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RESEARCH ARTICLE

Energy Consumption , Economic Development and CO_2 Emissions: A time series approach

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Abstract
Global economic growth is intrinsically linked to energy consumption, with fossil fuels accounting for over three-quarters of total energy use. A longstanding debate centers on the relationship between economic growth and CO_2 emissions, particularly regarding the potential to decouple growth from emissions. This study examines this relationship using World Bank data from 193 countries over the period 1965-2023. The analysis reveals a strong positive correlation between GDP per capita, energy consumption (r = 0.99), and CO_2 emissions, indicating that economic growth is closely tied to increasing energy use and emissions. Global energy consumption has grown by an average of 7.6 Exajoules annually, representing a 2% rise per year. Stationarity tests show that all variables are non-stationary in their level form but become stationary after first differencing. Cointegration analysis indicates a long-run equilibrium among the variables. VAR and Granger causality tests suggest that while past values influence each variable, short-term interactions remain weak. These findings highlight the need for structural changes and transformative policies to decouple economic growth from carbon emissions.

Keywords: Economic Growth; CO_2 Emissions; Fossil Fuels; GDP; Decouple Economic

Introduction

Energy is the driving force behind the global economy. The world's heavy reliance on energy, with fossil fuels accounting for 81.7% of total energy consumption(Raufi & Maniat, 2024b) , highlights the significant challenges in transitioning to sustainable energy sources. Over the past 28 years, the share of non-fossil energy sources has increased modestly by just 5.3%, pointing to slow progress despite ambitious global environmental goals (Raufi & Maniat, 2024b). This situation contributes to the ongoing debate over the relationship between economic growth and CO_2 emissions. According to the International Energy Agency (IEA), "The relationship between growth in GDP and CO_2 emissions has loosened"(Singh, 2024), suggesting the potential to "decouple" GDP from CO_2 emissions(Jackson & Victor, 2019). In theory, this decoupling could allow for continued economic growth while reducing emissions, largely through advances in energy efficiency and technology (Fedrigo-Fazio et al., 2016; Wu, Zhu, & Zhu, 2018). However, the effectiveness and feasibility of decoupling remain inconclusive, fueling ongoing debates about whether economic growth can truly align with environmental sustainability. Despite initiatives like the United Nations Framework Convention on Climate Change (UNFCCC), CO_2 emissions have increased by over 60% since 1990, underscoring the scale of the challenge and the complex interconnection between economic growth and environmental impact(P. A. Victor, 2019). Although relative decoupling has shown some efficiency improvements (Fedrigo-Fazio et al., 2016), the gap between economic growth and global emissions reduction remains daunting (Jackson & Victor, 2019). The debate continues as to whether continuous technological advancements can realistically reconcile economic expansion with environmental sustainability(Khan, Awais, Majeed, Beenish, & Rashad, 2024), or if alternative models are needed that prioritize ecological stability over unending economic growth (Jackson, 2016). Global evidence suggests that meeting sustainability goals may require more transformative approaches, beyond incremental decoupling, emphasizing the need to explore economic paradigms that align more closely with planetary boundaries(Bengtsson, Alfredsson, Cohen, Lorek, & Schroeder, 2018; Voulvoulis, 2022). Within the energy economics literature, the relationship between economic growth and CO_2 emissions remains a critical focus. Understanding this relationship is essential for developing policies that balance economic growth with environmental sustainability, and it remains a crucial area of research to guide future strategies in addressing global environmental challenges.

Literature Review

There are many studies that suggest a significant relationship between energy consumption, CO_2 emissions, and GDP. However, some studies argue that this relationship has weakened due to the advent of renewable energies and technological advancements. In this section, we will refer to both groups of studies to explore these contrasting perspectives. Some studies suggest an optimistic outlook on global trends by identifying a U-shaped relationship between CO_2 emissions and GDP, as illustrated in **Figure 1**. This pattern implies that, at certain income levels, economic growth can initially lead to increased emissions, followed by a phase where emissions start to decline as GDP continues to rise. This view supports the idea that economic growth does not inevitably lead to higher emissions in the long term, especially if countries implement effective environmental policies and invest in sustainable technologies(Bella, Massidda, & Mattana, 2014).

