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RESEARCH ARTICLE

# Relationship between Demography, Economic Growth and CO2 Emissions: An Econometric Study from 1990 To 2020

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**ABSTRACT**

This research delves into the complex interactions between demography, economic and social development and CO2 emissions over a period from 1990 to 2020. The fundamental objective is to precisely analyze the impact of population growth, economic expansion and urbanization on global CO2 emissions, using the Vector Error Correction Model (VECM). The results reveal a significant positive correlation between population growth, GDP growth, urbanization and the degree of development on CO2 emissions. In the short term, population and industry play a considerable role in the evolution of CO2 emissions. In the long term, these variables tend to lose their influence, while urbanization and GDP have a limited and positive effect on CO2 emissions. These results highlight the crucial role that these factors play in global environmental dynamics, underlining the need to integrate sustainable development strategies to mitigate these impacts.

## INTRODUCTION

$CO_2$ emissions, widely recognized as one of the principal drivers of global climate change, occupy a central position in international environmental discussions. Predominantly originating from the combustion of fossil fuels for energy production, transportation, and industrial activities, as well as from land-use changes such as agriculture (Liu et al., 2018), these emissions contribute substantially to climate disruptions. The repercussions for natural ecosystems and human societies are severe, including rising sea levels, intensification of extreme weather events, and disruptions to agricultural and hydrological systems, all of which threaten ecological and socio-economic stability worldwide (O'Neill et al., 2012).

Identifying the factors driving $CO_2$ emissions is therefore essential for devising effective mitigation and adaptation strategies. Among these factors, population growth stands out as a significant contributor, as it drives increased demand for energy, infrastructure, and consumer goods. A growing population necessitates expanded services, such as housing and transportation, which in turn amplify energy consumption. Urban areas, responsible for over 70% of global $CO_2$ emissions, are particularly noteworthy, serving as hubs of energy consumption and industrial activity (United Nations Environment Programme, 2020).

Economic growth, often measured through gross domestic product (GDP), also exerts a complex influence on $CO_2$ emissions. While economic expansion typically leads to higher energy consumption and greater production of goods and services, thereby increasing emissions, it can also incentivize investments in cleaner technologies and the implementation of stringent environmental policies, potentially reducing emissions over the long term (Grossman & Krueger, 1995). This dual role of economic growth is particularly evident in developing economies, such as Morocco, where economic growth and energy consumption significantly contribute to emissions (Kerfal and El Alaoui, 2024).

Urbanization adds another layer of complexity. As urban populations grow, the demand for infrastructure, services, and energy intensifies, exerting direct pressure on $CO_2$ emissions. Urban centers often concentrate industrial activities and motorized transport, key sources of emissions. However, these same urban areas can also foster energy efficiency through improved resource management and the adoption of sustainable technologies (Jiang & Hardee, 2011). Achieving sustainable economic growth, as emphasized by El Alaoui and Nekrache (2017), requires robust environmental protection measures to mitigate the adverse impacts of urbanization and industrial expansion.

The interaction between demography, urbanization, economic growth, and $CO_2$ emissions is therefore critical to understanding and formulating effective environmental policies. Over recent decades, the global population has increased significantly, rising from 5.3 billion in 1990 to more than 7.8 billion in 2020, alongside substantial growth in global GDP and accelerated urbanization, with an increasing proportion of the world's population residing in urban areas.

This multifaceted relationship is effectively captured by the Environmental Kuznets Curve (EKC), which suggests that emissions rise during the initial stages of economic development but eventually decline as cleaner technologies and stricter environmental policies are adopted. El Alaoui (2017) explored this phenomenon, particularly highlighting the role of trade liberalization policies and their potential impact on environmental quality within the context of economic growth.

Building on these insights, this article examines the intricate relationship between population growth, urbanization, economic development, and their combined influence on global $CO_2$ emissions. Using a quantitative analysis of global data on demography, urbanization, and economic growth from 1990 to 2020, the study is structured into three sections: a review of the relevant literature and theoretical frameworks, an explanation of the research methodologies employed, and an analysis and discussion of the results, with comparisons to existing studies.

## LITERATURE REVIEW

**This section is divided into two subsections. The first examines the relationship between demography and CO2 emissions, while the second discusses the link between economic growth and CO2 emissions.**

### Relationship between demography and CO2 emissions

Population growth is a major driver of CO2 emissions. The increasing global population leads to heightened demand for energy resources, primarily derived from fossil fuels, which in turn drives up CO2 emissions. For instance, Liu et al. (2018) demonstrated that densely populated urban areas generate higher levels of CO2 emissions due to the concentration of industrial and transportation activities. Their study highlights that although cities occupy a small fraction of the Earth's surface, they are responsible for the majority of global CO2 emissions because of their high energy consumption and dense infrastructure.

