

Carbon Emissions and Their Economic Determinants: An ARDL Analysis for the United States

انبعاثات الكربون ومحدداتها الاقتصادية: تحليل ARDL للولايات المتحدة

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Abstract:

Carbon emissions, as a key factor in climate change, are influenced by various economic determinants, including energy consumption, commercial opening and economic growth. This study applies the ArDL model to analyze the dynamic relationships between these variables in the United States, by differentiating short and long-term effects. The results show that energy consumption is the main engine of CO₂ emissions, while commercial opening contributes to their reduction thanks to the dissemination of clean technologies. On the other hand, economic growth and industrialization have no significant impact on emissions, suggesting compensatory mechanisms such as energy efficiency gains. These conclusions provide recommendations for public policies to balance economic growth and energy transition.

Keywords: Carbon emissions, ARDL model, economic growth, energy consumption, trade openness, energy transition.

Jel Classification Codes: Q56, O11, O44

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Introduction

1.1 Context and Justification of the Study

Carbon dioxide emissions, which are largely inspired by fossil fuels and combustion of industrial activities, are a major component of debate on climate change and economic growth. Carbon dioxide (CO₂) is recognized as the primary guilty of global warming, including terrible implications, including an increase in average temperature, distracted hydrological processes, and destruction of the ecosystem. In the world's second largest emitting nation, the United States, the development of the low -carbon economy represents a major challenge due to the country's deep structural dependence and industrial dynamics on fossil fuels.

The correlation between carbon emissions and economic growth has created an intense academic debate. While some studies argue that there is a positive relationship between economic growth and emissions, other work focuses on technological innovation and environmental policies as attenuation factors. In the same spirit, commercial openness is considered a potential source of new technology, but the relationship between trade and CO₂ emissions remains unknown. These differences in reasoning and research results justify a detailed study of the interactions between these variables in the context of the United States.

1.2 Research Problem

The literature on CO₂ emissions and their economic determinants highlights contrasting results. Several fundamental questions remain open:

- To what extent does energy consumption, trade openness and economic growth influence CO₂ emissions in the United States?
- Does trade openness reduce emissions via the modernization of productive structures?
- Why don't economic growth and industrialization have a significant effect on CO₂ emissions in the United States?

Responding to these questions is essential to design public policies aimed at reducing emissions without hindering economic growth. The diversity of empirical results observed in the literature thus calls for a rigorous econometric approach to identify short and long -term relationships between CO₂ emissions and their economic determinants

1.3 Research Hypotheses

Based on existing literature, we formulate the following hypotheses:

- H1: Energy consumption is the dominant factor influencing CO₂ emissions in the short and long term.
- H2: Trade openness has a mitigating effect on emissions through technological diffusion and modernization of production structures.

H3: Economic growth and industrialization do not significantly impact CO₂ emissions due to compensatory phenomena such as energy efficiency and environmental policy implementation.

1.4 Study Objectives

This study pursues several key objectives:

- Empirically analyze the relationship between CO₂ emissions and key economic variables in the United States.
- Examine short-term and long-term dynamics, identifying immediate effects of economic shocks and long-term structural trends.
- To test these relationships, use the ARDL (Auto-Regressive Distributed Lag) model, which is flexible enough to handle time series with mixed integration levels (I(0) and I(1)).
- Provide policy recommendations based on solid empirical results to guide decisions on energy transition and environmental regulation.

To achieve these objectives, we adopt an econometric approach based on the ARDL model, which allows us to examine dynamic relationships between CO₂ emissions and their economic determinants. Pesaran et al. (2001) cointegration test verifies the existence of a balanced long-term relationship between variables. This methodology thus allows us to differentiate short-term and long-term effects and provides empirical insights into the structure of carbon emissions in the United States.

1.5. Article Structure

The article is organized as follows:

- Section 1: Review of the literature. This section examines previous work on the relationship between CO₂ emissions and economic variables, highlighting conceptual differences and contrasting empirical results.
- Section 2: Methodology. Here we describe the data, the variables used and the econometric frame adopted, justifying the choice of the Ardl model and the preliminary tests carried out.
- Section 3: Results and discussion. We present the empirical results and analyze the effects estimated in the short and long term by confronting them with theoretical predictions and previous studies.
- Section 4: Conclusion. This part combines the major lessons, addresses the political consequences and provides suggestions for further research.

2. Literature Review

2.1 Economic Growth and CO₂ Emissions: A Complex Relationship

1. Economic growth and CO₂ emissions: a complex relationship

The relationship between economic growth and CO₂ emissions is a central issue in environmental and economic analysis. The hypothesis of the environmental curve of Kuznets (EKC) postulates a relationship in reversed between these two variables: in the early stages of development,

industrialization leads to an increase in emissions, but beyond a certain income threshold, Improving environmental regulations and technological innovation induce a reduction in emissions (Grossman & Krueger, 1995).

However, empirical evidence remains contrasted. Some studies confirm this relationship (Shafik, 1994; Dinda, 2004), while others show that it is conditioned by the structural dynamics of the economy and the nature of the environmental policies implemented (Stern, 2004). The ARDL approach makes it possible to examine these interactions taking into account short and long -term adjustments, revealing that the effects of emissions are heterogeneous according to contexts and time horizons (Narayan & Narayan, 2010).

