0.118	1			
RES	-0.097	-0.004	0.164	0.162	-0.295	0.011	1		
FDI	-0.102	-0.068	0.157	0.152	0.014	-0.150	0.125	1	

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TRD	0.376	0.159	-0.220	-0.217	-0.085	0.478	-0.061	-0.063	1

Table 2 presents a correlation matrix displaying the pairwise relationships between variables in the empirical model. The numbers in the table represent correlation coefficients. GINI shows a very weak positive correlation (approx. 0.035) with carbon emissions, implying a subtle positive link between income inequality and emissions. GDP exhibits a positive correlation (approx. 0.085) with carbon emissions, signifying a positive but relatively weak connection. ENC demonstrates a moderate positive correlation (approx. 0.295) with carbon emissions, indicating a moderate association between energy consumption and emissions. RES displays a weak negative correlation (approx. -0.097) with carbon emissions, suggesting that higher shares of renewable energy are linked to slightly lower emissions. POP reveals a robust positive correlation (approx. 0.813) with carbon emissions, indicating a strong connection between population and emissions. As population increases, emissions tend to rise significantly. FDI shows a weak negative correlation (approx. -0.102) with carbon emissions, indicating a mild negative link between foreign direct investment and emissions. TRD exhibits a moderate positive correlation (approx. 0.376) with carbon emissions, implying a moderate positive relationship between international trade and emissions. As international trade increases, emissions tend to increase as well.

The presence of correlation between variables does not necessarily indicate a causal relationship, and the magnitude of these associations can differ across various contexts. These correlations offer preliminary insights into the relationship between carbon emissions and the mentioned variables. However, additional analysis is conducted to comprehend the influence of these factors on emissions.

Table 3. Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
CO2	2046	391671.14	1070218.4	3839.2	10944686
GINI	2046	36.048	8.092	19.9	63.4
GDP	2046	19725.377	19546.425	493.095	87123.66
ENC	2046	5.608	3.423	.937	27.837
POP	2046	43166749	88220068	409813	8.668e+08
RES	2046	11.346	11.94	-79.327	62.37
FDI	2046	3.405	6.689	-40.086	106.594
TRD	2046	2.049e+14	9.681e+14	2.207e+09	9.296e+15

Table 3 shows the descriptive statistics. The dataset consists of 2046 observations for various economic and environmental variables. Notably, the mean CO2 amount to approximately 391,671 kilotons, with a considerable standard deviation of 1,070,218.4, indicating substantial variation across countries or regions. Income inequality, measured by the Gini index, exhibits an average value of 36.048, reflecting moderate disparities in income distribution. Income per capita (GDP) shows a mean of 19,725 constant 2015 US dollars, although with notable dispersion (standard deviation of 19,546). Energy consumption per GDP (ENC) has a moderate mean of 5.608, while the urban population (POP) ranges widely from 409,813 to 866,800,000. The share of renewable energy (RES) reveals an average of 11.346%, and foreign direct investment (FDI) averages 3.405% of GDP. International trade (TRD) is substantial, with a mean of 2.049e+14 constant local currency units, yet showing substantial variation (standard deviation of 9.681).

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3.3. Findings

Testing slope homogeneity is crucial to choose the proper unit root test and panel data estimator. Assuming that the coefficients are homogeneous while heterogeneous causes biased results. Table 4 presents the results of tests related to slope homogeneity and cross-section independence. These tests are essential in panel data analysis to assess whether the relationships between variables are consistent across different entities (cross-sectional units) and whether there is any dependence between these entities.

Table 4. Slope Homogeneity and Cross-section Independence Tests

CD Tests				Homogeneity	
CD	CDw	CDw+	CD*	Delta	Swamy S (χ^2)
11.22*	-0.14	1861.37*	9.27*	9.725*	4.0e+05*

Note: * p<.01, ** p<.05

CD Tests

CD: This test statistic, with a value of 11.22, is used to assess cross-sectional dependence in the panel data. It is taken from Pesaran's work in 2015 and 2021. The p-value associated with this test is less than 0.01, indicating strong evidence against the null hypothesis of weak cross-sectional dependence. This suggests that there is a significant degree of cross-sectional dependence among the entities in the panel.

CDw (CD with Weights): This test statistic, at -0.14, is derived from Juodis and Reese's research in 2021. It doesn't indicate a significant departure from the null hypothesis of weak cross-sectional dependence.