Furthermore, O'Neill et al. (2012) noted that population growth significantly contributes to CO2 emissions, particularly in developing countries where population growth rates are the highest. Their research reveals that rapid urbanization and the expansion of residential and industrial areas increase the demand for energy and natural resources, thereby exacerbating CO2 emissions. They suggest that population control policies, such as family planning and education initiatives, could play a critical role in curbing future emissions.

Cole and Neumayer (2004) also found that demographic trends significantly influence CO2 emissions. Their research showed that countries with faster population growth tend to experience a more rapid increase in CO2 emissions. By analyzing data from multiple countries, they concluded that population pressure amplifies energy demand, particularly in regions with underdeveloped energy infrastructure, thereby leading to higher CO2 emissions.

Similarly, Jiang and Hardee (2011) examined the relationship between population growth and CO2 emissions, concluding that population control policies could be an effective tool for reducing future emissions. They emphasized that slowing population growth could ease the strain on natural resources and reduce CO2 emissions while simultaneously improving overall quality of life. Their analysis suggests specific measures, such as improving access to contraception and promoting women's education, to manage population growth and mitigate its environmental impacts.

### Relationship between Economic growth and CO2 emissions

Gross Domestic Product (GDP) is a key factor influencing $CO_2$ emissions. Economic growth, often accompanied by industrialization and increased energy consumption, significantly contributes to greenhouse gas emissions. Grossman and Krueger (1995) introduced the Environmental Kuznets Curve (EKC) hypothesis, which posits that $CO_2$ emissions rise during the early stages of economic development but decline beyond a critical threshold due to the adoption of cleaner technologies and stricter environmental regulations. Their cross-country analysis highlights that while initial economic growth exacerbates environmental degradation, higher levels of per capita income tend to foster improvements in environmental quality.

York and Rosa (2003) further explored the link between economic growth and $CO_2$ emissions, finding a generally proportional increase in emissions with GDP growth. Expanding economies consume larger amounts of energy and produce higher levels of goods and services, thereby intensifying emissions. However, this correlation can be mitigated by effective environmental policies and technological advancements.

Stern (2004) provided a detailed analysis of the interplay between economic growth and $CO_2$ emissions, emphasizing the crucial role of technological innovation. He argued that breakthroughs in clean technology and significant investments in renewable energy can decouple economic expansion from escalating emissions, thus enabling sustainable growth. Stern also noted that wealthier nations are better equipped to invest in green infrastructure and advanced environmental technologies, reducing their carbon footprint.

In developing countries, Shahbaz et al. (2013) examined the link between industrialization, fossil fuel consumption, and $CO_2$ emissions using counteraction and Granger causality methods. Their findings revealed a strong association between rapid industrialization, reliance on fossil fuels, and elevated emissions. They concluded that diversifying energy sources and improving energy efficiency are critical to reducing emissions in these regions.

Urbanization is another key driver of rising $CO_2$ emissions, as it intensifies economic activity, increases transportation use, and raises energy demand. Poumanyvong and Kaneko (2010) studied this phenomenon in developing countries and found that urbanization generally exacerbates emissions. The rapid growth of urban populations and reliance on fossil fuel-dependent infrastructure significantly contribute to global emissions. However, they noted that this trend can be countered through sustainable urban development, green technology investments, and robust environmental policies

## RESEARCH METHODOLOGY

### Data

The study of the relationship between demography, economic growth, and CO2 emissions over the period 1990–2020 requires the inclusion of the following variables: global GDP, CO2 emissions, global population, urbanization rate, and industrial activity rate. The data for these variables were sourced from the World Bank Development Indicators.

Global GDP showed significant growth, increasing from **22,935 billion USD** (World Bank) in 1990 to **87,777 billion USD** in 2019. However, it slightly declined to **85,273 billion USD** in 2020, primarily due to the economic impacts of the COVID-19 pandemic. Similarly, global CO2 emissions increased during this period. In 1990, emissions were approximately **21,284 million tones** and peaked at **35,606 million tons** in 2018. In 2020, a significant decrease was observed, with emissions dropping to **33,566 million tons**, largely due to reduced industrial activities and transportation caused by the COVID-19 pandemic. In parallel, the global population grew steadily, rising from **5.29 billion** in 1990 to **7.82 billion** in 2020. This demographic increase exerted greater pressure on natural resources, which in turn contributed to the rise in CO2 emissions.

The urban population experienced a significant increase as a percentage of the total population. According to World Bank data, the proportion of people living in urban areas is a key indicator for assessing a country's urban development. Over the past decades, the number of urban inhabitants grew steadily, with an average annual increase of **2.5%** between 1990 and 2020 (World Bank, 2021).Economic growth has been accompanied by substantial industrial expansion, which requires significant amounts of energy and directly contributes to greenhouse gas emissions For instance, industrial activity has experienced an average annual growth rate of **3.8%** over the past decade, closely aligned with the increase in the urban population (World Bank, 2021; International Energy Agency, 2021). the following table presents the growth rates of the study's variables, enabling annual comparisons across four distinct periods:**1990–1999**, **2000–2009**, **2010–2019**, and **1990–2020**. This segmentation facilitates the evaluation of economic and environmental trends over time.