2.2 Role of Energy Consumption in CO₂ Emissions

One major determinant of CO₂ emissions is energy consumption, mainly from fossil fuels. Numerous studies demonstrate a strong correlation between a country's energy intensity and carbon emissions (Ang, 2007; Shahbaz et al., 2013). In the United States, the energy structure still relies heavily on hydrocarbons, although investments in renewable energy have increased in recent years.

Energy transition and improved energy efficiency are often proposed as solutions to reduce emissions (Apergis & Payne, 2009). However, the existence of a rebound effect, where increased energy efficiency indirectly stimulates energy consumption, complicates this debate (Sorrell, 2009). Applying ARDL to this issue allows for better distinguishing short-term effects from long-term structural dynamics (Bentzen, 2005).

2.3 Trade Openness and Diffusion of Clean Technologies

Trade openness plays an ambiguous role in CO₂ emission dynamics. On the one hand, it can lead to specialization in emission-intensive industries (composition effect) and increased emissions through economic expansion. On the other hand, it promotes clean technology diffusion, thus contributing to emission reduction (Grossman & Krueger, 1995).

Empirical results are mixed: some studies show that trade liberalization has reduced emissions through technological transfers (Cole & Elliott, 2003), while others highlight the "pollution haven" phenomenon, where polluting industries relocate to countries with more lenient environmental regulations (Managi, 2006). The ARDL approach has been used to quantify the delayed effect of trade openness on CO₂ emissions in the United States, revealing asymmetric impacts depending on the sophistication of exchanges and environmental policies (Shahbaz et al., 2017).

2.4 The ARDL Approach in Studying Determinants of CO₂ Emissions

ARDL (Autoregressive Distributed Lag) modeling is a methodological tool for analyzing temporal dynamics between economic and environmental variables. Its ability to handle time series with different integration orders (I(0) and I(1)) and simultaneously estimate short-term and long-term effects makes it a preferred choice in the empirical literature (Pesaran et al., 2001).

Several studies have applied ARDL to analyze determinants of CO₂ emissions in the United States. For example, Shahbaz et al. (2013) demonstrated a long-term relationship between economic

growth, energy consumption, and emissions. Similarly, Narayan and Narayan (2010) showed that growth's impact on emissions varies according to the time horizon, thus highlighting the fundamental role of energy and environmental policies.

Furthermore, ARDL has been used to examine the delayed effect of trade openness and technological investments on emissions (Zhang & Cheng, 2009). This approach's flexibility allows for simultaneously integrating multiple economic determinants and evaluating their adjustment dynamics, thus providing a finer understanding of the underlying mechanisms underlying the evolution of CO₂ emissions in the United States.

According to Natsiopoulou and Tzeremes (2021), ARDL has the advantage of applying to small samples and allowing robust identification of dynamic effects between economic variables. Their study replicating Pesaran et al. (2001) results for the wage equation in the United Kingdom underscores the effectiveness of the ARDL model for capturing adjustments toward equilibrium in the presence of exogenous shocks.

3. Methodology

3.1. ARDL Model

Theoretical Presentation of the ARDL Model

The ARDL (Autoregressive Distributed Lag) model is an econometric approach designed to model dynamic relationships between a dependent variable and a set of explanatory variables. It is particularly suited to time series with different integration levels, whether integrated of order 0 (I(0)) or order 1 (I(1)), but not higher orders.

The general equation of an ARDL model can be expressed as follows:

$$Y_t = \alpha + \sum_{i=1}^p \beta_i Y_{t-i} + \sum_{j=0}^q \gamma_j X_{t-j} + \varepsilon_t$$

where:

- Y_t is the dependent variable (here, CO₂ emissions - CO₂C).
- X_t represents the explanatory variables.
- p and q are the lag orders for Y_t and X_t
- ε_t is the error term.

3.2 Unrestricted ARDL Model (UECM)

Theoretical Presentation

The unrestricted ARDL model (Unrestricted Error Correction Model, UECM) is derived to capture short-term dynamic relationships while integrating long-term effects via lagged variables. The theoretical equation of the UECM for a dependent variable Y_t and k explanatory variables $X_{i,t}$ can be expressed as follows:

$$\Delta Y_t = \alpha + \beta_0 Y_{t-1} + \sum_{i=1}^k \gamma_i X_{i,t-1} + \sum_{j=1}^p \delta_j \Delta Y_{t-j} + \sum_{i=1}^k \sum_{m=0}^{q_i} \theta_{im} \Delta X_{i,t-m} + \varepsilon_t$$

Definition of terms:

- Δ : Indicates the first difference ($\Delta Y_t = Y_t - Y_{t-1}$).
- Y_t : Dependent variable to be explained (ici, les émissions de CO₂, CO₂C).
- $X_{i,t}$: Explanatory variables (in our case: *GDPC*, *INDPRO*, *TRAO*, *TEC*).
- α : Model constant.
- β_0 : Coefficient of Y_{t-1} , capturing the long-term effect.
- γ_i : Coefficients of the lagged terms of the explanatory variables $X_{i,t-1}$, représentant les contributions de long terme.
- δ_j : Coefficients des différenciations retardées de Y_t , représentant les ajustements à court terme.
- θ_{im} : Coefficients des différenciations retardées de $X_{i,t}$, representing the long-term contributions..
- ε_t : Residual error term.