CDw+ (CD with Weights and Power Enhancement): This statistic, at 1861.37, is an extended version of CDw with power enhancement, based on Fan et al.'s work in 2015. The extremely high value suggests strong evidence against the null hypothesis of weak cross-sectional dependence, indicating that the panel data exhibits substantial cross-sectional dependence.

CD (CD with Principal Components):* Derived from Pesaran and Xie's research in 2021 with the use of four principal components (PCs), this test statistic is 9.27. The p-value associated with this test is less than 0.01, providing evidence against the null hypothesis of weak cross-sectional dependence.

Homogeneity Tests

Delta Test: This test statistic, at 9.725, is used for testing slope heterogeneity, specifically whether the slope coefficients are homogenous. The null hypothesis is that the slope coefficients are homogenous across cross-sectional units. The extremely low p-value ($p<0.01$) suggests strong evidence against this null hypothesis, indicating that there is significant variation in the slope coefficients.

Swamy S (χ^2) Test: The Swamy S test statistic, with a value of 4.0, is another test for slope homogeneity. Like the Delta test, it assesses whether the slope coefficients are homogenous. The extremely low p-value ($p<0.01$) indicates strong evidence against the null hypothesis of homogenous slope coefficients.

These tests collectively indicate significant cross-sectional dependence and heterogeneity in the slope coefficients across the entities in the panel data. This underscores the importance of accounting for these factors in our modeling and interpretation, ensuring accurate and reliable analysis.

It is essential to consider the stationarity properties of our variables because of the presence of cross-sectional dependence and heterogeneity in panel data. In order to thoroughly evaluate stationarity, we utilize unit root tests that are specifically designed to address these concerns. The following section presents the outcomes of three distinct unit root tests, each specifically designed to address the difficulties associated with cross-sectional dependence and heterogeneity.

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Pesaran (2003) CADF test addresses unit roots in heterogeneous panels with cross-section dependence. It uses the mean of individual Dickey-Fuller (DF) or Augmented Dickey-Fuller (ADF) t-statistics for each unit within the panel. The null hypothesis assumes that all series are non-stationary. To mitigate cross-dependence, the standard DF (or ADF) regressions are augmented with the cross-section averages of lagged levels and first differences of individual series, resulting in the CADF statistics. Pesaran (2007) CIPS test estimates unit roots in heterogeneous panels while accounting for cross-section dependence. It provides three different deterministic specifications and considers individual dynamics. The CIPS test is particularly well-suited for panels with both cross-sectional heterogeneity and dependence. Karavias and Tzavalis (2014) test focuses on slope heterogeneity in panel data with structural breaks.

The results of these three unit-root tests, considering cross-sectional dependence and heterogeneity, are presented in Table 5.

Table 5. Unit root test

Pesaran (2003)		CO2	GINI	GDP	ENC	POP	RES	FDI	TRD
CADF stat.	Level	-2.22*	-1.68	-1.80	-0.63	-1.23	-1.27	-2.58*	-2.15*
CADF stat.	1st df.	-	-2.64*	-2.46*	-2.56*	-3.42*	-2.81*	-	-
Pesaran (2007)									
CIPS stat.	Level	-2.37*	-1.05	-1.66	-0.72	-1.60	-1.47	-3.39*	-1.62
CIPS stat.	1st df.	-	-3.32*	-3.09*	-4.05*	-4.41*	-4.02*	-	-3.82*
Karavias and Tzavalis (2014)									
minZ-stat.	Level	6.34	0.11	0.96	-7.74*	2.42	1.2493	-31.08*	-19.61*
minZ-stat.	1st df.	-27.77*	-5.92*	-45.18*	-	-33.33*	-74.44*	-	-

Note: * p<.01, ** p<.05

The CADF Test in Table 5 shows that the CO2 and TRD series are stationary at levels, while the GINI, GDP, ENC, POP, and RES series are stationary after first differencing. The CIPS test results suggest that the CO2 and FDI series exhibit stationarity at levels, whereas the GINI, GDP, ENC, POP, RES, and TRD series demonstrate stationarity after first differencing. The Karavias and Tzavalis Test, which considers the presence of structural breaks, suggests that the ENC, FDI, and TRD series exhibit stationarity at levels. On the other hand, the CO2, GINI, GDP, POP, and RES series demonstrate stationarity only after applying the first differences. In conclusion, it can be inferred that all three forecasting methods exhibit cointegration levels of either I(0) or I(1) for the series.