**Table 1. Growth rate of model variables, 1990–2020**

| Période | Urbanization (URB %) | GDP%) | CO2 emissions(%) | Global Population (Pop%) | Industrie (IND%) |
|---|---|---|---|---|---|
| 1990-1999 | 0,76 | 4,34 | 1,06 | 1,45 | -1,66 |
| 2000-2009 | 0,94 | 7,94 | 2,45 | 1,21 | -0,26 |
| 2010-2019 | 0,78 | 3,22 | 1,05 | 1,05 | 0,07 |
| 1990-2020 | 1,01 | 9,17 | 1,92 | 1,92 | -0,64 |

**Source: Authors based on World Bank data, 1990-2020**

Table 1 reveals significant trends in global GDP, CO2 emissions, and population growth over the period 1990–2020.

Global GDP grew at an average annual rate of 9.17%, reflecting consistent economic expansion despite periods of fluctuation, notably during the 2008–2009 global financial crisis. However, global CO2 emissions also increased, albeit at a slower average annual rate of 1.92%, underscoring the environmental challenges associated with economic growth.

The global population grew steadily, with an average annual growth rate of 1.59%, placing sustained pressure on natural resources and indirectly contributing to the rise in CO2 emissions.

The urbanization also advanced, with an average annual growth rate of 1.01% over the period. This trend highlights the ongoing shift toward urban living, fueled by migration to cities, infrastructure development, and industrialization in emerging economies. While urbanization plays a pivotal role in driving economic growth, it also leads to increased demand for energy, transportation, and infrastructure, thereby contributing to higher CO2 emissions.

In 2009, the global economic crisis caused a notable decline in GDP, accompanied by a temporary reduction in CO2 emissions. This illustrates the close relationship between economic activity and emissions, where a slowdown in the economy often results in reduced emissions. While global economic growth during this period has been remarkable, it has been accompanied by significant environmental challenges, particularly the increase in CO2 emissions. Managing these emissions is a critical priority to ensure sustainable development in the long term.

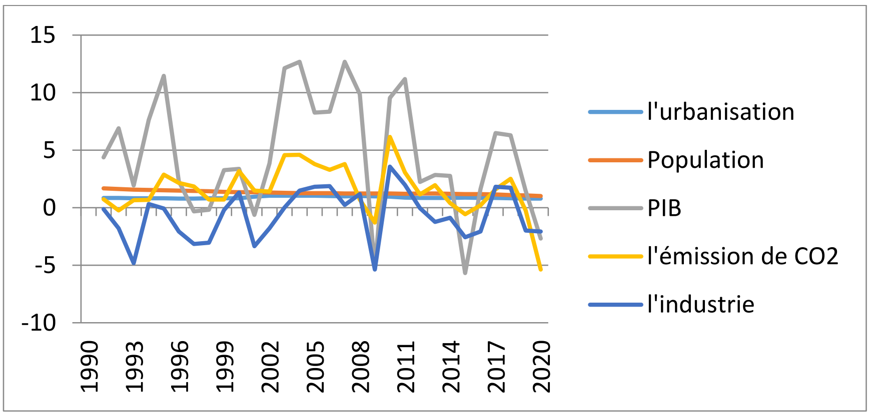

**Figure 1: Global GDP and urban planning and global CO2 emissions between 1990 and 2020**

**Source: Authors based on World Bank data, 1990-2020**

Figure 1 illustrates the relative contributions of GDP, CO2 emissions, and population growth to a variable of interest, expressed as percentages, over the period 1990–2020. Between 2005 and 2010, rapid economic expansion, particularly in developing countries, fueled GDP growth but also led to increased CO2 emissions due to accelerated industrialization and urbanization. Post-2010, GDP volatility reflects the lingering effects of the 2008 financial crisis and shorter economic cycles. In 2020, the COVID-19 pandemic caused a global economic contraction, significantly reducing CO2 emissions but also resulting in widespread job losses and a global recession. According to the Global Carbon Project (2020), fossil fuel-related CO2 emissions dropped by **7%** in 2020 due to lockdown measures associated with the pandemic.

Population growth, by contrast, demonstrated a stable but limited contribution, indicating that demographic changes have a less direct impact on short-term economic and environmental fluctuations. However, their long-term influence remains critical, particularly in driving demand and exerting pressure on environmental resources.

The urbanization rate exhibited a consistently increasing trend worldwide, underscoring its pivotal role in shaping both economic growth and environmental pressures. Urbanization remains a key factor influencing energy demand, infrastructure development, and CO2 emissions on a global scale.