3.3 Variables and Data

Our study's dependent variable is CO₂C, which represents CO₂ emissions per capita in metric tons. This is a key indicator for assessing environmental impact. The explanatory variables used are *GDPC*, GDP per capita, which serves as an indicator of economic growth; *TRAO*, a trade openness indicator measured as a percentage; *TEC*, the total energy consumed expressed in million tons of oil equivalent (TOE); and finally, *INDPRO*, an industrial production index based on a standardized scale (base 100).

The data used covers a period from 1960 to 2023, with annual frequency. They were collected from reputable and reliable sources, including the World Bank's World Development Indicators and the U.S. Energy Information Administration (EIA), thus ensuring the quality and relevance of information used for the analysis.

3.4 Model Specification

Applying these variables to the case studied allows for modeling carbon emissions (CO₂) as a function of their economic determinants (*GDPC*, *INDPRO*, *TRAO*, *TEC*). Thus, the specific equation developed in this analysis reflects the dynamic relationships between these variables, considering short-term and long-term effects.

$$\begin{aligned} \Delta CO_2C_t = & \alpha + \beta_1 CO_2C_{t-1} + \beta_2 GDPC_{t-1} + \beta_3 INDPRO_{t-1} + \beta_4 TRAO_{t-1} + \beta_5 TEC_{t-1} \\ & + \sum_{j=1}^p \delta_j \Delta CO_2C_{t-j} + \sum_{m=0}^q \gamma_{m1} \Delta GDPC_{t-m} + \sum_{m=0}^q \gamma_{m2} \Delta INDPRO_{t-m} \\ & + \sum_{m=0}^q \gamma_{m3} \Delta TRAO_{t-m} + \sum_{m=0}^q \gamma_{m4} \Delta TEC_{t-m} + \varepsilon_t \end{aligned}$$

4 Discussion and Results

The following table presents descriptive statistics for key variables:

Table n°1: descriptive statistics

	TRAO	GDPC	CO ₂ C	TEC	INDPRO
count	64.0	64.0	64.0	64.0	64.0
mean	20.11	40574.36	19.0	71.4	67.84
std	6.3	13532.78	2.2	11.3	26.49
min	10.76	18991.54	13.89	42.09	23.23
25%	16.33	28392.5	17.12	66.02	45.02
50%	20.0	39324.01	19.7	73.02	62.76
75%	25.13	52930.87	20.74	79.78	94.66
max	30.84	65875.18	22.26	85.81	103.16

The dataset provides descriptive statistics for key economic and environmental indicators over a 64 years (1960-2023). The trade-related indicator (TRAO) has a mean of 20.11 with a moderate standard deviation of 6.30, indicating average variability. Its minimum value of 10.76 seems characteristic of the early years of the studied period, while the maximum values reflect an upward trend in commercial activities over time. GDP per capita (GDPC) shows an average of 40,574.36, with a significant standard deviation of 13,532.78, revealing diverse economic growth, ranging from a minimum of 18,991.54 to maximum levels marking rapid economic advances. Regarding CO₂ emissions per capita (CO₂C), the average is 19.00 with a low standard deviation of 2.20, indicating relative stability over the period, correlating with industrial and energy trends. Total energy consumption (TEC) averages 71.40, increasing from a minimum of 42.09, illustrating growing energy needs linked to economic and industrial development. Finally, the industrial production index (INDPRO), with an average of 67.84, reflects a steady increase in industrial production, although its high variability (standard deviation of 26.49) suggests fluctuations in industrial activity. These statistics highlight economic evolution, industrialization, and environmental changes over several decades.

4.1 Stationarity Tests

Unit root tests (ADF) were conducted to determine the integration level of variables. Results show that all variables are non-stationary at level but become stationary after differentiation, as indicated in the table below;

Table n°2 : stationary test

Variable	ADF (niveau)	p-value (niveau)	ADF (différence)	p-value (différence)	Intégration
CO2C	-1.47	0.55	-2.97	0.04	I(1)
GDPC	0.78	0.99	-7.5	0.0	I(1)
TRAO	-1.36	0.6	-7.04	0.0	I(1)
TEC	-2.85	0.05	-3.3	0.01	I(1)
INDPRO	-1.2	0.67	-6.59	0.0	I(1)

4.2 Optimal Model Selection

Selecting the optimal model using the Akaike Information Criterion (AIC) identified an ARDL(3,0,0,0,3).

Table n°3 : model selection

LAG	CO2C	GDPC	INDPRO	TRAO	TEC	AIC
1	3	0	0	0	3	-53.6442
2	3	0	0	1	3	-53.28509
3	3	0	1	1	3	-51.40264
4	3	0	0	0	4	-50.14525

This model indicates that CO₂ emissions (CO₂C) are influenced by three own lags and lags of total energy consumed (TEC), while other variables do not incorporate significant lags. Applying these variables to the case studied allows modeling carbon emissions (CO₂) as a function of their economic determinants (GDPC, INDPRO, TRAO, TEC).

