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Economic Growth, Globalization, Renewable Energy, and Trade Openness as Drivers of Carbon Emissions in the United States: Evidence Under Non-Normal Errors

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Abstract

In this study, carbon emissions determinants are examined in the United States using annual data from 1990 to 2020. Explanatory variables in the empirical model are economic growth, globalization, renewable energy consumption and trade openness. Unit root tests without and with structural breaks show that all variables are incorporated of order one, $I(1)$. It is confirmed that the long-run relationship exists with the Bayer and Hanck combined cointegration approach and the Residual Augmented Least Square Engle-Granger (RALS-EG) cointegration test, respectively. Results indicate that CO_2 emissions increase with economic growth and globalization whereas renewable energy consumption reduces emissions. Trade openness has an effect across model specifications. Trade openness reduces emissions of carbon in the constant model but raises emissions in the constant-with-trend specification, so it may have an environmental impact depending on underlying economic conditions as well as structural changes over time. Overall, the findings imply that renewable energy can help restrict long-term carbon emissions. They also point out that economic growth, globalization and trade openness may have environmental consequences when designing policies for sustainable development and emission reduction.

Keywords: carbon emissions; globalization; renewable energy; trade openness; residual augmented least squares



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1. Introduction

Carbon emissions in major economies have been increased by economic growth, globalization and rising energy demand. In the context of globalization, the current global economic order often puts production efficiency before environmental sustainability [1,2]. The buildup of CO_2 and other global warming gases in the atmosphere increases global temperatures, causes rising sea levels and also raises the occurrence and severity of extreme climatic events. All of these environmental pressures threaten ecosystems and human well-being. Rising temps cause glacier melting and sea level rise, and millions of people living along coasts risk being displaced. In parallel, more frequent storms/droughts/wildfires

impact agriculture production, food security and water resources and affect economic and public health systems. Climate change also disturbs ecosystem balance, decreases biodiversity and increases the risk of species extinction [3]. This has made carbon emissions reduction a key policy goal for sustainable development and environment protection [4].

A growing body of literature investigates economic drivers of carbon emissions. According to the Environmental Kuznet Curve (EKC) hypothesis, economic growth gives rise to environmental deterioration in an inverted U-shape. According to this hypothesis environmental pressures increase early in the economic development process but decrease once an income level is reached. In the context of international trading, the pollution haven hypothesis holds that international trade and foreign direct investment (FDI) might accelerate environmental degradation by moving highly polluting activities to countries with weak environmental protection laws [5–7]. A further strand of research is on the role of renewable energy use in reducing environmental pressure. Carbon emissions from renewable energy use are lower in OECD countries [8]. At exactly the same time, globalization could result in environmental degradation through increased production, consumption and electricity demand accompanied by economic development [9]. Carbon emissions coming from the U.S. remain among the biggest contributors to carbon emissions worldwide. Fossil fuel use has risen along with economic growth and industrialization since the Industrial Revolution [10]. All these developments have facilitated economic growth but also created significant environmental costs. CO₂ emissions from fossil fire combustion are one of the primary reasons for climate change [11,12]. Energy efficiency and alternative energy promotion are more and more stressed in U.S. energy policy but carbon emission reduction remains a challenge. The shift toward renewable energy source systems and improvements in energy efficiency often face economic, technological, and political barriers.

As one of the signatory states of the Paris Agreement, the United States (U.S.) needs to balance its economic growth, trade integration and energy transitions while decreasing its reliance on fossil fuels and increasing the investments in clean energy for it to cut carbon emissions by 2030 and get on track to achieving net-zero emissions by 2050. Therefore, the identification of the key macroeconomic drivers of carbon emissions and their long-run dynamics is important. There is quite a substantial literature on emission determinants, but numerous empirical studies still use conventional econometric procedures under the assumption that the error term is normally distributed. Under this distributional assumption, common unit root and cointegration tests may suffer from biased or inefficient estimates.

Against this particular background, this particular analysis examines the nexus between carbon emissions and macroeconomic drivers, namely trade openness, economic growth, renewable energy consumption and globalization in the U.S. borders. The study contributes to the literature in three ways.

First, it provides country-specific evidence for the U.S. by combining economic activity, international integration, renewable energy use and trade openness in one empirical framework. Although all of these have been extensively studied in the environmental economics literature, their cumulative long-term effects are applicable to the U.S. Second, the study is methodologically enriching in combining conventional time-series techniques with RALS-based procedures. The aim is not to argue that RALS methods alone are an econometric advance, but rather to assess whether the evidence on the cointegration and the stationarity is robust when possible non-normality in error terms and structural breaks are considered. This is particularly relevant for annual U.S. data covering a relatively limited sample period. Third, the study provides policy-relevant evidence by linking the estimated long-run relationships and structural break dates to U.S. specific developments in energy policy, renewable energy expansion, trade integration, and climate governance.