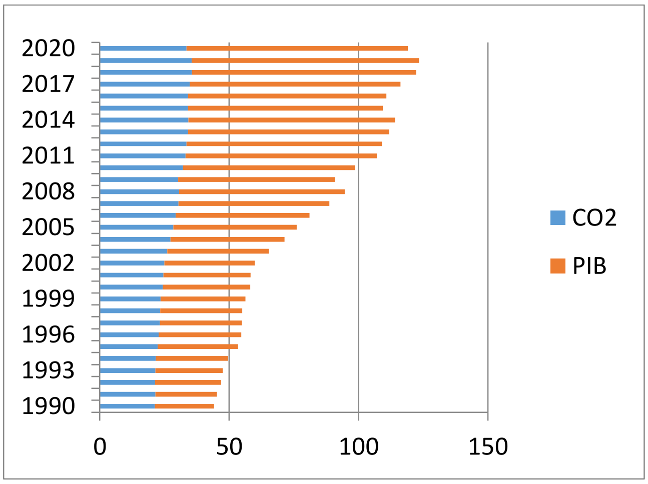


**Figure 2. Comparison of global GDP and CO2 emissions, 1999-2020**

**Source: Authors based on World Bank data, 1990-2020**

Figure 2 illustrates the sustained growth of global GDP and CO2 emissions over the period 1990–2020. Global GDP increased significantly, while CO2 emissions also rose, albeit at a slower pace. This trend indicates an improvement in energy efficiency, whereby economic output increased more rapidly than emissions, demonstrating the capacity of the global economy to generate greater value with proportionally smaller increases in environmental impact. However, the **2008–2009 financial crisis** resulted in a temporary contraction in GDP and a stabilization of CO2 emissions, underscoring the direct relationship between economic activity and emissions levels. This correlation highlights the extent to which fluctuations in economic performance influence environmental outcomes, with reduced economic activity typically leading to a decline in emissions.

## Econometric Methods

In the context of economic and environmental studies, it is crucial to understand the dynamics that link economic growth, demography and CO2 emissions, particularly on a global scale. The Vector Error Correction Model (VECM) is an adequate econometric method for analyzing these complex interactions. By taking into account long-term relationships and short-term adjustments between variables, the VECM explores how global GDP and global demography influence CO2 emissions..

The application of the VECM model requires several key methodological steps which are as follows:

**Step 1: Unit Root Test**

The unit root test is a statistical procedure used to evaluate the stationary of a time series. Stationary means that the statistical properties of the series, such as mean and variance, remain constant over time. If a time series is no stationary, this may indicate the presence of a unit root, suggesting that a shock or disturbance in the series will have a lasting effect.

There are several tests to detect the presence of a unit root, among which the augmented Dickey-Fuller test (ADF), the Phillips-Peron test (PP) and the Kwiatkowski-Phillips-Schmidt-Shin test (KPSS), the test (ADF) is the most commonly used.

The main challenge of the unit root test is to ensure that econometric models applied to a non-stationary data series will produce reliable results. In case of no stationary, the series can be transformed into a stationary series by taking the difference between successive observations, a method known as differentiation. The Augmented Dickey-Fuller (ADF) unit root test is used to determine whether a series is stationary or not, that is, whether its statistical properties, such as mean and variance, are constant over time. In most cases, economic series such as GDP and CO2 emissions are not stationary in level but become so after taking their first differences. If all variables are no stationary but integrated of the same order (e.g., I(1)), this opens the way to the examination of counteraction.

**Step 2: Counteraction Testing**

Once the stationary of the series is confirmed, the second step is to check if there is a counteraction relationship between the variables. counteraction indicates that there is a long-term equilibrium relationship between variables, even though they may deviate from this equilibrium in the short term. The Johansen test is widely used in this context. This test is used to determine the number of counteraction relationships between the variables studied. The application of the Johansen test is crucial, as it informs whether or not there are stable long-term relationships between global GDP, global demography, CO2 emissions, urbanization and industry.

**Step 3: Johansen test**

The results of the Johansen test determine the further analysis. If the test reveals the presence of one or more counteraction relationships, it means that there are long-term dynamic relationships between the variables. The VECM can then be used to model these relationships, while capturing the short-term adjustments needed to maintain long-term equilibrium. The coefficients of the adjustment matrix in the VECM indicate how well and how quickly the variables respond when there is a long-term imbalance.

On the other hand, if the Johansen test does not detect counteraction, it suggests that there is no long-term relationship between the variables. In this case, the error-free Vector Auto Regressive (VAR) model can be used to explore only the short-term relationships between variables. It is therefore important not to confuse a lack of counteraction with a total absence of relationship between variables, because a short-term dynamic may still exist.