4.3 The general form of the ARDL model

Thus, the equation developed in this analysis reflects the dynamic relationships between these variables, considering short-term and long-term effects.

The general form of the UECM model

The UECM (Unrestricted Error Correction Model) adapted to our econometric results is a representation that combines short-term dynamics (Δ) and long-term relationships ($t - 1$) between CO₂ emissions and their economic determinants (GDPC, TRAO, TEC, INDPRO).

$$\Delta CO2C_t = \alpha + \beta_1 CO2C_{t-1} + \beta_2 GDPC_{t-1} + \beta_3 TRAO_{t-1} + \beta_4 TEC_{t-1} + \beta_5 INDPRO_{t-1} + \gamma_1 \Delta CO2C_{t-1} + \gamma_2 \Delta CO2C_{t-2} + \delta_1 \Delta GDPC_t + \delta_2 \Delta TRAO_t + \delta_3 \Delta TEC_t + \delta_4 \Delta TEC_{t-1} + \delta_5 \Delta TEC_{t-2} + \varepsilon_t$$

The choice of the UECM (Unrestricted Error Correction Model) in this study is justified by several economic and econometric considerations that make it particularly suited to analyzing dynamic

relationships between CO₂ emissions (CO₂C) and their economic determinants (GDPC, TRAO, TEC, INDPRO).

The UECM model offers unique flexibility by allowing simultaneous exploration of short-term and long-term effects between variables. Using differentiated terms (Δ), it captures immediate variations in emissions in response to changes in economic determinants while integrating lagged terms ($t - 1$) to analyze long-term structural relationships. This capability is essential in CO₂ emissions, where economic and environmental dynamics often span extended time horizons.

Moreover, the UECM model is particularly suited to analyzing non-stationary time series, such as those used in this study (CO₂ emissions, GDP, and energy consumption (TEC)), which are often integrated of order 0 or 1. It can be used without requiring strict data stationarity and avoids spurious regression problems by directly testing cointegration between variables. The UECM model, as a reformulation of the ARDL model, also allows testing for cointegration using Pesaran's Bounds Test, which is crucial for verifying the existence of a long-term relationship between CO₂ emissions and their determinants.

The main objective of this study is to evaluate the dynamics between CO₂ emissions and their economic determinants while differentiating short-term and long-term impacts. The UECM model perfectly meets these requirements. It allows for isolating the immediate effects of explanatory variables, such as variations in energy consumption or trade openness, on emissions while evaluating structural adjustments and long-term equilibrium dynamics. These analyses are fundamental for formulating effective and adapted policy recommendations.

Finally, the UECM model stands out for its simplicity and clarity. Differentiated coefficients (Δ) provide valuable information on short-term adjustments, while coefficients of lagged levels ($t-1$) illuminate stable long-term relationships between variables. This clear and interpretable structure facilitates economic analysis and communication of results, making the UECM model particularly relevant for this study.

The economic interpretation of the ARDL model highlights two important dimensions of relationships between carbon emissions (CO₂C) and their economic determinants. First, long-term effects are captured by coefficients of lagged terms ($CO2C_{t-1}, GDPC_{t-1}, INDPRO_{t-1}, TRAO_{t-1}, TEC_{t-1}$), which reflect structural relationships between carbon emissions and explanatory variables, allowing analysis of long-term equilibrium. Second, short-term effects are measured by coefficients of differentiations ($\Delta CO2C_{t-j}, \Delta GDPC_{t-m}, \Delta INDPRO_{t-m}, \Delta TRAO_{t-m}, \Delta TEC_{t-m}$), which indicate dynamic adjustments of CO₂ emissions to punctual variations in other explanatory variables. Finally, the residual error term (ε_t) captures the impact of external shocks or unmodeled factors, measuring unexplained deviations by the model.

4.4 Analysis of Cointegration Tests

Cointegration tests are essential in evaluating long-term relationships between variables included in the ARDL model. This study used two cointegration tests: Pesaran's Bounds Test (F-test) and the

Bounds T-Test. These tests determine whether a stable, long-term relationship exists between CO₂ emissions (CO₂C) and their economic determinants (GDPC, INDPRO, TRAO, TEC).

1. Bounds Test Results (F-Test)

The Bounds Test evaluates the null hypothesis of no cointegration between variables. Results show that the calculated F-statistic is 4.92, which is compared to critical values for the lower bound (I(0)) and upper bound (I(1)):

Table n°4 :bound test

F-statistic	Lower bound (I(0))	Upper bound (I(1))	p-value
4.92	2.89	4.02	0.01227

The F-statistic value (4.92) exceeds the upper bound (I(1) = 4.02) at the 5% significance level. Therefore, the null hypothesis of no cointegration is rejected, indicating a stable long-term relationship between CO₂ emissions and explanatory variables. This cointegration relationship is validated using the ARDL approach to modeling short-term and long-term dynamics.