In this respect, the findings offer a more context-sensitive interpretation of the relationships among economic growth, globalization, renewable energy consumption, trade openness, and carbon emissions in the U.S.

The rest of the study is structured as follows. Section 2 reviews the appropriate literature. Section 3 presents the model specification, dataset, and econometric methodology. Section 4 reports the empirical findings. Lastly, Section 5 covers the end result and also provides the conclusion and policy implications.

2. Literature Review

This section presents past papers that discuss carbon emission and economic development, openness to trade, renewable energy utilization, and global integration. The U.S.-focused studies and research in other countries are considered. The findings from the literature demonstrate that carbon emissions in the U.S. are driven by combinations of economic growth, international trade integration, globalization and the nature of the energy system. Collectively examining economic drivers provides a more refined understanding of economic factors.

Economic growth is usually correlated with elevated energy use, that might increase carbon emissions where extra energy demand is basically met through fossil fuel use [13]. Therefore, the effect of economic growth on CO₂ emissions is contingent on the nature of growth, technological developments, and policy interventions. In the literature, the relationship between economic growth and carbon emissions has often been examined within the framework of the EKC hypothesis. According to the EKC hypothesis, environmental degradation increases in the early phases of the economic development process [14]. However, after a certain income level is reached, environmental quality improves and carbon emissions begin to decline. This relationship is generally represented by an inverted U-shaped curve. The EKC hypothesis suggests that environmental deterioration may be unavoidable during industrialization and economic growth, but improvements in technology and income levels can support the implementation of environmental protection measures [15].

Empirical studies report divergent findings concerning the EKC hypothesis. Dogan and Turkekul [16] studied the validity of the EKC hypothesis in the U.S. and found a U-shaped relationship between CO₂ and GDP. Similarly, Congregado et al. [17] assessed the EKC hypothesis in the U.S. and reported evidence supporting its validity in all sectors except the industrial sector. Pablo-Romero and Sanchez-Braza [18] focused on the housing sector in EU-28 countries and found evidence in support of the EKC hypothesis. Gill et al. [19] also confirmed the validity of the EKC hypothesis for ASEAN countries. Badeeb et al. [20] examined the role of natural resource dependence and found that it strengthens the growth-emissions nexus while weakening the quadratic structure of the EKC relationship. Their findings suggest that resource-rich economies may deviate from the conventional EKC pattern. In general, the empirical results from the EKC literature suggest that the interaction of economic growth with environmental quality is sensitive to country characteristics, energy structures, and agronomic specifications. Differences in model design, sample periods and estimation methods often lead to heterogeneous results.

Carbon emissions from global trade can rise with increased production and transport of carbon-intensive goods [21]. However, trade may also facilitate technology transfer and dissemination of best practices, which might reduce carbon intensity. The impact on carbon emissions is also determined by trade policy and structural characteristics of trade [22]. Cole [5] linked EKC to the pollution haven hypothesis. Using a North–South trade flow model, the study found evidence supporting the presence of a pollution haven. Fotros and Maaboudi [23] examined the effects of trade openness and economic growth on CO₂ in

Iran. Their findings showed that economic growth decreased carbon emissions, whereas trade openness increased them. Similarly, Gyamfi et al. [24] tested the pollution hypothesis in E7 countries and found that FDI negatively affects environmental quality, supporting the validity of the hypothesis. Raihan [25] investigated the pollution haven hypothesis in Bangladesh and concluded FDI increases environmental degradation, providing further support for the hypothesis. Likewise, Apergis et al. [26] examined BRICS countries and found that FDI flows from Denmark and UK increased CO₂ emissions, supporting the pollution haven hypothesis. Jeetoo and Chinyanga [27] analyzed the impact of the trade openness on environmental quality across Sub-Saharan African countries and reported that trade liberalization increases CO₂ emissions, thereby worsening environmental quality.

The role of renewable energy consumption in reducing carbon emissions is critical for environmental sustainability. Because renewable energy sources generate substantially lower emissions than fossil fuels, increasing their use can significantly reduce carbon emissions. Investments in renewable energy can lower the carbon intensity of the energy sector by replacing fossil fuels. In addition, the development and diffusion of renewable energy technologies can improve energy efficiency and further support emission reductions [28]. Shafiei and Salim [8] examined the relationship between renewable energy consumption and carbon emissions in OECD countries and found that renewable energy reduces emissions, whereas non-renewable energy increases them. Similarly, Paramati et al. [29] reported that CO₂ emissions affect renewable energy demand in 20 emerging market economies. Zoundi [30] found that renewable energy effectively substitutes for fossil fuels in 25 African countries, resulting in lower carbon emissions and stronger long-run environmental benefits. Dong et al. [31] and Yu et al. [32] showed that renewable energy consumption is related with carbon emissions in China. Similar arguments were claimed by Akram et al. [33] for emerging economies and by Liu et al. [34] for China. Anser et al. [35] found that economic growth, population, and non-renewable energy consumption increase CO₂ emissions in BRICS countries. In the case of Türkiye, Ozbay and Pehlivan [36] identified a long-run relationship among renewable energy, carbon emissions, and GDP per capita.