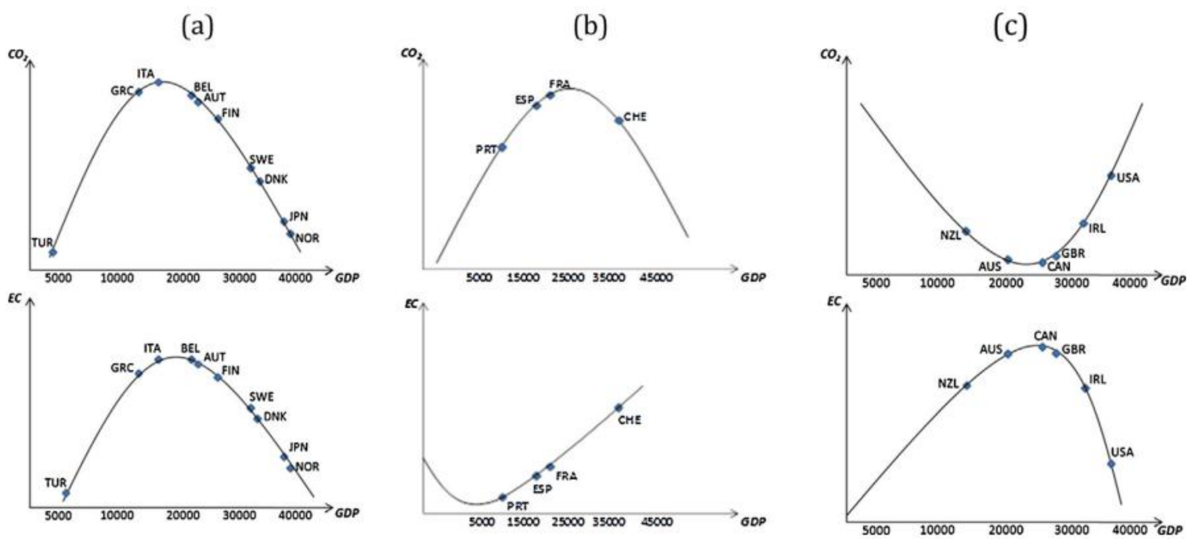

Figure 1. U-shaped relationship between CO_2 emissions and GDP(Bella et al., 2014).

However, identifying a U-shaped relationship as a special case for certain countries suggests that GDP has a low correlation with CO_2 emissions. Contrarily, a resent article published in Nature, depicted in **Figure 2**, demonstrates a significant correlation between GDP and CO_2 emissions, quantified at 0.82(Haberl et al., 2023). This finding underscores the strong and pervasive link between economic growth and carbon emissions globally, challenging the notion that GDP and CO_2 emissions can be decoupled uniformly across different contexts.

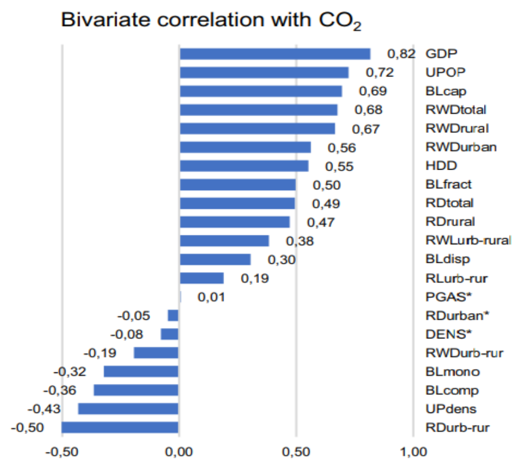

Figure 2. Correlation between GDP and CO_2 emissions(Haberl et al., 2023).

The economic relationship between GDP and CO_2 emission is significant, as numerous studies use CO_2 emissions as an indicator to predict GDP trends(Kumar & Muhuri, 2019; Kumar, Shukla, Muhuri, & Lohani, 2023; Marjanović, Milovančević, & Mladenović, 2016). A study analyzes the relationship between real GDP, CO_2 emissions, and energy use in GCC countries (1960–2013). Results show energy use drives GDP growth in Kuwait, Oman, and Qatar ("growth hypothesis"), while only Oman exhibits a long-run cointegration(Magazzino, 2016).
Research on EU countries has shown a long-run cointegrating relationship between economic growth and CO_2 emissions. Using the Dynamic Ordinary Least Squares (DOLS) method, studies indicate a statistically significant impact of GDP on emissions. On average, a 1% increase in GDP results in a 0.072% change in CO_2 emissions, underscoring the persistent link between economic activity and environmental impact(Onofrei, Vatamanu, & Cigu, 2022). CO_2 levels are influenced by various factors, including the absorption capabilities of soil and oceans**.** Another issue in correlation comparisons commonly used in most studies is the argument that the correlation between GDP and CO_2 emissions is lower in developed countries compared to developing ones(Qin et al., 2023). Two main conclusions can be drawn from this observation. First, the reduction in correlation can be attributed to the adoption of new technologies in developed countries over recent decades(Chen & Lee, 2020; Etesami, Raufi, & Maniat, 2024). Second, developing countries tend to produce more CO_2 emissions as they grow economically(Galeotti & Lanza, 1999). Maniat et al. demonstrated a reduction in air pollution during COVID-19 lockdowns(Maniat et al., 2023; Maniat et al., 2024) , while another study showed a concurrent decline in GDP(Gagnon, Kamin, & Kearns, 2023; König & Winkler, 2021). Although there are instances where conflicts arise between sustainable development and technological progress(Maniat, Elmie, Feli, & Mansouri, 2023; Maniat, Hayati, Talifard, & Rustaie, 2023), various international conventions continue to address the challenges of global warming(Akpuokwe, Adeniyi, Bakare, & Eneh, 2024; D. G. Victor, 2011). This study aims to evaluate whether advancements in new technology have effectively reduced CO_2 emissions or if the world remains far from achieving this goal. The discussion extends to whether continuous improvements in technology and

efficiency can realistically reconcile economic expansion with environmental sustainability. The economic relationship between GDP and CO_2 emission is significant, as numerous studies use CO_2 emissions as an indicator to predict GDP trends(Kumar & Muhuri, 2019; Kumar et al., 2023; Marjanović et al., 2016). A study analyzes the relationship between real GDP, CO_2 emissions, and energy use in GCC countries (1960–2013). Results show energy use drives GDP growth in Kuwait, Oman, and Qatar ("growth hypothesis"), while only Oman exhibits a long-run cointegration(Magazzino, 2016).