**Step 4: Granger Causality Test**

To complete the analysis, it is essential to examine the direction of causation between the variables, which can be achieved using the Granger causation test. This test is used to determine whether a variable can be considered a cause in the Granger sense of another variable. For example, the test could reveal whether global GDP "causes" CO2 emissions, or whether population growth "causes" or urbanization "causes" an increase in CO2 emissions. This causality analysis is crucial to understanding not only the correlation between the variables, but also the direction of the influences between them. Tape 5 : Model VECM

The VECM model allows for both long-term relationships and short-term adjustments between economic and environmental variables such as CO2 emissions, GDP, demographics, and urbanization. This model is distinguished by the introduction of the error correction term (ECM), which captures deviations from long-run equilibrium and allows variables to adjust over time.

**Long-term equation:** The long-term equation shows the relationship between CO2 emissions and economic variables such as GDP, demographics and urbanization, and industry. This equation captures the long-term dynamics between these variables, explaining their co-integration over time

**Eq. 1** $CO2 = \alpha_0 + \alpha_1 * GDP + \alpha_2 * \text{POPs} + \alpha_3 * URB + \alpha_4 * IND + \varepsilon$

**Short-term equation**: The short-term equation takes into account immediate adjustments in CO2 emissions in response to changes in GDP, demographics, industry and urbanization. The error correction term (ECM) is included to capture deviations from long-term equilibrium.

**Eq.2:** $\Delta CO2(t) = \alpha + \Sigma(i = 1, p)\lambda\text{i}\ \Delta\text{CO2 (t} - \text{i)} + \Sigma(j = 1, q)\beta j\ \Delta GDP(t - j) + \Sigma(k = 1, r)\delta k\ \Delta\text{POPs}(t - k) + \Sigma(l = 1, s)\gamma l\ \Delta URB(t - 1) + \Sigma(m = 1, t)\theta m\ \Delta IND(t - m) + \beta ECM\{\text{t} - 1\} + \varepsilon t$

## RESULTS AND DISCUSSIONS

### Unit Root Test

The analysis of the time series of the variables studied reveals that all are integrated of order 1 (I (1)), meaning that they are not stationary in level, but become so after a first differentiation. This means that these variables, namely CO2 emissions, GDP, population (POPs), urbanisation (URB) and industry (IND), change over time with an underlying trend, and their fluctuations can be stabilized by data transformation.

The following table reports the test results.

**Table 2. Order of integration of the variables studied**

| **Variables** | **Ordre d'intégration** | **Processus** |
|---|---|---|
| CO2 | I(1) | DS |
| PIB | I(1) | DS |
| POP | I(1) | TS |
| URB | I(1) | TS |
| IND | I(1) | DS |

**Source: Authors**

The results indicate that CO2 emissions (CO2), GDP and industry (IND) are processes that follow a simple difference (DS). This implies that these variables undergo variations that require differentiation to make them stationary, which is common in economic analyses, especially when the data are influenced by exogenous shocks or long-term economic trends. AS for population (POP) and urbanization (URB), these variables follow a stochastic trend (TS), which shows that their evolution is influenced by random factors and unpredictable trends. This suggests that these phenomena are subject to fluctuations not only due to economic variables, but also due to broader demographic and social dynamics

Thus, econometric modeling of these variables requires a tailored approach to capture both deterministic and stochastic trends, and to understand their interrelationships, they need to be deferred for modeling, These results provide a basis for assessing the impact of economic changes on CO2 emissions, as well as the interactions between them. To ensure an accurate specification of our model, it is essential to determine the optimal delay lengths (p), which are identified using several criteria: the modified LR sequential test, the final prediction error (FPE), the Akaike information criterion (AIC), the Schwarz information criterion (SC), and the Hannan-Quinn information criterion (HQ). The number of delays retained is therefore P=2 (Table 3).

**Table 3. Determination of the optimal length of lags .**

| Lag | LogL | LR | FPE | AIC | SC | HQ |
|---|---|---|---|---|---|---|
| 0 | -310,1569 | NA | 4113,261 | 22,51120 | 22,74910 | 22,58393 |
| 1 | -48,91456 | 410,5236 | 0,000200 | 5,636754 | 7,064116 | 6,073113 |
| 2 | 16,62913 | 79,58877* | 1,33e-05 | 2,740776 | 5,357606* | 3,540767 |
| 3 | 55,19265 | 33,05445 | 8,85e-06* | 1,771953* | 5,578252 | 2,935577* |

**Source: Authors**

## Johansen counteraction Test

The Johansen counteraction test was used to determine the existence of a long-term relationship between non-stationary variables. By identifying the number of possible counteraction relationships, this test can confirm whether the variables evolve together over the long term. The results are reported in Table 4