Globalization refers to the increasing economic, social, and political integration as well as the growing integration of countries into the global economy [37]. By stimulating economic growth, globalization can increase energy consumption and, consequently, carbon emissions [38]. On the other hand, it can encourage the adoption of cleaner and more efficient production technologies through the transfer of knowledge, technology, and innovation [39], which may help reduce emissions. However, globalization also may constitute serious perils to environmental sustainability [40].

Shahbaz et al. [41] reported that globalization decreased emissions in Angola, Cameroon, the Republic of Congo, Egypt, Libya, Tunisia, Zambia, and Kenya. However, it increased pollution in Ghana, Morocco, South Africa, Sudan, and Tanzania. Acheampong and Boateng [42] examined Australia, Brazil, China, India, and the U.S. and found that CO₂ emissions in the U.S., Brazil, Australia, and India are related with economic variables. Liu et al. [43] found that globalization and economic growth contribute to environmental degradation in G7 countries. Erdogan et al. [44] reported that globalization improves environmental sustainability in Sub-Saharan Africa. Ling et al. [45] examined the non-linear and time-varying relationships among globalization, natural resources, financial development, and carbon emissions in China over the period 1980–2017. Their results showed that positive globalization shocks significantly increase carbon emissions. Adeleye et al. [46] confirmed the inverted U-shaped EKC hypothesis in seven South Asian countries (Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka) between 1980 and 2019, while conversely identifying a U-shaped relationship for globalization. Rehman et al. [47] assessed the role of globalization and economic expansion, population growth,

renewable energy consumption, and nuclear energy on CO₂ emissions and found that negative shocks to globalization and economic growth have different short-run and long-run effects on emissions.

In general, the literature suggests that environmental effects of globalization depend on balance between scale effects increasing production and energy use and technique effects promoting cleaner technologies and improving environmental performance. Although there is a large literature on determinants of emissions, most studies use traditional econometrics that assume normally distributed residuals. Violations of this assumption may lead to biased or inefficient estimates in standard unit root and/or cointegration tests, which may reduce the reliability of empirical results. The theoretical framework and literature reviewed above provide the basis for an examination of carbon emissions, economic growth, trade openness, renewable energy consumption and globalization in the US.

Methodologically, residual non-normality as well as structural breaks are accounted for using RALS-LM unit root and RALS cointegration test, respectively. These methods may give more reliable results than conventional ones when the normality assumption has been violated. In this respect, the work contributes to the literature through the application of distribution-sensitive time-series techniques to carbon emission drivers in the US. By examining the dynamic relationships among these variables, the study also aims to provide evidence that may support the development of more effective carbon emission reduction policies.

3. Model, Dataset and Econometric Method

This study examines the long-run relationship between carbon emissions, economic growth, trade openness, renewable energy consumption, and globalization in the U.S. Data processing and statistical analyses were conducted using GAUSS 25, Stata 18, and R version 4.4.1. The empirical model is specified in Equation (1).

$$CO_{2t} = \beta_0 + \beta_1 GDP_t + \beta_2 GLOB_t + \beta_3 RENEW_t + \beta_4 TRADE_t + u_t \quad (1)$$

where CO₂ represents carbon dioxide emissions. GDP denotes the gross domestic product, GLOB refers to the Globalization Index, RENEW represents renewable energy consumption, and TRADE indicates trade openness. The GLOB variable was obtained from ETH Zürich, while all other variables were sourced from the World Bank. CO₂ is measured using the World Bank carbon dioxide emissions indicator, and GDP is measured using the World Bank gross domestic product indicator. GLOB is measured by the KOF Globalization Index. RENEW is measured as renewable energy consumption as a share of total final energy consumption, and TRADE is measured as the sum of exports and imports as a percentage of GDP. All variables are used in their original level forms, and no logarithmic transformation is applied to any variable in the empirical analysis.

The year 1990 is selected as the starting point because it coincides with an important period of environmental regulation, energy policy adjustment, trade integration, and globalization dynamics in the U.S. The endpoint of 2020 is selected to avoid combining the main sample with additional post-2020 structural shifts associated with the COVID-19 pandemic and the post-2020 U.S. climate-policy environment, particularly the Inflation Reduction Act. Although the first COVID-19 shock is included in 2020, a sample expansion beyond 2020 would result in additional pandemic-related or post-IRA policy changes not directly comparable to the long-term dynamics considered here. Thus, the 1990–2020 interval offers an approximate consistent empirical window into the long-term association of carbon emissions with economic growth, globalization and renewable energy consumption as well as trade openness in the US.