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Methodology

This study investigates the relationship between GDP per capita, energy consumption, and CO_2 emissions across 193 countries from 1965 to 2023. Data from the World Bank and other reliable global sources were utilized. The methodology consists of several stages: data collection, data preprocessing, unit root testing, correlation analysis, causality tests, regression modeling, and sectoral decomposition of energy sources. Each component is detailed below:

Data Preprocessing

The dataset was carefully preprocessed to ensure consistency and completeness. Missing values were handled using linear interpolation, especially for small gaps. For countries with significant missing data, exclusion was preferred to maintain the integrity of the analysis. Outliers were identified using z-scores (threshold: ±3) and removed where justified. All variables were converted to standard units where necessary, and GDP per capita values were adjusted for inflation to reflect economic changes over time.

Unit Root Tests

To examine the stationarity of the variables (GDP per capita, energy consumption, CO_2 emissions), Unit Root Tests were performed using the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), Kwiatkowski-Phillips-Schmidt-Shin (KPSS), and Elliott-Rothenberg-Stock (ERS) tests. These tests help determine whether the time series data for each variable exhibit a unit root, suggesting that they are non-stationary. Non-stationary data would require transformation to ensure that the statistical models yield reliable and meaningful results.

Granger Causality and Toda-Yamamoto Causality Tests

In addition to correlation analysis, we conducted Granger Causality and Toda-Yamamoto (TY) Causality Tests to examine the direction of causality between GDP per capita, energy consumption, and CO_2 emissions. The Granger Causality Test is used to determine whether past values of one variable can help predict future values of another, assessing the temporal dynamics of the relationship between these variables. However, the standard Granger Causality Test requires the series to be stationary. Therefore, the Toda-Yamamoto (TY) Causality Test was also performed, which accommodates potential non-stationarity by allowing for the inclusion of higher-order lags, making it more robust to the inclusion of unit roots in the data.

Measurements, Pearson Correlation Analysis, and Linear Regression Model

To identify the strength and significance of the relationship between GDP per capita, total energy consumption, CO_2 emissions, and other related variables, Pearson correlation coefficients were calculated. These correlations help evaluate preliminary associations among the variables, with specific attention to the GDP-energy and GDP-CO_2 emission relationships. High correlation values would suggest a strong linkage, guiding the focus for subsequent regression analysis. In the majority of studies(Ağbulut, 2022; Akalpler & Shingil, 2017; Azmodeh, Attar, Maniat, Rahmati, & Bahmani; Haldar & Sethi, 2021; Maniat, Abdoli, Raufi, & Marous; Maniat & Eebrahimzadeh, 2024; Raufi & Maniat, 2024a, 2024b), researchers commonly employ Pearson correlation for assessing the relationship between variables. While some studies use Kendall and Spearman correlation, the differences in results are not significant. To facilitate comparison with other research, we also utilize Pearson correlation. Pearson's correlation coefficient (r) is a widely used measure that evaluates the strength, type, and direction of the relationship between two variables. The Pearson correlation (r) is defined as shown in Equation (1)(Akoglu, 2018).

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 (y_i - \bar{y})^2}} \tag{1}$$

where:

- r =correlation coefficient,
- x_i , y_i are the values of the variable in a sample i,
- $\bar{x}$,$\bar{y}$= mean of the values of the y-variable.

A linear regression model was applied to quantify the effect of GDP per capita on total energy consumption. The regression model uses total energy consumption as the dependent variable and GDP per capita as the independent variable.The model's form is as follows(Equation (2):

$$\text{Total Energy Consumption} = \beta_0 + \beta_1 \times \text{GDP per capita} \tag{2}$$

Where:

- β_0 represents the intercept,
- β_1 denotes the slope coefficient for GDP per capita,

Model Evaluation & Statistical Significance Testing

The regression model's goodness of fit was assessed using the R^2 value, indicating the proportion of variance in energy consumption explained by GDP per capita. An Analysis of Variance was conducted to evaluate the statistical significance of the regression model, with particular attention to the F-statistics and p-values. A p-value threshold of 0.01 was applied, corresponding to a confidence level of 99%. A low p-value confirms the statistical significance of the model and its parameters.