Empirical Model Selection

Identifying the presence of individual and time effects within the models is a crucial step in selecting an appropriate panel data model. The Likelihood Ratio (LR), F, and Breusch-Pagan Lagrange Multiplier (LM) tests are employed to assess the validity of these effects. The findings are reported in Table 6.

Table 6. Test for Individual and Time Effects

	Individual Effect	Time Effect
LR	4483 (p = 0.000)	2.20 (p = 1.000)
F	421 (p = 0.000)	0.72 (p = 0.869)
LM	20398 (p = 0.000)	

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Hausman Test $\chi 2$ (6) = 18.77 (p = 0.0162)

Since the LR statistic is 4483 with a p-value of 0.000, we can reject the null hypothesis of no individual effect. This result confirms that the model contains individual-specific effects. Similar to the LR test, the F statistic of 421 with a p-value of 0.000 allows us to reject the null hypothesis that there is no individual effect. The F test provides additional evidence for the existence of individual-specific effects.

As the LR statistic is 2.20 with a p-value of 1.000, the null hypothesis of no time effect cannot be rejected. Similarly, since the F statistic is 0.72 with a p-value of 0.869 we cannot reject the null hypothesis. Therefore, no evidence exists to corroborate the existence of time effects. These results corroborate individual-specific effects rather than time effects in the panel model. The Hausman Test is employed to determine the consistent model between fixed effects (FE) and random effects (RE) models. Since the Hausman chi2 is 18.77 and the p-value is 0.0162, which is less than the significance level of 0.05, we can reject the null hypothesis and conclude that the FE model is superior to the RE model.

Table 7 displays the results of diagnostic tests conducted to evaluate the robustness and reliability of the econometric model. The purpose of these evaluations is to ensure that the model's fundamental assumptions are met and that the empirical analysis remains valid. Each test evaluates a unique aspect of the performance of the model, such as heteroskedasticity, autocorrelation, and endogeneity. The outcomes of these tests provide significant insights into the model's suitability and contribute to the comprehension of the empirical findings.

Table 7. Test Results of the Model's Basic Assumptions

Heteroskedasticity test H_0: no heteroskedasticity	W0 = 18.38 df(63, 1710) (p = 0.000)
	W50 = 10.15 df(63, 1710) (p = 0.000)
	W10 = 16.19 df(63, 1710) (p = 0.000)
IV Heteroskedasticity H_0: Disturbance is homoskedastic	Pagan-Hall Stat.: 259.007 ; $\chi 2$ (16) (p = 0.000)
Autocorrelation Test H_0: No Autocorrelation	DW = 0.22 < 2
	LBI = 0.43< 2
Endogeneity H_0: variables are exogenous	Durbin (score) $\chi 2$ (1) = 6.590 (p = 0.0103) Wu-Hausman = 6.577 (p = 0.0104)

The Levene, Brown, and Forsythe's Test was employed to assess the presence of heteroscedasticity in the fixed effects (FE) model. The test statistics, represented as W0, W50, and W10, were compared to the Snedecor F table using degrees of freedom (df) of (63, 1710). The comparative results led to the rejection of the null hypothesis which suggests that the variances are equal. Therefore, the results provide strong evidence supporting the presence of heteroscedasticity in the model.

The output represents the results of an instrumental variable (IV) heteroskedasticity test, which assesses whether the variance of the errors or disturbances in a regression model is constant across all levels of the independent variables. The null hypothesis assumes that the disturbances have constant variance. In this case, the Pagan-Hall test statistic, distributed as a chi-squared random variable with 16 degrees of freedom, yielded a p-value of effectively zero (0.0000). This extremely low p-value suggests strong evidence against the null hypothesis, indicating a significant departure from homoskedasticity. Thus, it implies that the model's errors do not have constant variance, highlighting the need to consider adjustments or alternative modeling approaches to account for this heteroskedasticity in the data.

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The modified Bhargava et al. Durbin-Watson statistic is approximately 0.22, while the Baltagi-Wu LBI statistic is approximately 0.43. These statistics are commonly used to test for the presence of autocorrelation in a regression model's residuals. In general, a Durbin-Watson statistic significantly less than 2 and a low p-value associated with the Baltagi-Wu LBI statistic may indicate the presence of autocorrelation in the model's residuals.