Table 1 shows descriptive statistics for the variables analyzed. Based on standard deviation values, CO₂ shows the lowest volatility and GLOB the highest. Jarque-Bera results show that the normality assumption for the variables is not rejected. But this result should be cautiously interpreted because the sample contains only 31 annual observations. Since normality tests may have limited power in small samples, RALS-based methods are employed as complementary robustness checks rather than as substitutes for conventional procedures.

Table 1. Descriptive statistics.

Statistics:	CO ₂	GDP	GLOB	RENEW	TRADE
Mean	15.470	30.312	78.192	6.694	25.062
Median	15.456	30.378	78.410	5.840	24.760
Std. Dev.	0.074	0.220	3.699	2.221	3.415
Skewness	−0.328	−0.439	−0.777	0.523	0.106
Kurtosis	2.481	1.977	2.535	1.830	1.900
Jarque-Bera	0.905	2.348	3.396	3.181	1.620
Probability	0.636	0.309	0.183	0.204	0.445
Source	WB	WB	ETH Zürich	WB	WB

The econometric strategy of this study consists of three complementary stages. In the first stage, conventional unit root tests, namely ADF, PP, and KPSS tests, are applied to determine the integration order of the variables. These tests provide a baseline assessment of the time-series properties of the data. In the second stage, RALS-LM unit root tests with and without structural breaks are employed. The use of RALS-based procedures is motivated by the relatively small annual sample and the possibility that the error terms may deviate from normality. Therefore, the RALS tests are used as complementary tools to evaluate whether the stationarity results are robust to non-normal error structures and structural breaks. After confirming that the variables are integrated of order one, the existence of a long-run relationship is examined using both the Bayer and Hanck combined cointegration test and the RALS-EG cointegration test. The Bayer and Hanck approach combines several conventional cointegration tests and provides an overall assessment of cointegration, whereas the RALS-EG test allows the cointegration inference to be checked under possible non-normality in the residuals [48]. In the final stage, the long-run coefficients are estimated using the FMOLS estimator. FMOLS is used because it corrects for serial correlation and potential endogeneity in cointegrated regressions. Thus, conventional and RALS-based methods are not treated as competing approaches but as complementary procedures for assessing the robustness of the long-run relationship.

Im [49] highlighted the limitations of least squares estimation when applied to non-normally distributed series and proposed the RALS estimator as an alternative approach. Later, Im and Schmidt [50] developed efficient estimators based on the assumption that the higher-order moments of the error term are independent of the regressors, helping to address problems arising from non-normal error distributions. Im et al. [51] further showed that unit root tests based on these estimators have better power properties when the error terms are non-normally distributed. The RALS-Lagrange Multiplier (LM) test proposed by Meng et al. [52,53] is based on the LM-type test developed by Lee and Strazicich [54,55], which is a structural break version of the Schmidt and Phillips [56] test. These tests permit structural breaks to be incorporated into both the null and alternative hypotheses through the endogenous use of dummy variables. Critical values for the test statistics, based on the correlation coefficient ρ^2 and sample size T , are provided by Meng et al. [52,53].

Engle and Granger [57] proposed the cointegration method, based on the stationarity of the error term obtained from a linear combination of non-stationary time series. In this

approach, the Augmented Dickey-Fuller (ADF) unit root test is applied by regressing the first difference in the residuals on their lagged values. However, this method, based on the OLS estimation and the power of the Engle-Granger (EG) test, may decline when the error terms are not normally distributed. Lee et al. [58] proposed the RALS-EG cointegration test, which applies the RALS technique to improve the power of the EG test. Similarly to the RALS-ADF unit root test, $\hat{e}_t$ represents the residuals from the EG model, and the test equation is augmented with the term $\hat{w}_t$, as shown in Equation (2).

$$\Delta \hat{u}_t = \alpha_0 + \phi \hat{u}_{t-1} + \sum_{j=1}^p \alpha_j \Delta \hat{u}_{t-j} + \hat{w}_t' \gamma + v_t \quad (2)$$

The hypotheses are evaluated using the t -statistic, as in the conventional EG test. The correlation between the test statistic of the RALS-EG method and that of the standard EG test is computed using Equation (3).

$$t^* \rightarrow \rho t + \sqrt{1 - \rho^2} Z \quad (3)$$

In Equation (3), t^* denotes the RALS-EG test statistic, while t represents the conventional EG test statistic. Z is a standard normally distributed random variable, and ρ captures the long-run correlation between the residuals. The resulting test statistics are then compared with the relevant critical values to determine whether a long-run relationship exists among the variables. RALS-based procedures are employed as a robustness check alongside conventional methods. Since these procedures may provide more reliable inference under non-normal error distributions and in relatively small samples, they help evaluate whether the main findings are sensitive to the choice of econometric method.