Limitations

The study acknowledges limitations such as reliance on historical data and the inherent variability in country-level reporting, which may introduce biases. The reliance on historical data may overlook short-term fluctuations and recent developments in energy consumption patterns.The assumption of a linear relationship between GDP and energy consumption might not fully capture complex interactions, especially with technological advancements or policy interventions. Country-level data reporting inconsistencies and methodological differences across regions could introduce biases in the analysis.

Results

Figure 3 illustrates the global energy consumption trends from 1983 to 2023, measured in terawatt-hours (TWh). A significant shift towards renewable energy sources is evident, with substantial growth observed in solar, wind, biofuels, and other renewables. While fossil fuels (gas, oil, and coal) remain dominant, particularly oil and coal, their relative contribution to the energy mix has declined. Nuclear energy has experienced a slower but steady increase over the period, maintaining a relatively stable share of the overall energy consumption.

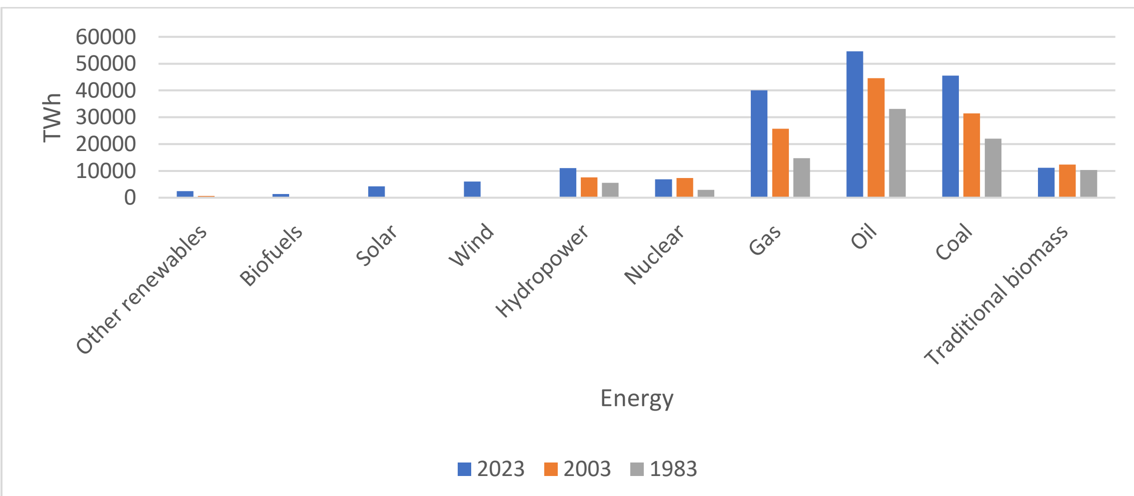

Figure 3. Energy consumption of various energy sources in three different years

Figure 4 illustrates the energy mix across three distinct years: 1983, 2003, and 2023. Each chart represents the share of various energy sources, including oil, coal, gas, nuclear, hydropower, and renewables. In 1983, fossil fuels accounted for approximately 90% of total energy consumption. By 2023, this share had decreased to around 83%, showing a steady decline over the past 40 years. Meanwhile, the share of renewable energy in the energy mix was about 6.5% in 1983 and had increased to approximately 13.7% by 2023, more than doubling over the observed period. Despite the growth in renewable energy, fossil fuels still constitute a substantial portion of global energy consumption, highlighting that a complete transition to clean energy remains a long-term goal.