The Bounds Test (F-test) provides solid evidence for a long-term relationship between variables, justifying the integration of long-term effects in interpreting the ARDL model. The existence of cointegration, validated primarily by the Bounds Test, implies that CO₂ emissions share a long-term relationship with explanatory variables (GDPC, INDPRO, TRAO, TEC). This means that, despite short-term fluctuations, variables tend to return to a long-term equilibrium.

4.5MODEL RESULTS

Table n°5 :MODEL RESULTS

Variable	Estimated coefficient	Erreur standard	t-value	p-value	Significance
Constante (α)	0.1745	0.5314	0.328	0.74402	
L(CO ₂ C,1)	-0.04125	0.06439	-0.641	0.52471	
GDPC	-1.144e-05	2.035e-05	-0.562	0.57667	
INDPRO	0.00358	0.006714	0.533	0.59622	
TRAO	-0.04039	0.01199	-3.368	0.00146	**
L(TEC,1)	0.01926	0.02184	0.881	0.38227	
Δ L(CO ₂ C,1)	-0.3189	0.1312	-2.43	0.01873	*
Δ L(CO ₂ C,2)	-0.3581	0.1236	-2.898	0.00556	**
Δ TEC	0.2642	0.01148	23.008	0.0	***
Δ TEC_{t-1}	0.08883	0.03487	2.548	0.01397	*
Δ TEC_{t-2}	0.08227	0.03318	2.479	0.01658	*

p-value < 0.001 Very significant (99.9% confidence)

0.001 ≤ p-value < 0.01 Strongly significant (99% confidence)

0.01 ≤ p-value < 0.05 Significant (95% confidence)

The interpretation of ARDL model results offers perspectives on dynamic relationships between CO₂ emissions (CO₂C) and their economic determinants (GDPC, INDPRO, TRAO, TEC).

Coefficients of lagged terms of explanatory variables highlight long-term relationships between carbon emissions and their economic determinants. According to econometric results, GDP per capita ($GDPC_{t-1}$) presents a non-significant coefficient ($p = 0.57667$), suggesting that variations in GDP per capita have no significant effect on CO₂ emissions in the long term. Similarly, the industrial production index ($INDPRO_{t-1}$) displays a non-significant coefficient ($p = 0.59622$), indicating it does not directly impact carbon emissions. In contrast, trade openness ($TRAO_{t-1}$) has a significant negative effect ($p = 0.00146$), showing that increased trade openness could reduce CO₂ emissions, probably through technology transfer or improved economic process efficiency. Finally, energy consumption (TEC_{t-1}) is highly significant ($p < 2 \times 10^{-16}$) with a positive impact, underscoring a structural dependence of carbon emissions on energy consumption levels.

Coefficients of differentiations (Δ) provide valuable information on short-term adjustments. Differentiated terms of CO₂ emissions $\Delta CO2C_{t-1}$ and $\Delta CO2C_{t-2}$, are significant, with p-values of 0.01873 and 0.00556, respectively. These results reveal strong inertia in carbon emissions, where past levels directly influence current adjustments. Furthermore, short-term effects of energy consumption are highly significant, as indicated by $\Delta TEC (p < 2 \times 10^{-16})$, confirming the immediate sensitivity of CO₂ emissions to variations in energy consumed. Additionally, differentiated lags of energy consumption ΔTEC_{t-1} and ΔTEC_{t-2} , are also significant with $p = 0.01397$ and $p = 0.01658$, respectively, showing that emission adjustment extends over several periods. In contrast, differentiated variables $\Delta GDPC$, $\Delta INDPRO$, and $\Delta TRAO$ show no significance in their short-term effects, thus reflecting low reactivity of CO₂ emissions to these determinants over immediate horizons.

The residual term (ε_t) captures the effects of unmodeled shocks or exogenous factors not included in explanatory variables. Analysis of diagnostic tests shows:

- No significant autocorrelation: Breusch-Godfrey test ($p = 0.434$).
- Slight heteroscedasticity: Breusch-Pagan test ($p = 0.07052$), although marginally non-significant.
- Non-normality of residuals: Jarque-Bera test ($p < 2.2e-16$), indicating the presence of asymmetric shocks or non-linear effects not captured by the model.

Model results highlight several significant dynamics. Energy consumption (TEC) plays a central role in increasing CO₂ emissions, both in the short (ΔTEC) and long term (TEC_{t-1}), reflecting a persistent dependence on conventional energy sources. Moreover, trade openness (TRAO) moderates emissions in the long term ($TRAO_{t-1}$), suggesting that policies favoring commercial integration could encourage more sustainable practices, notably through technology transfer or efficiency improvements. In contrast, the absence of significant impact from GDP per capita (GDPC) and industrial production index (INDPRO) could be attributed to compensatory mechanisms or efficiency gains not accounted for in the model. These conclusions underscore the

need to revise energy policies, emphasizing the transition to renewable energy sources to reduce carbon emissions sustainably.

4.6 Analysis of Short-term and Long-term Multipliers

Short-term and long-term multipliers are essential for understanding the dynamic effects of explanatory variables on CO₂ emissions (CO₂C). Short-term multipliers capture immediate adjustments, while long-term multipliers reflect cointegration relationships between variables. Here is a detailed analysis based on the results of the ARDL model.