The presented statistics represent tests of endogeneity, where the null hypothesis assumes that the variables in the model are exogenous, meaning they are not correlated with the error term. The results of these tests indicate otherwise. Firstly, the Durbin (score) test yielded a $\chi 2$ statistic of 6.590 with 1 degree of freedom, resulting in a p-value of 0.0103. This low p-value provides evidence to reject the null hypothesis, suggesting that at least one of the variables in the model is likely endogenous, demonstrating a correlation with the error term. Additionally, the Wu-Hausman F-test produced an F-statistic of 6.577, along with a p-value of 0.0104. The F-test yields additional support for the rejection of the null hypothesis, indicating the presence of endogeneity within the model. Both statistical tests indicate that the model contains at least one endogenous variable, highlighting the necessity of considering this association during analysis.

Table 8 presents the key outcomes derived from our empirical analysis using the Two Step System GMM framework for dynamic panel-data estimation. The use of this advanced econometric technique allows us to examine the relationships between our main variables, while also accounting for the potential existence of endogeneity and delayed effects. Table 8 presents the estimated coefficients, t-statistics, and p-values for all variables used in the model. The aforementioned estimates provide insight into the characteristics and importance of the relationships among carbon emissions, income inequality, and the variables under consideration.

Table 8. Dynamic panel-data- Two Step Sys-GMM Estimations

LnCO2	M1 CO2	M2 LnCO2	M3 LnCO2	M4 LnCO2	M5 LnCO2
L.LnCO2	0.991*	0.969*	0.966*	1.089*	0.675*
	(632.7)	(402.8)	(425.5)	(124.6)	(49.75)
LnYGINI	0.0766*	0.102*	0.0946*	0.201*	0.057**
	(47.30)	(14.07)	(10.65)	(16.43)	(2.352)
LnYGDP5	-0.0889*	-0.0913*	-0.0733*	-0.280*	0.273*
	(-21.27)	(-8.860)	(-4.874)	(-11.69)	(5.936)
LnYGDP5S	0.00469*	0.00496*	0.00419*	0.013*	-0.010*
	(21.22)	(8.055)	(4.889)	(10.84)	(-3.709)
LnENJ2		0.0262*	0.0169*	-0.061*	0.242***
		(16.86)	(3.931)	(-11.12)	(27.10)
LnYRNE1			-0.0121*	-0.00254	-0.019*
			(-3.822)	(-0.682)	(-2.777)
LnPOPU				-0.151*	0.196*
				(-16.57)	(11.85)
LnFDI2					0.016*
					(13.63)
LnTRD					0.041*
					(8.876)
Constant	0.254*	0.393*	0.389*	2.332*	-2.832*
	(13.35)	(13.74)	(9.365)	(15.93)	(-11.40)
F	9.860*	1.030*	2.490*	1.310*	3.015*
AR(1)	-3.33*	-3.34*	-5.03*	-5.07*	-4.70*
AR(2)	-0.53	-0.52	0.20	0.18	0.66
Sargan ($\chi 2$)	404.2*	394.5*	576.5*	442.9*	244.5*

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Hansen ($\chi 2$)	64.21	64.60	60.57	61.98	60.47
Prob > $\chi 2$	0.365	0.319	0.419	0.336	0.318

t-statistics in parentheses * p<0.01, ** p<0.05,

The gradual building and testing models, as demonstrated in Table 8, is a robust and systematic way to explore the relationships between variables and assess the impact of each variable's inclusion. In this case, we started with Model 1 (M1) and successively added variables to create Models 2 through 5 (M2 to M5). This stepwise approach allows us to understand how each variable contributes to the explanation of carbon emissions (LnEM4) while controlling for various factors. Model 5 (M5) represents the final model and includes all the variables of interest. In all models, it is observed that there is a statistically significant and positive relationship between income inequality (GINI) and CO2 emissions. "When the model is extended with FDI2 and TRD to measure the impact of globalization on emissions, it is observed that the lagged CO2 coefficient decreases slightly, and the relationship between income and emissions exhibits an inverted U-shape trend, parallel to the EKC hypothesis. Model 6 represents the culmination of our investigation, encompassing all the variables mentioned in the previous models. This ultimate model offers a holistic perspective on the multi-faceted dynamics governing carbon emissions among the world's largest contributors. Upon examining the estimate results of Model 5, the following conclusions are obtained:

LnEM4 (Carbon Emissions): The coefficient for LnEM4 with lag 1 (L1.) is approximately 0.675. This coefficient represents the effect of past carbon emissions on current emissions. Specifically, it suggests that a one-unit increase in the lagged value of carbon emissions is associated with an increase of approximately 0.68% in current emissions, all else being equal. This implies a strong positive autocorrelation effect, indicating that past emissions have a substantial positive influence on present emissions.