**Table 4. Results of Johansen counteraction Test**

| **Hypothesized** | | **Trace** | **0.05** | |
|---|---|---|---|---|
| No. of CE(s) | Eigenvalue | Statistic | Critical Value | Prob.** |
| None * | 0,886210 | 144,4852 | 69,81889 | 0,0000 |
| At most 1 * | 0,653539 | 83,62994 | 47,85613 | 0,0000 |
| At most 2 * | 0,608121 | 53,95036 | 29,79707 | 0,0000 |
| At most 3 * | 0,479256 | 27,71988 | 15,49471 | 0,0005 |
| At most 4 * | 0,286447 | 9,449958 | 3,841466 | 0,0021 |

**Source: Authors**

The Trace test shows the existence of five counteraction relationships between the variables CO2, PIB, IND, POP and URB. These relationships suggest that, over the long term, these variables are related and tend to evolve together, despite short-term fluctuations. This means that shocks affecting one variable could be absorbed by the others, thus maintaining equilibrium in the long run. This result is confirmed at the 5% threshold, as indicated by the successive rejections of the null hypotheses.

## Granger causality Test

The Granger causality test is used to check if variations in one variable influence those in another over time. By observing whether past values of one variable help predict those of another, this test provides an indication of the presence of a causal relationship between the two variables.

**Table 5. Granger Causality Test**

| **Null Hypothesis:** | **Obs** | **F-Statistic** | **Prob.** |
|---|---|---|---|
| IND does not Granger Cause CO2 | 29 | 1,93729 | 0,1660 |
| CO2 does not Granger Cause IND | | 1,27897 | 0,2966 |
| PIB does not Granger Cause CO2 | 29 | 3,86199 | 0,0351 |
| CO2 does not Granger Cause PIB | | 6,58841 | 0,0052 |
| POP does not Granger Cause CO2 | 29 | 0,31077 | 0,7358 |
| CO2 does not Granger Cause POP | | 7,31318 | 0,0033 |
| URB does not Granger Cause CO2 | 29 | 3,28889 | 0,0547 |
| CO2 does not Granger Cause URB | | 0,68388 | 0,5142 |
| PIB does not Granger Cause IND | 29 | 0,66764 | 0,5222 |
| IND does not Granger Cause PIB | | 1,61724 | 0,2193 |
| POP does not Granger Cause IND | 29 | 0,94769 | 0,4017 |
| IND does not Granger Cause POP | | 0,87528 | 0,4296 |
| URB does not Granger Cause IND | 29 | 0,87155 | 0,4311 |
| IND does not Granger Cause URB | | 2,82979 | 0,0788 |
| POP does not Granger Cause PIB | 29 | 2,92185 | 0,0732 |
| PIB does not Granger Cause POP | | 1,37351 | 0,2724 |
| URB does not Granger Cause PIB | 29 | 4,21556 | 0,0270 |
| PIB does not Granger Cause URB | | 2,25508 | 0,1266 |
| URB does not Granger Cause POP | 29 | 2,37073 | 0,1149 |
| POP does not Granger Cause URB | | 9,01859 | 0,0012 |

**Source: Authors**

## Table 5 shows the following results

Relationship between industry (IND) and CO2 emissions: the data show that industry does not have a significant effect on CO2 emissions, and conversely CO2 emissions do not significantly influence the industry.

Bidirectional relationship between GDP and CO2 emissions: Data shows that GDP has a significant impact on CO2 emissions, indicating that economic growth influences emissions. Similarly, CO2 emissions have a significant influence on GDP.Unidirectional relationship between population (POPs) and CO2 emissions: Population does not have a significant impact on CO2 emissions. But the reverse is not true, since CO2 emissions have a significant influence on the population.

Non-existent relationship between urbanization (URB) and CO2 emissions at the statistically significant level: the data revealed that urbanization has an almost significant influence on CO2 emissions, although not confirmed at the 5% threshold, while CO2 emissions have no significant effect on urbanization

Non-existent relationship between GDP and industry: The data indicate that GDP does not have a significant influence on industry, nor does industry have a significant effect on GDP

Non-existent relationship between population and industry: Population does not have a significant effect on industry. The industry also does not have a significant impact on the population

Non-existent relationship between urbanization and industry: Urbanization has no significant influence on industry, and industry has a marginal, but not significant, influence on urbanization. Relation

Unidirectional between population and GDP: Population has an almost significant influence on GDP, but it remains marginal. While the reverse is not true, GDP does not have a significant impact on the population..

Unidirectional relationship between urbanization and GDP: Urbanization has a significant effect on GDP, suggesting a positive influence of urbanization on economic growth. On the other hand, GDP does not have a significant impact on urbanization

Unidirectional relationship between urbanization and population: Urbanization does not significantly influence population. In contrast, population has a significant effect on urbanization, indicating that population growth contributes to the urbanization process.

In conclusion, there is a bidirectional relationship between GDP and $CO_2$ emissions. Additionally, unidirectional relationships are observed in the influence of GDP, population, and urbanization on $CO_2$ emissions, as well as between population and urbanization.