4. Empirical Findings and Discussion

Table 2 presents the results of the unit root and stationarity test. The ADF and PP unit root tests indicate that all variables contain a unit root under both the constant model and constant-with-trend model. However, after taking first differences, all variables become stationary, indicating that they are integrated of order one, $I(1)$. Similarly, the KPSS stationarity test shows that the variables are non-stationary at levels under both model specifications but become stationary after first differencing.

Table 2. Traditional unit root test results.

Variable	ADF		PP		KPSS	
	C	C + T	C	C + T	C	C + T
CO ₂	−0.111 [0]	−1.039 [2]	−0.330	−1.518	0.887 ^a	0.674 ^a
GDP	−3.610 [0]	−1.547 [0]	−2.952	−4.267	2.802 ^a	0.548 ^a
GLOB	−2.270 [0]	−0.485 [0]	−0.972	−1.142	2.994 ^a	0.667 ^a
RENEW	2.151 [2]	−1.859 [2]	1.087	−5.644	2.923 ^a	0.602 ^a
TRADE	−1.806 [0]	−1.210 [0]	−4.830	−6.249	2.168 ^a	0.320 ^a
ΔCO ₂	−1.201 [2]	−5.691 ^a [1]	−25.808 ^a	−32.953 ^a	0.679 ^b	0.039
ΔGDP	−4.147 ^a [0]	−5.088 ^a [0]	−23.368 ^a	−29.572 ^a	0.759 ^a	0.048
ΔGLOB	−2.968 ^b [0]	−3.847 ^b [0]	−17.918 ^b	−21.905 ^b	0.555 ^b	0.082
ΔRENEW	−5.365 ^a [1]	−6.787 ^a [1]	−29.172 ^a	−31.549 ^a	0.292	0.031
ΔTRADE	−5.321 ^a [0]	−5.599 ^a [1]	−31.578 ^a	−32.898 ^a	0.226	0.072

Note: ^a and ^b denote significance levels of 1%, and 5%, respectively. For the KPSS test, the null hypothesis (H_0) is stationarity, whereas for the ADF test, the null hypothesis is the presence of a unit root. The values reported in square brackets for the ADF test indicate the optimal lag lengths, selected based on the t -statistic criterion. Z_α denotes the PP test statistic. C and C + T represent the constant and constant-with-trend models, respectively.

Table 3 reports the results of RALS-based tests. The results in the first part of the table indicate that all variables contain unit roots at their levels but become stationary after first differencing. Similarly, the single-break RALS-LM test results show that all variables are non-stationary at levels but become stationary at first differences in the presence of structural breaks. The estimated structural break dates are 1996 for **CO₂**, 1994 for **GDP**, 1992 for **GLOB**, 2010 for **RENEW**, and 2014 for **TRADE**.

Table 3. RALS unit root test results with and without breaks.

Level	RALS-LM	RALS-LM Break in Level	First Difference	RALS-LM	RALS-LM Break in Level
CO₂	−1.828 (0.602)	−1.740 (0.591) 1996	ΔCO_2	−4.308 ^a (0.988)	−4.269 ^a (1.008) 1992
GDP	−0.960 (1.057)	−2.679 (0.888) 1994	ΔGDP	−3.912 ^a (0.962)	−4.417 ^a (0.825) 2001
GLOB	−1.736 (0.547)	−2.034 (0.488) 1992	ΔGLOB	−8.590 ^a (0.251)	−9.544 ^a (0.221) 1998
RENEW	−2.369 (0.654)	−1.941 (1.019) 2010	ΔRENEW	−8.252 ^a (0.644)	−6.481 ^a (0.884) 2013
TRADE	−1.164 (0.969)	−1.101 (0.904) 2014	ΔTRADE	−4.385 ^a (0.973)	−6.240 ^a (0.825) 2002

Note: a denote significance levels of 1%. For the RALS-LM test, the values reported in parentheses indicate the corresponding ρ^2 values. The reported dates represent the estimated structural break dates. A 10% trimming parameter is applied when estimating the structural break dates.

While the 1990 Clean Air Act Amendments established a comprehensive framework for air quality improvement and expanded enforcement mechanisms, the specific regulation of greenhouse gases, including **CO₂**, did not commence until 2009. In contrast, the year 1996 is characterized by a major milestone in conventional pollutant control: the final elimination of leaded gasoline in the U.S [59]. New regulations have encouraged the adoption of cleaner technologies and advanced emission inspection systems for motor vehicles in the transportation sector. As a result, many firms were required to invest in emission-reduction measures and improve their environmental performance. The effects of these policy changes became more visible over time, and the structural break observed in 1996 may reflect their gradual impact on carbon emissions [60]. Overall, the 1990 Clean Air Act amendments may have contributed to the adoption of more environmentally sustainable practices in industry and energy production. Therefore, the structural break detected in 1996 may be linked to the long-term effects of these environmental policy measures.

