



Breaking the unsustainable paradigm: exploring the relationship between energy consumption, economic development and carbon dioxide emissions in Ecuador

Jennifer Borja-Patiño¹  · Andrés Robalino-López^{1,2}  · Angel Mena-Nieto^{3,4} 

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Abstract

Energy consumption is a crucial driver for economic development, improving the quality of life of the population of a country. This study attempts to contribute to the discussion by employing a systemic approach and methodology to examine the relationship between energy consumption (EC), gross domestic product (GDP) and carbon dioxide emissions (CO₂) in Ecuador using time series from 1990 to 2018 with a mixed methodology (quantitative and qualitative). The energy balance and the enlarged Kaya identity are utilised to quantify the environmental impact of human activities. Furthermore, correlational cointegration and Granger causality tests are used to analyse the long-term and short-term relationships between variables in different sectors. The results reveal that there is no Granger causality between the variables in the agriculture and transport sectors, but there are unidirectional causality relationships in the industry and services sectors. In the industry sector, the study finds that EC Granger causes GDP (Wald test p value = 0.0038) and CO₂ Granger causes GDP (Wald test p value = 0.0433). In the services sector, GDP Granger causes CO₂ (Wald test p value = 0.0075), and EC Granger causes CO₂ (Wald test p value = 0.0122), reinforcing the loop between GDP and CO₂ in both the sectors. The analysed relationships help to inform policymakers about the likely impact of interventions. In addition, the study shows that Ecuador is in the initial phase of the Environmental Kuznets Curve, and provides strategies to manage sectoral energy consumption and valuable insights for other developing countries in Latin America seeking to pursue sustainable development.

Keywords Energy consumption · CO₂ emissions · Economic development · Granger causality · Kaya identity · Ecuador

Introduction

There is an inseparable link between economic development and energy consumption (EC); it has significant policy and geopolitical implications intersecting with future energy demand, economic growth and climate change (Howarth et al. 2017). This paper aims to contribute to the sustainable development of developing countries, focussing on Ecuador, a country recognised worldwide for its rich biodiversity (MAATE 2016). In this context, it is intended to urge policymakers to consider the importance of economic development with environmental sustainability by understanding the existing short- and long-term relationships between economic growth (GDP), energy consumption and CO₂ emissions, and also contributing to the fulfilment of the United Nations' Sustainable Development Goals, particularly Goal 7: Affordable and Clean Energy, and Goal 13: Climate Action (United Nations: Department of Economic and Social Affairs 2022).

Handled by So-Young Lee, Institute for Global Environmental Strategies, Japan.

✉ Angel Mena-Nieto
mena@uhu.es

Jennifer Borja-Patiño
jennifer.borja@epn.edu.ec

Andrés Robalino-López
andres.robalino@epn.edu.ec

¹ Departamento de Estudios Organizacionales y Desarrollo Humano, Escuela Politécnica Nacional, Quito, Ecuador

² Departamento de Economía, Universidad Técnica Particular de Loja, Loja, Ecuador

³ Department of Electrical and Thermal Engineering, Design and Projects, University of Huelva, Huelva, Spain

⁴ Centre for Advanced Studies in Physics, Mathematics and Computation, University of Huelva, Huelva, Spain

This link has been widely studied in recent decades, becoming one of the most critical topics in energy economics (Kaya et al. 2019; Durusu-Ciftci et al. 2020; Le 2020; Ortega-Ruiz et al. 2020). Social and economic activities depend on energy; human activities increase economic growth, while energy consumption stimulates these activities and generates carbon dioxide emissions (Basu et al. 2020; Rani et al. 2022). System Dynamics can represent those causal relationships through a positive feedback loop (Nwani 2017; Robalino-Lopez 2014; Robalino-López et al. 2014). Further, the Granger causality analysis can be applied to explore the possible causal relationships amongst energy consumption, CO₂ emissions and economic growth to improve environmental policies. However, previous studies on causality between energy consumption, CO₂ emissions and economic growth show different results (Kahia et al. 2019), which presumably come from the selection of countries, time and econometric methods of each country (Moya-Clemente et al. 2019; Le 2020; Wang et al. 2020a, b, c).

It is widely known that energy consumption is one of the factors that stimulates the economic development of countries, improving the living standards and quality of life of the inhabitants and offering a wide variety of uses in recent decades. As countries progress, their energy consumption increases, reinforcing the link between energy needs and economic development (Basu et al. 2020; González-Eguino 2015).

In Latin America, energy consumption increased at higher rates than economic growth (Hdom 2019). National official information (MEER 2017; MEM 2023; MIEM 2018) shows that in Ecuador, currently, fossil fuels continue to be the most important source of energy, with 83% in 2019. Consequently, 47% of the country's greenhouse gas (GHG) emissions correspond to this sector, which focuses its concern on the amount of GHGs resulting from the use of vehicles.