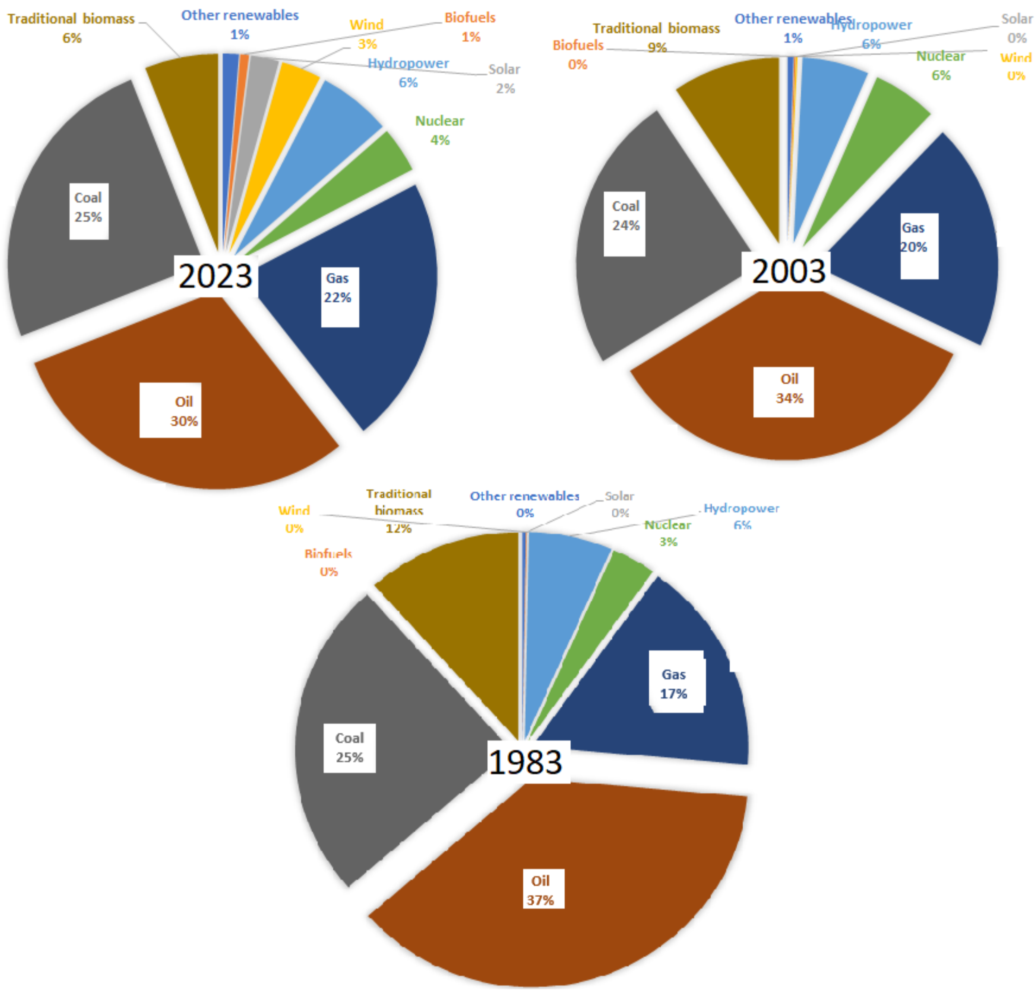

Figure 4. Shifting Global Energy Landscape

Despite the growth in renewable energy sources, fossil fuels (oil, gas, and coal) continue to play a dominant role in the global energy mix, although oil has experienced a slight decline in its share. Table 1 presents the Pearson correlation coefficients among various economic and environmental variables, including GDP, population, fossil fuel consumption, CO_2 emissions, oil, coal, gas, and total energy consumption. GDP shows a strong positive correlation with nearly all other variables, particularly with total energy consumption (0.977), CO_2 emissions (0.975), and fossil fuel use (0.977). This indicates that economic growth is closely associated with both energy consumption and CO_2 emissions. Similarly, population is highly correlated with fuel consumption (0.994), CO_2 emissions (0.986), and total energy use (0.994), suggesting that as the population increases, so do energy consumption and CO_2 emissions.Fossil fuel consumption is nearly perfectly correlated with CO_2 emissions (0.997) and total energy consumption (1.000), confirming that fossil fuels are the primary source of both energy and CO_2 emissions. Additionally, CO_2 emissions exhibit a strong correlation with total energy consumption (0.997), further suggesting that emissions are closely tied to overall energy use, particularly as fossil fuels continue to dominate the energy mix..

Table 1. Pearson correlation primary source of energy and CO_2 emissions in wolrd

Pearson Correlation									
	GDP	Population	Fuel	GDPP	Co_2	Oil	Coal	Gas	Total energy
GDP	1	.963**	.977**	.994**	.975**	.911**	.981**	.983**	.977**
Population	.963**	1	.994**	.981**	.986**	.966**	.965**	.993**	.994**
Fuel	.977**	.994**	1	.990**	.997**	.972**	.981**	.998**	1.000**
GDPP	.994**	.981**	.990**	1	.989**	.937**	.989**	.990**	.990**
Co_2	.975**	.986**	.997**	.989**	1	.973**	.988**	.991**	.997**
Oil	.911**	.966**	.972**	.937**	.973**	1	.926**	.960**	.972**
Coal	.981**	.965**	.981**	.989**	.988**	.926**	1	.975**	.981**
Gas	.983**	.993**	.998**	.990**	.991**	.960**	.975**	1	.998**
Total energy	.977**	.994**	1.000**	.990**	.997**	.972**	.981**	.998**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Energy consumption has increased by an average of 7.6 EJ per year, which corresponds to a 2% annual rise. **Figure 5** illustrates the steady rise in global energy demand, driven by factors such as population growth, industrialization, and economic expansion.