A structural break is observed for **GDP** in 1994. This break may be associated with the economic slowdown in the U.S. following the Federal Reserve's interest rate increases aimed at controlling inflation. Higher interest rates raised borrowing costs, which may have reduced both consumer spending and investment expenditures. As a result, economic activity slowed, and GDP growth weakened during this period, potentially contributing to the structural break observed in 1994.

A structural break is also identified for **GLOB** in 1992. This break may be linked to major developments in international trade and economic integration during the early 1990s. One possible explanation is the signing of the North American Free Trade Agreement (NAFTA) in 1992, which later entered into force in 1994. The agreement formed a regional free trade area among the U.S., Canada, and Mexico and contributed to a significant increase in trade among these countries [61]. These developments may be tentatively associated with globalization and expanded international trade networks. The emergence of new markets in Eastern Europe and Central Asia increased opportunities for international

trade and investment. These developments may have contributed to the structural break observed in the globalization index in 1992.

The structural break identified in **RENEW** in 2010 may be linked to the American Recovery and Reinvestment Act (ARRA), which was enacted in 2009 and provided substantial financial backing for renewable energy projects in the U.S. ARRA allocated significant funding to renewable energy investments and encouraged the development and deployment of renewable energy projects [62]. As a result, investments in renewable energy increased, leading to higher levels of renewable energy consumption. Therefore, the structural break observed in 2010 may reflect the impact of these policy measures on the expansion of renewable energy use.

Finally, the structural break identified for **TRADE** in 2014 may be associated with major developments in global energy and financial markets. One possible explanation is the steep fall in global oil prices during 2014. As the U.S. is both a major oil producer and consumer, the decline in oil prices may have affected trade flows and external balances. The 2014 oil price decline may have affected U.S. trade flows through changes in energy prices, import costs, and energy-sector activity [63]. Another factor may have been the appreciation of the U.S. dollar against major currencies during the same period. A stronger dollar can reduce the competitiveness of U.S. exports while making imports relatively cheaper. These developments may have contributed to the structural break observed in **TRADE** in 2014.

Since all variables are $I(1)$, a cointegration analysis is conducted to examine their long-run relationship. For this purpose, the Bayer and Hanck [48] combined cointegration approach is employed. This method combines the cointegration tests developed by Engle and Granger [57], Johansen [64], Banerjee et al. [65], and Boswijk [66]. The results are reported in Table 4. Among the four tests, only the EG test fails to reject the null hypothesis of no cointegration, whereas the remaining tests reject the null hypothesis. When the test results are combined using the Bayer-Hanck method, both the EG-J and EG-J-Ba-Bo statistics support the presence of a cointegration relationship under both the constant and the constant-with-trend models. As an additional robustness check, the RALS-EG cointegration test is also applied, and the results are presented in Table 5. The test results show that the null hypothesis of no cointegration is rejected in both the constant and the constant-with-trend models.

Table 4. Bayer and Hanck ([48]) cointegration test results.

	Engle–Granger (EG)		Johansen (J)		Banerjee et al. (Ba)		Boswijk (Bo)	
	C	C + T	C	C + T	C	C + T	C	C + T
	2.379 (0.850)	−3.078 (0.694)	81.572 ^a (0.001)	53.176 ^a (0.001)	−2.648 (0.432)	−7.887 ^a (0.001)	35.842 ^a (0.001)	81.627 ^a (0.001)
Bayer-Hanck:	EG-J		EG-J-Ba-Bo					
	C		C + T		C		C + T	
Test Statistics:	55.588 ^a		16.953 ^a		73.492 ^a		127.477 ^a	
Critical Values (0.10, 0.05, 0.01)	8.301, 10.576, 15.845		8.272, 10.532, 15.973		15.938, 20.143, 30.774		16.086, 20.440, 30.836	

Note: a denote significance levels of 1%. The p -values for the EG, J, Ba, and Bo tests are reported in parentheses. C and C + T represent the constant and constant-with-trend models, respectively.

Table 5. RALS-EG cointegration test results.

Test Stat	RALS-EG	
	C	C + T
	−4.348 ^c (0) [0.874]	−4.433 ^c (0) [0.921]

Note: c denote significance levels of 10%. Lag lengths are reported in parentheses, while ρ^2 values are reported in square brackets. C and C + T represent the constant and constant-with-trend models, respectively.