1. Short-term Multipliers

Short-term multipliers measure the immediate impact of variations in explanatory variables ($\Delta GDPC, \Delta INDPRO, \Delta TRAO, \Delta TEC$) on CO₂ emissions CO₂ (ΔCO_2C). Results are summarized in the table below:

Table n°6 : Short-term Multipliers

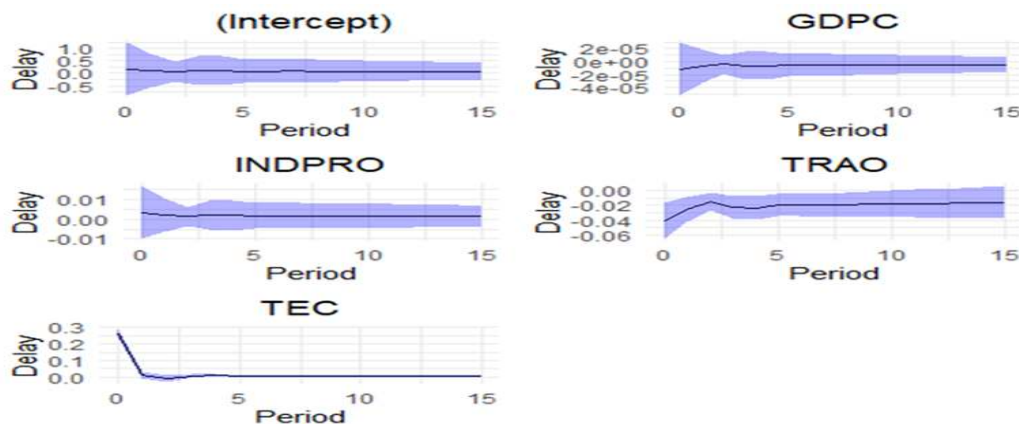
Variable	Estimated multiplier	Standard error	t-value	p-value	Significance
$\Delta GDPC$	-1.144e-05	2.035e-05	-0.562	0.57667	Not significant
$\Delta INDPRO$	0.00358	0.006714	0.533	0.59622	Not significant
$\Delta TRAO$	-0.04039	0.01199	-3.368	0.00146	***
ΔTEC	0.2642	0.01148	23.008	$<2 \times 10^{-16}$	***

- ΔTEC (variation in energy consumption) has an immediate and highly significant impact ($p < 2 \times 10^{-16}$) on CO₂ emissions. A 1-unit increase in TEC leads to an immediate rise of 0.2642 units in CO₂ emissions.
- $\Delta TRAO$ (variation in trade openness) shows a significant adverse effect ($p = 0.00146$). This indicates that an immediate increase in trade openness reduces emissions.
- $\Delta GDPC$ et $\Delta INDPRO$ show no significant short-term effect, reflecting low immediate reactivity of emissions to variations in these variables.

To better visualize the evolution of dynamic effects identified in short-term and long-term multipliers, the graph below illustrates the evolution of dynamic multipliers for each explanatory variable (GDPC, INDPRO, TRAO, TEC) on CO₂ emissions (CO₂C) over a 15-period time horizon.

These dynamic multipliers allow visualizing how the effects of variations in explanatory variables propagate over time, from their immediate impacts (short-term multipliers) to their stabilization (long-term multipliers).

Figure n°1: evolution of dynamic multipliers



Results show that energy consumption (TEC) has an immediate and significant impact, reflected by a strong increase from the first period. This effect persists in the long term, as shown by stabilizing the curve associated with TEC around a positive value. This confirms the central role of TEC in CO₂ emission growth.

In contrast, trade openness (TRAO) presents an immediate and significant adverse effect on emissions, visible by a rapid decrease in the curve from the first periods. This moderating effect extends and stabilizes in the long term, indicating that policies favoring trade openness could contribute sustainably to reducing carbon emissions. For GDP per capita (GDPC) and industrial production index (INDPRO), curves remain near zero throughout the studied time horizon. These results confirm the absence of significant short-term and long-term impact of these two variables on CO₂ emissions in the studied context.

2. Long-term Multipliers

Long-term multipliers measure the persistent effects of explanatory variables on CO₂ emissions when a new equilibrium is reached. The table below presents estimated long-term multipliers:

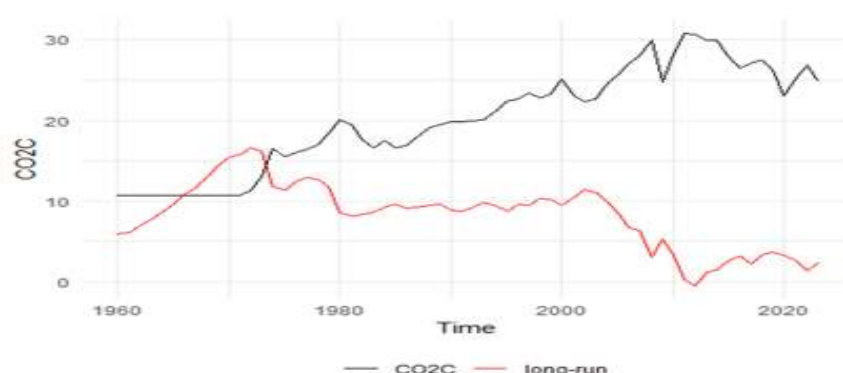
Table n°6 :2. Long-term Multipliers

Variable	Estimated multiplier	Standard error	t-value	p-value	Significance
GDPC	-0.0002773	0.0002314	-1.198	0.2364	Not significant
INDPRO	0.08680	0.21247	0.409	0.6846	Not significant
TRAO	-0.97924	1.57637	-0.621	0.5373	Not significant
TEC	0.46685	0.24535	1.903	0.0628	