Latin American increases in production are still associated with increased environmental pollution and global warming, particularly with increased carbon dioxide emissions (CO₂), which should decrease when the economies reach a higher level of development (KoengKan et al. 2022; Raihan and Tuspekova 2022). The case study of Ecuador is important mainly because 20% of the national territory corresponds to protected areas such as the Galapagos Islands or the Yasuní National Park, unique sites in the world for their invaluable and endemic biodiversity. Under this context, the 2008 Constitution was the first in the world to recognise the rights of ecosystems (TCELDF 2011). According to the IPCC report, energy remains the primary contributor to global anthropogenic greenhouse emissions due to its role in economic development. Still, global warming is a major problem faced by all humanity, and emission reduction has become a significant challenge for sustainable development in the future (Allen et al. 2020; Chiu and Lee 2020; Wang et al. 2022). The

Ecuadorian National Determined Contribution (NDC 2019) presents various goals for Ecuador to join the global fight to combat climate change according to its capabilities, like a reduction for 2025 of greenhouse gas emissions by 9% from the energy, industrial processes, waste and agriculture sectors, compared to the trend scenario (a 20.9% supported by international cooperation), and a 4% reduction in deforestation and land degradation. Further, Ecuador has committed to reducing an average of 6.5 million tons of emissions of carbon dioxide equivalent per year until 2025.

Ecuador's energy consumption refers to its productive sectors and the sources of energy consumption used in them. Studying the relationship between energy consumption, economic development and carbon dioxide emissions will place the stage of the Environmental Kuznets Curve (EKC) in which the country can be found according to its development. It allows for targeted improvements in sectors that have the most significant impact on the economy and require special attention to ensure sustainable development. Policymakers bear the primary responsibility for understanding and managing these complex phenomena, and several studies have highlighted the need for policymakers to have access to tools that foster sustainable growth (Khan et al. 2022a; Shahzad et al. 2022). Quantitative evidence is essential for developing reasonable policies at all levels. It is important to emphasise that quantification privileges the perspectives of those with the infrastructure, financial, professional and experienced resources to produce knowledge over those who do not have these resources (Rottenburg and Merry 2017). In addition, quantification and management technologies play an essential role in society due to the critical support they provide to decisions through criteria, indicators, methodologies, and necessary instruments in the technical advance and development process (Robalino-López et al. 2021). Amidst this context, the study aims to answer the following research question: what is the relationship between the variables associated with economic development, energy consumption and emissions in the short and long run? In addition, how can this knowledge influence policymakers in their decision-making process on energy policy?

The work is structured as follows: “Literature review” reviews the literature, “Methodology” presents the method and assumptions of the model, “Empirical results and discussion” provides statistical validation of the model and “Policy implications” presents the conclusions.

Literature review

Several studies related to energy consumption and economic development include the environmental axis through the CO₂ emissions variable. The approaches are diverse and include the study of cointegration techniques, causality

analysis, the use of theoretical frameworks of understanding such as the Kaya identity, the hypothesis of the Kuznets curve and complex adaptive systems, among others, to study the phenomenon and explain the relationship between variables (Dagher 2012; Dagher & El Hariri 2013; Shahzad et al. 2022; Udemba et al. 2023).

Khan et al. (2022b) employ long-run random effect generalised least squares (GLS), generalised least square mixed effect models (GLMM) and robust correlated panel corrected standard errors (PCSEs) to study trilemma energy balance, clean energy transitions and economic expansion of Switzerland, Sweden and Denmark, from 1990 to 2016. According to their findings, the trilemma of balancing energy needs, transitioning to clean energy sources, and preventing natural resource depletion benefits economic growth. However, the adoption of clean energy has a negative impact on economic growth. In addition, the study highlights that achieving the trilemma and transitioning to clean energy sources help promote environmental sustainability, while the depletion of natural resources harms the environment.

Khan et al. (2022a) investigate the relationship between energy policies, economic growth and environmental sustainability across various countries included in the SDGs Index 2021. Their findings show that global energy trilemma and innovative energy advancements positively impact both economic growth and environmental stability. However, investments in non-financial assets and energy consumption lead to economic growth but at the cost of environmental damage.

Sarwar et al. (2021) propose the analysis of the empirical relationship between the main objectives of sustainable development: economic growth, labour, capital, education, health and greenhouse gas emissions, using data from 179 countries divided into subcategories: income level, OECD level and regional level applying cross-sectional dependency test, panel unit root test, cointegration and causality test. The short-run empirics mention the significance of labour, capital and health in economic growth, whereas education and carbon emission were found insignificant. In the case of long-run analysis, labour, capital, education and carbon emissions tend to impact the economic growth of most countries positively.