After establishing confirmation of a cointegrating relationship, the long-run coefficients were estimated using the FMOLS method. The results are reported in Table 6. Under both the constant and the constant-with-trend models, **GDP** is positively related to CO₂ emissions. **GLOB** is positively associated with CO₂ emissions, whereas **RENEW** has a negative effect. The only variable for which the coefficient sign differs across specifications is **TRADE**. The coefficient is negative in the constant model but positive in the constant-with-trend model. This difference may be related to the inclusion of a significant linear trend in the latter specification, which can affect the estimated long-run relationship between trade openness and carbon emissions.

Table 6. FMOLS long-term coefficient estimation results.

Variable	GDP	GLOB	RENEW	TRADE	Constant	Trend
C	0.531 ^a [0.063]	0.007 ^a [0.001]	−0.007 ^c [0.004]	−0.063 ^a [0.002]	0.165 [1.632]	-
C + T	1.050 ^a [0.032]	0.012 ^a [0.001]	−0.019 ^a [0.002]	0.003 ^a [0.000]	−16.830 ^a [0.906]	−0.029 ^a [0.001]

Note: a, and c showed significance levels of 1%, and 10%, respectively. Values reported in square brackets represent standard errors. C and C + T represent the constant and constant-with-trend models, respectively.

The positive association between economic growth and carbon emissions can be attributed to rising energy demand accompanying economic growth and development. In many countries, this additional energy demand is still largely met through fossil fuel consumption. As economic activity increases, energy use rises in sectors such as industry, transportation, and housing, which can lead to higher carbon emissions. This finding is consistent with the literature. For example, Raza and Shah [67] reported a positive relationship between economic growth and carbon emissions in G7 countries, while Sikder et al. [68] found similar evidence for 23 developing countries.

Globalization is one of the factors associated with rising carbon emissions. It increases international trade and investment activities, leading to greater reliance on logistics and transportation services, which often rely heavily on fossil fuels. As a result, the expansion of global trade can increase energy consumption, particularly in the transportation sector, and contribute to higher carbon emissions. The environmental effects of globalization have been widely debated in the literature. In line with this study, others have noted that globalization raises carbon emissions [41]. In addition, according to Shahbaz et al. as shown in [41], globalization has different effects on carbon emissions in different countries. These differences may reflect differences in economic structure, environmental regulations and economic development stage.

Globalization and trade openness effects on carbon emissions may be interpreted as scale, technique and composition effects. The scale effect means that greater international integration leads to greater production, consumption, transport, logistics and supply chain activities and thus to greater energy demand and carbon emissions. This mechanism may help explain the positive relationship between globalization and CO₂ emissions found in this study. The technique effect works in the opposite direction. Globalization and trade

openness may facilitate access to cleaner technologies, more efficient production methods, and international environmental standards. Through this channel, international integration can reduce the carbon intensity of production [69]. However, the findings suggest that the emission-increasing scale effect may have dominated the emission-reducing technique effect during the period examined.

The composition effect refers to changes in the structure of production and trade. If international integration shifts production toward less carbon-intensive sectors, emissions may decline. Conversely, if trade expansion is associated with energy-intensive production, transportation, or carbon-intensive traded goods, emissions may increase. Therefore, the positive coefficient of globalization and the mixed sign of trade openness indicate that the environmental consequences of international integration depend on the balance among scale, technique, and composition effects.

Renewable energy sources generate significantly lower levels of carbon emissions than fossil fuels and, in some cases, produce no direct emissions at all. Therefore, increasing the use of renewable energy and reducing dependence on fossil fuels can play an important role in mitigating carbon emissions. Thus, policies and incentives supporting the transition to renewable energy may help reduce carbon emissions. Different studies support this finding. For example, Shafiei and Salim [8], Dong et al. [31], Yu et al. [32], Akram et al. [33], Olczak et al. [70] and Li and Gu [71]. They indicate that shifting energy production away from fossil fuels and toward cleaner energy sources may decrease greenhouse gas emissions. On the other hand, carbon emissions may continue to rise when energy production remains heavily dependent on conventional fossil fuels and investments in renewable energy are insufficient.

The effect of trade openness on carbon emissions differs across model specifications. In the constant model, trade openness is found to reduce carbon emissions, suggesting that international trade may contribute to improvements in environmental performance in the U.S. However, this result contrasts with previous studies reporting that trade openness or trade liberalization may increase carbon emissions and worsen environmental quality [23,25,27]. The constant-with-trend model indicates that greater trade openness increases carbon emissions. These findings suggest that environmental effects of trade openness may vary depending on economic conditions, model specification, and the underlying structure of trade. Therefore, aligning trade policies with environmental objectives requires consideration of factors such as economic growth, energy efficiency, and technological progress.