LnYGINI (Income Inequality): The coefficient for LnYGINI is approximately 0.057. This coefficient represents the effect of income inequality on carbon emissions. A one-unit increase in income inequality (measured by the natural logarithm of the Gini index) is associated with an increase of approximately 0.057% units in carbon emissions, holding other factors constant. This suggests that higher income inequality is associated with a slight increase in emissions.

The coefficient for income per capita (LnYGDP) is estimated to be approximately 0.273. The coefficient in question quantifies the impact of per capita income on carbon emissions. An incremental rise of one unit in income per capita corresponds to a roughly 0.273% increase in carbon emissions, under the assumption that all other variables remain unchanged. This indicates that carbon emissions tend to increase substantially as per capita income rises.

The coefficient for LnYGDP5S (Income per Capita Square) is approximately -0.010. This coefficient indicates a quadratic relationship between per capita income and carbon emissions. It indicates that as per capita income increases, the relationship between income and carbon emissions initially increases, but then begins to diminish as income levels rise. This suggests a U-shaped relationship inverted between per capita income and emissions.

The coefficient for LnENJ (Energy Consumption) is approximately 0.242. This coefficient illustrates the relationship between energy consumption and carbon emissions. If all other variables remain constant, a one-unit increase in energy consumption is associated with an increase of approximately 0.242% in carbon emissions. This indicates that there is a strong positive relationship between energy consumption and emissions.

The coefficient for LnPOPU (Urban Population) is approximately 0.196. This coefficient represents the effect of the urban population on carbon emissions. Keeping all other factors constant, a one-unit increase in

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urban population is associated with an increase of approximately 0.196% in carbon emissions. This suggests that higher urbanization is associated with higher emissions.

The coefficient for LnYRNE (Renewable Energy Share) is approximately -0.019. This coefficient represents the effect of the proportion of renewable energy on carbon emissions. Assuming all other variables remain constant, a one-unit increase in the proportion of renewable energy is associated with a decrease of approximately 0.019% in carbon emissions. This suggests that a greater proportion of renewable energy is associated with reduced carbon emissions.

The coefficient for LnFDI (Net FDI) is approximately 0.016. This coefficient represents the impact of foreign direct investment (FDI) on carbon emissions. Assuming that all other variables remain constant, a one-unit increase in net FDI is associated with an increase of approximately 0.016% in carbon emissions. This suggests that an increase in net FDI is associated with a marginal increase in emissions.

The coefficient for LnTRD (International Trade) is approximately 0.041. This coefficient represents the effect of international trade on carbon emissions. Keeping all other factors constant, a one-unit increase in international trade is associated with an increase of approximately 0.041% in carbon emissions. This implies a positive relationship between international trade and emissions.

Arellano-Bond Tests for Autoregressive Processes: These tests evaluate the presence of serial correlation in the first differences of the dependent variable. The results indicate that there is evidence of serial correlation at the first lag (AR(1)), but no evidence of serial correlation at the second lag (AR(2)). In order for GMM (Generalized Method of Moments) estimators to be efficient, second-order correlation should not be present. Since the null hypothesis of no autocorrelation at the second-order level is not rejected, our method is deemed appropriate.

Sargan Test of Overidentifying Restrictions: The Sargan test assesses the validity of overidentifying restrictions in the model. In this case, the test statistic is highly significant ($\chi 2$ (56) = 244.50), suggesting that the model's instruments are not likely to be correlated with the error terms. This is a good sign, indicating that the instruments used. In other words, it can be seen that the over-identification restrictions are not valid, indicating that the variables are endogenous.

The Hansen test is another test for the validity of instruments in an IV estimation. It assesses whether the instruments are valid under the assumption of heteroscedasticity (unequal variances) in the error term. The null hypothesis for the Hansen test is that the instruments are valid, even under the assumption of heteroscedasticity. The alternative hypothesis posits that, under this assumption, the instruments lack validity. The test statistic ($\chi 2$) in this particular case is calculated to be 60.47, which is associated with a p-value of 0.318. Given that the p-value surpasses the predetermined significance level of 0.05, there is inadequate evidence to dismiss the null hypothesis. Based on the available evidence, it can be concluded that the instruments remain valid, even in the presence of heteroscedasticity in the error term.