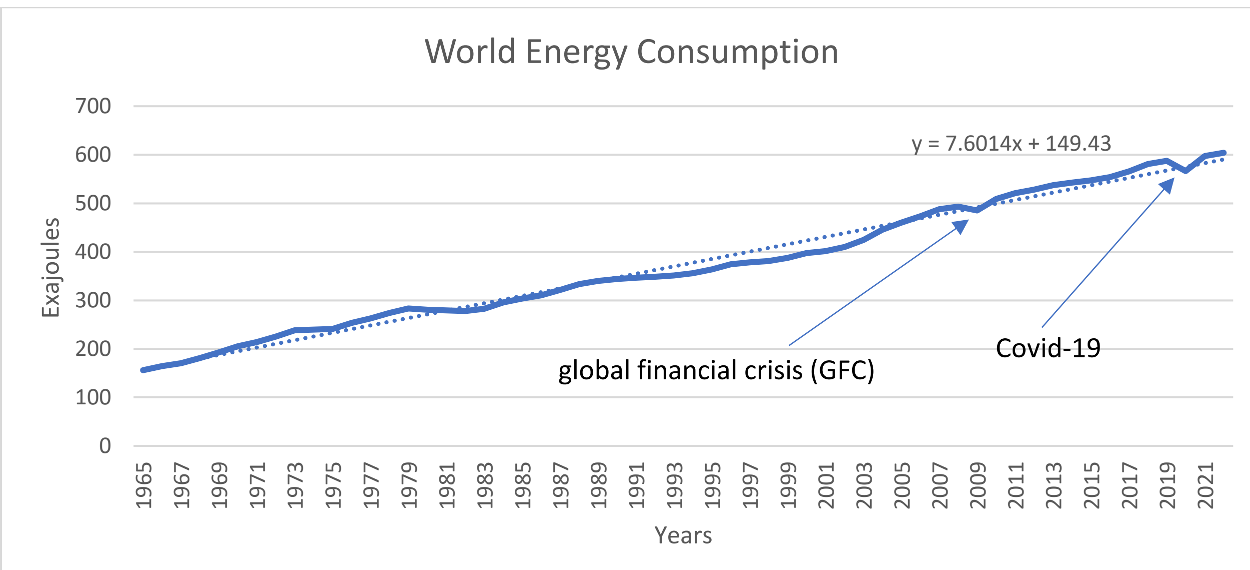

Figure 5. Trend world energy consumption

Figure 6 shows that GDP per capita has increased by an average of $215 annually, reflecting a 5.6% growth rate each year. The linear trendline illustrates consistent growth, with temporary dips during significant events such as the 2008 Global Financial Crisis (GFC) and the COVID-19 pandemic. However, following the pandemic, energy demand rebounded, demonstrating resilience. This trend underscores the ongoing link between economic health and energy consumption, highlighting the need for sustainable energy solutions to address growing demand while mitigating environmental impacts. Despite setbacks, the overall trend points to continued growth, emphasizing the importance of transitioning to more efficient, low-carbon energy sources.

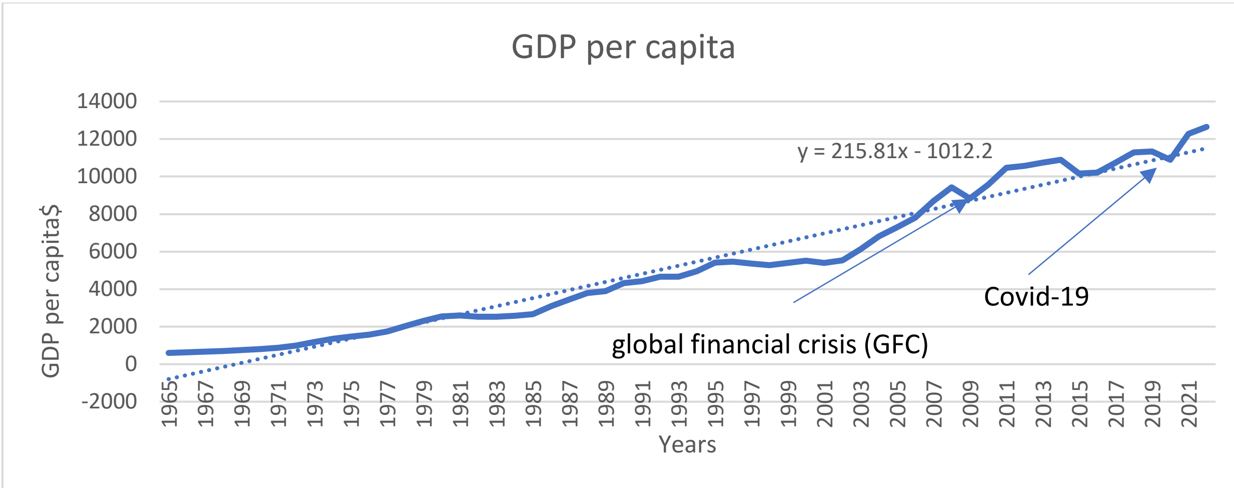

Figure 6. Trend GDP per capita in current US$

The stationarity of the data series was assessed using four common unit root tests: the Augmented Dickey-Fuller (ADF), Elliott-Rothenberg-Stock (ERS), Phillips-Perron (PP), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests. The results indicate that at the level form, the test statistics for CO_2 emissions per capita, energy consumption per capita, and GDP per capita are not statistically significant at the 1% level in the ADF, ERS, and PP tests. This suggests the presence of a unit root, implying that these series are non-stationary. However, after taking the first difference, all three variables become stationary, as evidenced by the significant test statistics in the ADF, ERS, and PP tests at the 1% level. The KPSS test, which has a null hypothesis of stationarity, confirms these findings, as the test statistics at the first difference fall below the critical value, further supporting the stationarity of the differenced series.