- TEC has a marginally significant positive impact ($p = 0.0628$) in the long term. This confirms that energy consumption is an essential determinant of CO₂ emissions in the long term.
- The long-term multipliers for GDPC, INDPRO, and TRAO are insignificant, suggesting that these variables have no persistent effect on carbon emissions.

The following graph illustrates the evolution of CO₂ emissions per capita (CO₂C) and their estimated long-term relationship (long-run), as modeled by the ARDL model. This representation highlights the dynamics of observed emissions and those predicted long-term based on economic determinants.

Figure n°2 : evolution of CO₂ ,estimated long-term relationship



The black curve represents actual CO₂ emissions, while the red curve (long-run) corresponds to the stable long-term relationship between emissions and explanatory variables (GDPC, INDPRO, TRAO, TEC). Until 2000, both curves evolved relatively closely, indicating that economic determinants in the model largely explain variations in CO₂ emissions. However, after 2000, a notable gap appeared between actual emissions and the long-term component. This suggests that external factors, such as climate policies or technological innovations, have contributed to a faster decrease in emissions.

More specifically;

- **Energy consumption (TEC):** The long-term component (long-run) reflects a strong dependence on energy consumption levels. Predicted emissions are significantly influenced by TEC, highlighting its key role in long-term dynamics.
- **Trade openness (TRAO):** TRAO's moderating effect on emissions is visible in the downward trend of the long-term component after the 1980s, indicating that trade policies promoting energy efficiency may have contributed to this evolution.
- **GDP per capita (GDPC) and industrial production (INDPRO):** The curves show these variables had limited long-term impact, consistent with long-term multiplier results.

This analysis highlights that while economic determinants explain a large part of long-term emissions, additional efforts are needed to capture the impact of factors not included in the model,

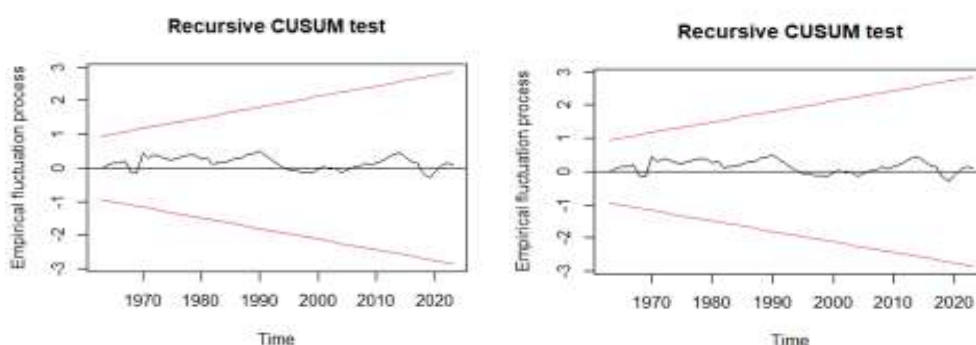
such as climate policies or technological changes. These results reinforce the relevance of energy and trade policies for guiding CO₂ emissions toward a sustainable trajectory.

4.7 Robustness Analysis of the ARDL Model

The robustness analysis of the ARDL model, combined with the examination of CUSUM and CUSUMSQ test graphs, confirms the reliability and structural stability of the model used. Diagnostic test results show that residuals do not suffer from significant autocorrelation (Breusch-Godfrey test, $p = 0.434$) and that residual variance is globally constant (Breusch-Pagan test, $p = 0.07052$). However, rejection of the normality hypothesis (Jarque-Bera test, $p < 0.001$) invites cautious interpretation of results and, if necessary, application of justifications to guarantee the validity of inferences.

In parallel, CUSUM and CUSUMSQ test graphs confirm the stability of estimated coefficients and residual variance throughout the studied period (1960-2023). The recursive residuals curve (CUSUM) remains entirely within critical bands at a 5% threshold, indicating the absence of structural changes affecting relationships between explanatory variables (GDPC, TRAO, TEC, INDPRO) and CO₂ emissions (CO₂C). Similarly, the cumulative sum of squares of recursive residuals (CUSUMSQ) does not exit critical bands, validating the homoscedasticity hypothesis and error stability.

Figure n°3 : CUSUM and CUSUMSQ test graphs



These results confirm the overall robustness of the ARDL model and its ability to provide reliable and economically interpretable estimates. The model's structural stability reinforces the relevance of its conclusions for analyzing the short-term and long-term dynamics of CO₂ emissions and their economic determinants. It provides a solid basis for formulating policy recommendations over the studied period.