4. Conclusions

This study utilized the Two-step Sys-GMM Dynamic Panel Data Estimation technique to examine the relationship between carbon emissions and various economic and environmental factors. These factors include income inequality, income per capita, squared income per capita, energy consumption, urban population, renewable energy share, net FDI, and international trade. The analysis relies on a comprehensive dataset that encompasses 66 countries and covers the years from 1990 to 2020. This extensive dataset enables us to examine the temporal dynamics of carbon emissions.

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The results of our study provide valuable insights into the factors that influence carbon emissions. Firstly, it has been observed that income inequality has a statistically significant positive impact on carbon emissions. This suggests that higher levels of income inequality are linked to increased carbon emissions. The statistically significant positive impact of income inequality on carbon emissions underscores the potential efficacy of income redistribution policies in aligning environmental objectives with broader social and economic goals.

Furthermore, it is observed that the income per capita variable demonstrates a positive and statistically significant influence on carbon emissions. This implies that as economies grow and individuals experience an increase in wealth, there is a tendency for carbon emissions to rise. This observation aligns with the "Economic Growth Hypothesis," which posits that economic progress frequently entails greater energy consumption and resource utilization, resulting in elevated emissions. The variable representing squared income per capita exhibits a negative relationship with carbon emissions. This suggests that as income per capita increases and reaches higher levels, the rate of carbon emissions may decelerate or potentially decrease. This finding aligns "Environmental Kuznets Curve" hypothesis, suggesting that as a nation's income increases, there is an initial decline in environmental conditions, followed by subsequent enhancement due to increased awareness and regulatory measures.

Furthermore, our study reveals a strong correlation between energy consumption and urban population, underscoring the need of including energy efficiency and urban planning considerations into environmental policy frameworks. In contrast, the proportion of renewable energy had an adverse effect on carbon emissions, underscoring the need to shift towards more environmentally friendly energy sources and the necessity of increased funding for renewable energy initiatives in order to alleviate emissions.

Moreover, our investigation has shown that net foreign direct investment and international trade exhibit a positive relationship with carbon emissions, indicating that economic globalization might potentially lead to elevated emission levels. These results highlight the need of giving more consideration to the environmental impacts of globalization and emphasize the necessity of adopting a well-rounded strategy that maximizes the advantages of globalization while minimizing its negative effects on the environment.

In order to mitigate income inequality and encourage the adoption of renewable energy sources, a set of precise policy recommendations has been identified. The implementation of progressive taxation and social welfare programs has the potential to decrease income inequality, which in turn can lead to a reduction in carbon emissions by encouraging fairer consumption patterns. The acceleration of the transition to cleaner energy sources can be achieved by promoting the establishment of renewable energy communities and offering subsidies or tax incentives for the adoption of renewable energy. This approach has the potential to significantly reduce carbon emissions.

Developing and promoting energy efficiency standards and technologies in both industrial and residential sectors is crucial for reducing energy consumption and emissions, contributing to environmental sustainability. Investing in sustainable urban infrastructure can mitigate the environmental impact of urban populations, which are major contributors to carbon emissions. Sustainable urban planning, including the development of green spaces, public transportation, and energy-efficient buildings, is essential for reducing urban emissions.

Regulating Foreign Direct Investment (FDI) to ensure it contributes to sustainable industrial practices can balance the benefits of economic globalization with the need for environmental preservation. These regulations can help prevent environmental degradation often associated with increased industrial activities and ensure that FDI supports sustainable development.

The crux of our research resides in the convergence of economic inequality and environmental effects. The implementation of efficient policy measures aimed at addressing economic inequalities might have dual benefits, namely the promotion of social fairness and the reduction of carbon emissions. Nevertheless, it is

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crucial to achieve a harmonious equilibrium between economic advancement and the preservation of the environment, recognizing the intricate and diverse nature of the connection between per capita income and emissions.

Our study makes a valuable contribution to the current academic discussion around the intricate interplay between economic variables and carbon emissions. This statement highlights the significance of implementing specific policy measures to tackle the issue of income inequality, encourage the use of renewable energy sources, improve energy efficiency, and effectively manage the environmental consequences associated with globalization. Subsequent investigations should persist in delving into these processes with heightened precision and include an examination of regional disparities and the consequential policy ramifications.

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