Table2. Unit Root Test Results for CO_2 Emissions, Energy Consumption, and GDP per Capita

	Test statistics	At Level	At First Difference
Co2 per capita	ADF	-2.418 (–4.127)	-6.169*** (–4.130)
	ERS	-1.617 (–3.743)	-6.214*** (–3.747)
	PP	-2.569 (–4.127)	-6.159*** (–4.131)
	KPSS	0.092 (0.146)	0.113 (0.146)
Energy per capita	Test statistics	At Level	At First Difference
	ADF	-2.961 (–4.127)	-6.357*** (–4.131)
	ERS	-1.696 (–3.743)	-6.375*** (–3.747)
	PP	-2.989 (–4.127)	-6.357*** (–4.131)
	KPSS	0.093 (0.146)	0.124 (0.146)
GDP per capita	Test Statistics	At Level	At First Difference
	ADF	-1.846 (–4.127)	-7.003*** (–4.131)
	ERS	-1.372 (–3.743)	-7.126*** (–3.747)
	PP	-1.904 (–4.127)	-7.005*** (–4.131)
	KPSS	0.216 (0.146)	0.037 (0.146)

The Johansen cointegration test was conducted to determine whether a long-term equilibrium relationship exists among the analyzed variables. The test results are presented using both the Trace Test and the Max-Eigenvalue

Test, each assessing the presence of cointegration at different ranks (r). The Trace Test results indicate that for r = 0, the test statistic (32.706) exceeds the 5% critical value (29.797) with a p-value of 0.0225, leading to the rejection of the null hypothesis (H_0) and suggesting at least one cointegrating relationship. However, for r ≤ 1 and r ≤ 2, the null hypothesis is not rejected, indicating no additional cointegrating vectors. Similarly, the Max-Eigenvalue Test confirms this finding, as the null hypothesis for r = 0 is rejected (28.135 > 21.132, p = 0.0044), but it is not rejected for higher values of r. These results collectively suggest the existence of a single cointegrating relationship among the variables. This implies that, despite short-term fluctuations, the variables share a stable long-run equilibrium, reinforcing the notion that GDP per capita, energy consumption, and CO_2 emissions are interlinked over time.

Table3. Johansen Cointegration Test Results for Long-Run Relationship Analysis

Test	H0	λmax / Trace Stat	CV (5%)	p-value	Decision
Trace Test	r = 0	32.706	29.797	0.0225	Reject H0
	r ≤ 1	4.571	15.495	0.8526	Do not reject
	r ≤ 2	0.258	3.841	0.6115	Do not reject
Max-Eigenvalue Test	r = 0	28.135	21.132	0.0044	Reject H0
	r = 1	4.313	14.265	0.8249	Do not reject
	r = 2	0.258	3.841	0.6115	Do not reject

Table 4 presents the results of the Vector Autoregression (VAR) model, highlighting the relationships between CO_2 emissions, energy consumption, and GDP per capita. The autoregressive components of each variable exhibit strong persistence over time. Specifically, the coefficient for CO_2(-1) is 0.948 with a t-statistic of 7.95, indicating a significant and strong positive relationship, meaning past CO_2 levels strongly influence current levels. Similarly, ENERGY(-1) has a coefficient of 0.843 (t = 7.61), and GDPP(-1) has a coefficient of 0.966 (t = 26.17), both highly significant, demonstrating that past values strongly predict current values for energy consumption and GDP per capita, respectively. These results indicate that only the lagged values of the dependent variables significantly explain their current values, reinforcing the notion that historical trends within each variable are key determinants of their present state. However, the cross-variable relationships show weaker and largely insignificant effects. The impact of past energy consumption on current CO_2 emissions (ENERGY(-1)) is negative (-0.0078) but not statistically significant (t = -0.86), suggesting no clear linkage between energy consumption and CO_2 emissions within this model. Similarly, the effect of GDP per capita on CO_2 emissions (GDPP(-1)) is positive (1.27E-05) but statistically insignificant (t = 1.25), implying that changes in GDP per capita do not have an immediate or substantial effect on emissions. Likewise, the effects of CO_2 emissions on energy consumption (CO_2(-1)) and GDP per capita on energy consumption (GDPP(-1)) are also statistically insignificant. These findings suggest that while CO_2 emissions, energy consumption, and GDP per capita exhibit strong autoregressive patterns, their short-term interdependencies are weak. The lack of significant cross-variable relationships implies that external factors, structural economic shifts, or long-term mechanisms may play a more dominant role in shaping the interactions between these variables, rather than direct short-term causality.