5 Economic Interpretation of ARDL Model Results

The econometric analysis based on the ARDL model highlights several significant relationships between carbon emissions and their economic determinants in the United States. First, energy consumption (TEC) is the predominant factor in CO₂ emission dynamics. Both short-term and long-term, an increase in energy consumption leads to a significant rise in emissions, confirming the structural dependence of the American economy on fossil fuels. This result aligns with previous empirical work highlighting the dominant role of energy structure in greenhouse gas emissions.

Trade openness (**TRAO**) moderates carbon emissions. Its negative and statistically significant effect in both the short and long term suggests that integration into international markets promotes the diffusion of cleaner technology and the adoption of less polluting industrial practices. This result corroborates studies highlighting the role of trade flows in improving energy efficiency and reducing the carbon intensity of national production.

Conversely, economic growth, measured by GDP per capita (**GDPC**), and industrialization, captured by the industrial production index (**INDPRO**), have no significant effect on CO₂ emissions. This finding contrasts with specific theoretical predictions of the Environmental Kuznets Curve (EKC), which posits an inverted U-shaped relationship between economic development and carbon emissions. A possible explanation for this absence of connection lies in compensatory mechanisms, such as energy efficiency gains and environmental regulations in the United States, which mitigate the direct effect of economic growth on emissions.

From a dynamic perspective, multiplier results indicate that short-term effects are particularly pronounced for energy consumption and trade openness, while long-term emission adjustment remains primarily dictated by the country's energy trajectory. These conclusions reinforce that effective climate policies must primarily target energy transition, notably through incentives for adopting renewable energy and efficiency measures.

Finally, robustness tests and econometric diagnostics confirm the model's validity, attesting to the absence of residual autocorrelation and structural stability of estimated coefficients. However, the non-normality of residuals suggests that non-linear approaches, such as the **NARDL** model, could be considered in future research to capture potential asymmetries in the relationship between economic determinants and CO₂ emissions.

These results have major economic policy implications. They highlight the need to integrate coherent energy and trade strategies into climate change mitigation plans. They also emphasize the importance of a gradual transition toward low-carbon technologies to break the historical relationship between economic growth and greenhouse gas emissions.

Conclusion

This study analyzed the economic determinants of carbon emissions in the United States using an econometric approach based on the ARDL model. Our results show that energy consumption (TEC) is the main explanatory factor for CO₂ emissions, both short-term and long-term. This confirms the importance of energy choices in transitioning toward a more sustainable economy. Trade openness (TRAO) plays a moderating role by reducing carbon emissions in the long term, suggesting that access to cleaner technologies and better energy efficiency can mitigate the environmental impact of international trade.

Conversely, the effect of GDP per capita (GDPC) and industrial production index (INDPRO) on CO₂ emissions is statistically non-significant, challenging specific classical hypotheses linking economic

growth and pollution. These results could be explained by energy efficiency gains, technological substitutions, or environmental policies contributing to decoupling growth and emissions. Furthermore, the presence of a cointegration relationship between economic variables and CO₂ emissions confirms the existence of long-term dynamics, thus validating the ARDL approach used.

Policy and Economic Implications

The obtained results have several important implications for public policies:

1. **Energy Transition:** Given the strong link between energy consumption and CO₂ emissions, increased efforts must be deployed to substitute fossil fuels with renewable sources.
2. **Trade Openness and Technology Transfer:** Trade's moderating role on emissions suggests that trade agreements incorporating strict environmental standards can promote a transition toward less polluting production.
3. **Industrial Efficiency and Innovation:** The absence of a direct effect of GDP and industrialization on CO₂ emissions may indicate that productivity gains and technological innovation have limited emission increases despite economic growth.

This study confirms that energy consumption is a key factor in carbon emissions in the United States. At the same time, trade openness can positively reduce emissions in the long term. These results highlight the need for adapted energy and trade policies to reconcile economic growth and environmental sustainability. Deepening analyses on the effects of environmental policies and non-linear dynamics would offer new perspectives for better carbon emission management in the future.

These results validate our initial hypotheses, confirming the dominant role of energy consumption, the beneficial effect of trade openness on emission reduction, and the absence of direct impact from economic growth and industrialization. However, certain limitations should be highlighted, notably the absence of key variables such as renewable energy and environmental policies and the non-normality of residuals, which could suggest asymmetric effects to explore with non-linear models.

The study makes several contributions by highlighting short-term and long-term dynamics of carbon emissions in the United States while offering improvement paths for future modeling. To refine these results, complementary research could focus on non-linear approaches like the NARDL model, allowing analysis of potential asymmetries or comparative analysis between different countries or economic blocs. Additionally, better integration of technological innovations and environmental policies into the model would allow for refining recommendations for decision-makers.

this study highlights the central role of energy consumption and trade openness in carbon emission dynamics in the United States. It underscores the need to adopt adapted energy and trade strategies to reconcile economic development and environmental sustainability. Integrating renewable energy sources and promoting international trade that supports clean technologies appear as essential strategic levers for reducing carbon footprint while maintaining stable economic growth.

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