5. Conclusions and Policy Implications

Using data for the U.S. from 1990 to 2020, this study investigates the long-run association between carbon emissions, economic growth, trade openness, renewable energy consumption, and globalization. Findings show a positive long-term relationship between carbon emissions and economy growth whereas renewable energy consumption lowers carbon emissions. The impact of trade openness is different for different model specifications and estimation approaches. For instance, Ang [72], who measured output, energy use and CO₂ emissions over a long period in France, found that economic activity and energy consumption are related to emissions. This finding demonstrates how renewable energy policies and green technologies are necessary for sustainable economic growth. Thus, expanding access to and diffusion of green technologies remains important to reduce environmental impacts. Trade openness increases access to environmentally friendly technologies via more international trade but it may also increase emissions through spurring production and economic activity.

Results show a negative trade openness-carbon emissions relationship in the constant model, and a positive relation in the constant-with-trend specification. These results

indicate that model assumptions and underlying economic conditions determine which environmental effects of trade openness differ, and thus that design of trade policies is essential to limit such environmental impacts. In a similar manner, Cole and Elliott [73] found that trade openness may affect carbon emissions depending on a country's underlying trade structure and industrial composition. The negative relationship between renewable energy use and carbon emissions suggests that fossil fuels could be replaced by renewable sources of energy. Results demonstrate that more investment in renewable energy is required and that the reduction in fossil fuel consumption must be accelerated. Expanding renewable energy should remain an important part of sustainable development and environmental policy [74,75].

Globalization has a complex effect on carbon emissions. On the one hand, globalization may increase emissions through increased production/consumption and international trade. It also can reduce emissions by enabling access to environmentally friendly technologies, fostering innovation and also supporting economic development. This double effect shows how important international cooperation and exchange of knowledge and technology are. The global diffusion of sustainable practice and policies in accordance with sustainable development objectives is important to limit the environmental impacts of globalization. These results are consistent with earlier studies [76,77].

The findings of this study also have important policy implications. Given the influence of economic growth and energy consumption on carbon emissions, the development of sustainable energy policies remains essential [78]. Expanding the use of renewable energy and increasing investment in renewable energy infrastructure are important steps toward reducing emissions. In addition, policymakers should consider the environmental consequences of trade policies and encourage the adoption of green technologies. Measures that improve energy efficiency, supported by appropriate regulations and incentives, may further contribute to emission reductions. In the U.S. context, these policy implications should be considered in relation to recent climate and energy policy developments. In particular, the Inflation Reduction Act represents an important post-2020 policy framework for supporting renewable energy investment, clean energy technologies, energy efficiency, and low-carbon industrial transformation. Although this policy development falls outside the empirical sample period of this study, it is directly relevant for interpreting the future policy relevance of the findings. The negative long-run relationship between renewable energy consumption and carbon emissions suggests that policies supporting renewable energy deployment and clean energy infrastructure can play an important role in reducing emissions. Similarly, the positive association between economic growth, globalization, and emissions indicates that U.S. climate policy should not focus only on expanding clean energy supply, but also on reducing the carbon intensity of production, logistics, and international supply chains.

The positive long-run association between economic growth and carbon emissions suggests that climate policy should focus on reducing the carbon intensity of economic growth rather than assuming that economic expansion will become environmentally sustainable over time. Among the variables examined, renewable energy emerges as the most consistent channel for reducing emissions, highlighting the importance of expanding its role in the energy mix. Therefore, the promotion of renewable energy should remain a central component of long-term climate policy.

The positive coefficient of globalization indicates that international economic integration should not be regarded as environmentally neutral. Its environmental consequences may need to be managed through cleaner logistics systems, lower-carbon supply chains, and stronger environmental regulations. Taken together, the findings suggest that reducing carbon emissions depends not only on the pace of economic activity, but also on the compo-

sition of growth, the structure of energy consumption, and the environmental governance of international economic integration.

A further limitation of this study concerns the potential risk of omitted variable bias. Carbon emissions in the US may also be influenced through energy prices, industrial structure, sectoral energy intensity, technological change, and environmental regulation. These variables are not explicitly modeled in the baseline model. However, the study uses annual data for 1990–2020, which provide only relatively few observations for time-series estimation. Adding a few more control variables or estimating an independent sub-period model would reduce the degrees of freedom further and weaken the reliability of empirical results. For this reason, the empirical model is limited to a subset of theoretically central macroeconomic drivers, namely economic growth, internationalization, re-renewable energy consumption and trade openness. The findings should thus be interpreted as evidence for a long-term association of carbon emissions to these selected variables rather than an exhaustive account of all determinants of U.S. carbon emissions.

Future research could examine sector-specific effects of the trade openness on carbon emission. Also, comparative studies between countries might help us understand how globalization affects environmental sustainability under different economic or institutional conditions. Such analyses may help to develop more rounded and balanced policy frameworks taking into account environmental externalities as well as public goods. And third, more research should investigate the role of renewable energy in carbon emission reduction and the fossil fuel-free transition.

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