Table4. Vector Autoregression (VAR) Estimates

Dependent Variable	Independent Variable	Coefficient	Std. Error	t-Statistic	Significance
CO_2	CO_2(-1)	0.948	0.119	7.95	Significant
CO_2	ENERGY(-1)	-0.0078	0.0089	-0.86	Not Significant
CO_2	GDPP(-1)	1.27E-05	1.00E-05	1.25	Not Significant
ENERGY	ENERGY(-1)	0.843	0.11	7.61	Significant
ENERGY	CO_2(-1)	0.212	1.477	0.14	Not Significant
ENERGY	GDPP(-1)	0.000198	0.00013	1.57	Not Significant
GDPP	GDPP(-1)	0.966	0.036	26.17	Significant

Table 5 presents the fit statistics for the Vector Autoregression (VAR) model, evaluating the explanatory power of the regressions for CO_2 emissions, energy consumption, and GDP per capita. The R^2 values for CO_2 (0.917), energy consumption (0.971), and GDP per capita (0.991) suggest that the model explains a substantial proportion of the variance in each dependent variable. Similarly, the Adjusted R^2 values remain high, confirming that the inclusion of explanatory variables improves the model fit while accounting for the number of predictors. The F-statistics for all three equations—197.5 for CO_2, 610.14 for energy consumption, and 2140.84 for GDP per capita—indicate that the overall model is highly significant. However, despite the strong model fit, the significance of relationships primarily stems from the own-lagged terms of each variable, as indicated in Table 4. This reinforces the finding that historical values of CO_2, energy consumption, and GDP per capita are the dominant predictors of their respective current values, while cross-variable effects remain weak. The Akaike Information Criterion (AIC) and Schwarz Criterion (SC) values provide additional measures of model performance, with lower values indicating better model efficiency. While GDP per capita has the highest AIC (14.59) and SC (14.73), CO_2 has the lowest AIC (-1.8) and SC (-1.65), suggesting that the CO_2 equation is relatively more parsimonious compared to the other variables. Overall, the high R^2 values confirm the strong explanatory power of the VAR model, but the results further support the conclusion that significant relationships exist predominantly for own-lagged terms, rather than cross-variable interactions.

Table 5. VAR Model Fit Statistics

Variable	R^2	Adjusted R^2	F-Statistic	Akaike AIC	Schwarz SC
CO_2	0.917	0.913	197.5	-1.8	-1.65
ENERGY	0.971	0.97	610.14	3.23	3.37
GDPP	0.991	0.991	2140.84	14.59	14.73

The Granger causality test results indicate that no variable significantly predicts another in the short term, as all p-values exceed 0.05. This means that past values of CO_2 emissions, energy consumption, and GDP per capita do not provide meaningful information for forecasting each other. These findings align with the VAR model results (Table 4), suggesting that while each variable exhibits strong internal persistence, their short-term interdependencies are weak. This implies that their relationships may be influenced by long-term structural factors rather than immediate causal effects.

Table 6. Granger Causality (Toda-Yamamoto) Results

Dependent Variable	Excluded Variable	Chi-Square	p-Value	Conclusion
CO_2	ENERGY	0.757	0.384	No Causality
CO_2	GDPP	1.553	0.213	No Causality
ENERGY	CO_2	0.021	0.886	No Causality
ENERGY	GDPP	2.459	0.117	No Causality
GDPP	CO_2	1.576	0.209	No Causality
GDPP	ENERGY	2.428	0.119	No Causality

The optimal lag length for the VAR model was determined using Akaike Information Criterion (AIC) and Schwarz Criterion (SC). Lag 1 was selected as the best fit, as it had the lowest AIC (13.55) and a relatively low SC (14.00) compared to other lag orders. This selection ensures that the model captures the autoregressive dynamics while avoiding overfitting. These results align with previous findings, confirming strong persistence within each variable but weak short-term interactions between CO_2 emissions, energy consumption, and GDP per capita. The absence of short-term causality suggests that long-term structural factors play a more significant role in shaping these relationships.

Table 7. Lag Order Selection Criteria

Lag	Log Likelihood	AIC	SC	Selected?
0	-558.35	21.18	21.29	No
1	-347.2	13.55	14	Yes
2	-341.42	13.67	14.45	No
3	-335.1	13.77	14.89	No

Conclusions

This study examines the relationship between economic growth, energy consumption, and CO_2 emissions across 193 countries from 1965 to 2023. The findings confirm a strong positive correlation between GDP per capita, energy consumption, and CO_2 emissions, highlighting the continued dependence on fossil fuels despite a shift towards renewables. Fossil fuels still account for 82% of global energy use, emphasizing the challenge of reducing carbon dependency. Econometric analysis further supports these findings. Unit root tests confirm long-term trends, while cointegration analysis suggests a stable long-run equilibrium, albeit with weak short-term interactions. VAR estimates show that each variable is primarily influenced by its own past values, reinforcing strong autoregressive behavior with limited cross-variable effects. Granger causality tests indicate no short-term causal links, suggesting that economic growth and energy consumption do not directly drive CO_2 emissions in the short run. The lag order selection confirms that a one-lag model is optimal, balancing explanatory power with model efficiency. These results highlight the need for transformative policies beyond incremental efficiency improvements to achieve sustainable economic growth while reducing carbon emissions.

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