*VECM Model Estimation*

The VECM was estimated in order to model the dynamic relationship between the variables CO2, GDP, population (POPs), urbanization (URB) and industry (IND). This model (Eq 1 and Eq 2) captures both short-term effects (via the first differences) and adjustments towards long-term equilibrium (via the counteraction term).

The long-term relationship of the model is expressed as follows:

**Equation 3:** $D(CO2) = -0{,}8425 * (CO2(-1) + 1{,}5109 * IND(-1) - 0{,}0003 * GDP(-1) + 8{,}3808 * POPs(-1) - 0{,}3675 * URB(-1) - 89{,}7520 + \sum\big(C(i) * D(Variable_i)\big) + 24{,}3619$

Equation 3 shows how CO2 emissions evolve as a function of the lags of the other variables and their own lags, while accounting for the long-term imbalance captured by the counteraction term. The force back to long-run equilibrium is -0.8425, a negative and significant coefficient (p = 0.0011), which indicates that the model effectively corrects for long-run imbalances: deviations from this equilibrium are adjusted at a rate of 84.25% per period.

The coefficients associated with industry are positive and significant (C(4) = 0.9914, p = 0.016 and C(5) = 0.8302, p = 0.0303), suggesting that changes in industrial activity have a significant impact on CO2 emissions in the short term, reflecting the direct effect of industrial production on greenhouse gas emissions.

The coefficient C(6), relative to GDP with a delay of one period, is negative and significant (C(6) = -0.000167, p = 0.0324), indicating that economic growth leads to a small reduction in CO2 emissions in the short term, although this effect is small. Moreover, the coefficient C(8) = 304.2594 is significant (p = 0.0056), showing that population growth has a significant effect on CO2 emissions in the short term.

However, some coefficients, such as those related to urbanization (C(10), C(11)) and some lagging GDP (C(7)), are not statistically significant, suggesting that their short-term effects on CO2 emissions are more limited.

The model is generally acceptable, as shown by the adjustment statistics (adjusted $R^2$), the information criteria (AIC and SC) and the F statistic. The adjusted $R^2$ of 0.5371 indicates that the model explains about 53.7% of the change in CO2 emissions, an acceptable level given the complexity of the economic and environmental interactions. The Akaike Information Criterion (AIC) is 1.5808 and the Schwarz Criterion (SC) is 2.1518, which shows a good balance between fit and complexity. Finally, the F statistic of 3.8482, with a probability of 0.0075, confirms the overall significance of the model

In the short term, CO2 emission adjustments in response to changes in other variables are captured by the following equation:

**Equation 4**: $D(CO2_t) = -0{,}8425 * (CO2_{\{t-1\}} + 1{,}5109 * IND_{\{t-1\}} - 0{,}0003 * GDP_{\{t-1\}} + 8{,}3809 * POP_{S\{t-1\}} - 0{,}3675 * URB_{\{t-1\}} - 89{,}7520) + \sum \left(\mathrm{C(i)} * \mathrm{D}\left(\mathrm{Variable}_{\{t-1\}}\right)\right) + 24{,}3619$

The results show that the different variables have significant and distinct effects on CO2 emissions in the short term, depending on the coefficients calculated. First of all, industry exerts a significant influence with coefficients of C(4)=0.9914 and C(5)=0.8302. This means that any increase in industrial activity leads to an immediate and significant increase in CO2 emissions. This relationship highlights the direct and substantial impact of industry on emissions in the short term.

The population has a particularly high coefficient of C(8)=304.2594, which underlines the major impact of population growth on CO2 emissions. This suggests that population growth is one of the main drivers of rising emissions in the short term, reflecting significant demographic pressure on the environment. Moreover, the effect of short-term GDP, although negative and significant, remains marginal (C(6) = -0.000167). This indicates that in the short term, a small reduction in CO2 emissions may be associated with economic growth, but this impact is marginal compared to that of industry and the population.

The long-run equation derived from the VECM model is as follows:

**Equation 5:** $CO2_t = -1{,}5109 * IND_{\{t-1\}} + 0{,}0003 * \mathrm{GDP}_{\{t-1\}} - 8{,}3809 * \mathrm{POP}_{s\{t-1\}} + 0{,}3675 * \mathrm{URB}_{\{t-1\}} + 89{,}7520$

In the long run, the interactions between variables are more stable and show differentiated tendencies. The coefficients associated with industry (-1.5109) and population (-8.3808) are negative, indicating an inverse long-term relationship, suggesting that increases in the industrial sector or in the population eventually have a negative effect on CO2 emissions. While the coefficients associated with urbanization (+0.3675) and global GDP (+0.0003) are positive, suggesting a positive effect of urbanization and economic growth on long-term C02 emissions.

It can therefore be seen that the VECM model estimate confirms the existence of important dynamic relationships between CO2 emissions and economic and demographic variables. The negative and significant error correction term (C(1) = -0.8425) validates the relevance of the model and shows that long-run imbalances are corrected quickly. Short-term variations in industry and population have a notable effect on $CO_2$ emissions, while the impact of GDP, while significant, and are smaller. This model can therefore be used as a basis for forecasting and analyzing environmental policies aimed at regulating $CO_2$ emissions according to economic and demographic dynamics.

The analysis conducted through the VECM has made it possible to identify the dynamics that link $CO_2$ emissions, GDP, population, urbanization and industry. This model revealed significant relationships between these variables, both in the short and long term, confirming their interdependence over time

*Validation of model*

The validation of the model goes through a number of tests, such as the homoscedasticity test, the normality test, and the residue autocorrelation test.

**Homoscedasticity Test**

The ARCH test is used to determine if the residuals are homoscedastic or heteroscedastic. Acceptance of the null hypothesis indicates that the residues are homoscedastic (Table 7).

**Table 7. ARCH Residue Test**

| | | | | |
|---|---|---|---|---|
| Heteroskedasticity Test: ARCH | | | | |
| | | | | |
| F-statistic | 0,639574 | Prob. F(1,25) | | 0,4314 |
| Obs*R-squared | 0,673510 | Prob. Chi-Square(1) | | 0,4118 |
| | | | | |

**Source: Authors**

Table 7 shows that the null hypothesis of homoscedasticity of residues is accepted at the 5% threshold (P-value = 0.4118).

**Residue normality test**

The Jarque-Bera (JB) test is applied to verify the normality of the residues (Table 8)

**Table 8. The Jarque-Bera Test on residues**

| Component | Jarque-Bera | Def. | Prob. |
|---|---|---|---|
| **1** | 0,475163 | 2 | 0,7885 |
| **2** | 1,985917 | 2 | 0,3705 |
| **3** | 2,747886 | 2 | 0,2531 |
| **4** | 1,757881 | 2 | 0,4152 |
| **5** | 0,783161 | 2 | 0,6760 |
| **Joint** | 7,750008 | 10 | 0,6532 |

**Source: Authors**

The probability of JarqueBera is equal to 0.653 which is much greater than 0.05. Therefore, the null hypothesis of the normality of the residuals is accepted at the 5% threshold. Test autocorrelation des residua

The Lagrange Multiplier (LM) test is used to validate whether or not there is no autocorrelation between the residuals.

**Table 9. Residue Autocorrelation Test (LM)**

| Lag | LRE* stat | df | Prob. | Rao F-stat | Df | Prob. |
|---|---|---|---|---|---|---|
| 1 | 17,12360 | 25 | 0,8773 | 0,606401 | (25. 27,5) | 0,8944 |
| 2 | 18,84251 | 25 | 0,8046 | 0,683290 | (25. 27,5) | 0,8298 |
| 3 | 22,49244 | 25 | 0,6072 | 0,858240 | (25. 27,5) | 0,6482 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | 19,92332 | 25 | 0,7508 | 0,733401 | (25. 27,5) | 0,7812 |
| 5 | 28,98073 | 25 | 0,2647 | 1,212678 | (25. 27,5) | 0,3102 |
| 6 | 23,57653 | 25 | 0,5439 | 0,913435 | (25. 27,5) | 0,5882 |
| 7 | 39,84515 | 25 | 0,0303 | 1,955563 | (25. 27,5) | 0,0446 |
| 8 | 24,57213 | 25 | 0,4865 | 0,965495 | (25. 27,5) | 0,5330 |
| 9 | 33,85642 | 25 | 0,1110 | 1,520635 | (25. 27,5) | 0,1427 |
| 10 | 15,57386 | 25 | 0,9269 | 0,539924 | (25. 27,5) | 0,9378 |
| 11 | 29,34278 | 25 | 0,2498 | 1,234246 | (25. 27,5) | 0,2946 |
| 12 | 26,82282 | 25 | 0,3648 | 1,088196 | (25. 27,5) | 0,4127 |

**Source: Auteurs**

Table 9 shows p-values greater than 5% for all delays from 1 to 12, which confirms the hypothesis of no autocorrelation between the residuals.

Conclusion

The results obtained clearly show that industry and population have a decisive effect on CO2, both in the short and long term. In the short term, these tow variables play a dominant role in the evolution of emissions, while in the long term, their influence tends to diminish due to economic and technological adjustments. The urbanization and GDP have a moderate but positive impact on long term emission, indicating a complex relationship between economic growth, urban development and greenhouse gas emissions.

These results offer important perspectives for implementation policies. The necessity to regulate industrial sectors and to provide measures adapted to demographic growth is crucial for containing $CO_2$ emissions in the short term. In the long term, the focus must be on innovation and energy efficiency to reduce the impact of economic and demographic activities on the environment.

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