Ortega-Ruiz et al. (2020) analyse and compare the driving forces of the carbon dioxide emissions of the six highest emitters of the world (China, the United States of America, the European Union, India, Russia and Japan), which are responsible for more than the 67% of the emissions, during the period 1990–2016. They apply an enlarged Kaya-LMDI decomposition, considering five driving forces and a Granger causality study. They find that economic growth has been the main driving force that increases CO₂ emissions and, to a much lesser extent, the increase in population. Their Granger causality analysis suggests that energy

intensity Granger causes GDP in the developed countries, also energy intensity Granger causes CO₂ emissions in half of the countries, and GDP Granger causes CO₂ emissions only in Japan. The methodology selected is the long-run panel causality analysis recommended by Canning and Pedroni (2008). Consistent causality results were found for 12 different panels in two demand models, and income causes per capita consumption in a Granger way.

A more detailed analysis proposed by Wang et al. (2020a, b, c) is the study of the causal relationships between CO₂ emissions and economic factors in China through the use of a vector autoregressive model and panel data analysis for 1997–2015, demonstrating unidirectional causal relationships between the variables studied, which allows the study to conclude that to reduce CO₂ emissions, China not only has to implement strategic regulatory policies but must also generate research, technological innovation, circular economy and sustainable development.

Pinzón (2018) studies the dynamics between energy consumption and economic growth in Ecuador. The study aims to determine the Granger causality link between Ecuador's economic growth and energy consumption by analysing aggregate and disaggregated data from 1970 to 2015. The study of energy consumption has focussed on two sources: hydroelectric consumption and fossil fuel consumption. The results show that energy consumption in Ecuador causes economic growth without a feedback effect and is caused directly or indirectly by the economic growth of the primary, secondary and tertiary sectors. In addition, oil consumption and hydroelectricity are the cause and consequence, respectively, of economic growth, and energy consumption and economic growth have a bidirectional causal relationship in the transportation sector.

Pablo-Romero and De Jesús (2016) proposed a panel analysis from 22 Latin American and Caribbean countries from 1990 to 2011 using the Kuznets curve, the Wooldridge test for autocorrelation, the Wald test for homoscedasticity and the Pesaran test for contemporaneous correlation for analysing economic growth and energy consumption that is commonplace. Energy consumption is taken as an indicator of environmental pressure, and the results show that the environmental energy Kuznets curve hypothesis is not supported for the region. There are notable differences between the economies analysed, but based on this methodology, it is possible to make recommendations for improving the policies of the countries studied (Alsaedi et al. 2022).

There are also two studies for Venezuela and Ecuador linked to the study of the relationships between economic growth and CO₂ emissions (Robalino-López et al. 2014, 2015). These studies explore if it is possible to stabilise CO₂ emissions under an assumption of rapid economic growth in the medium term, focussing on the detailed analysis of how the forces of the economy affect CO₂ emissions from 1980

to 2025, based on the methodology of using an extension of the Kaya identity and GDP formation including the effect of renewable energies. The Kuznets curve is tested in several scenarios considering past data and also the projection of the different scenarios using cointegration techniques. The results show that in both Ecuador and Venezuela, the EKC hypothesis is not fulfilled; however, the countries could be on the way to reaching environmental stabilisation in the medium term, which can be achieved if economic growth is combined with the use of renewable energies, appropriate changes in the energy matrix and the structure of the productive sector (Robalino-López et al. 2014, 2015). As a further step, a System Dynamics model for renewable energy and CO₂ consumption is proposed for Ecuador, with the main objective of showing how the change in the energy matrix and GDP affects CO₂ emissions, with particular attention to the reduction of fossil fuels focussing on a variation of the Kaya identity and GDP that depends on renewable energy, which allows the introduction of a feedback mechanism in the model (Robalino-López et al. 2014). In addition, it has been widely demonstrated that the use of fossil fuels causes negative effects on the quality of the environment, causing various diseases that increase the population's mortality rate (Godil et al. 2021).

Liddle and Lung (2015) study energy consumption and GDP causality. The study uses disaggregated data on final energy consumption and GDP for analysis in developed

and developing countries grouped into panels by similar characteristics. Production and demand patterns were examined in reduced form for the industrial and service/commercial sectors. Dagher and Yacoubian (2012) studied the dynamic causal relationship between energy consumption and economic growth in Lebanon over the period 1980–2009, based on a variety of causality tests, namely Hsiao, Toda-Yamamoto and vector error correction-based Granger causality tests. The study shows that energy is a limiting factor to economic growth in Lebanon. The confirmation of the feedback hypothesis from a policy perspective indicates that relying on policy instruments that restrict energy consumption is not advisable. Such measures may negatively impact economic growth, so alternative policy instruments should be considered. Causality and cointegration analysis have been widely used to evaluate the link between energy consumption and economic growth.

Based on the literature review summarised in Fig. 1, two significant research gaps were identified. The first is the scarcity of studies that detail the causal relationships between the variables of the Kaya identity for Ecuador, particularly in the last years. The second is that, to our knowledge, there is a non-existence of papers that study the Granger causal relationship between the driving forces of CO₂ emissions in Ecuador.

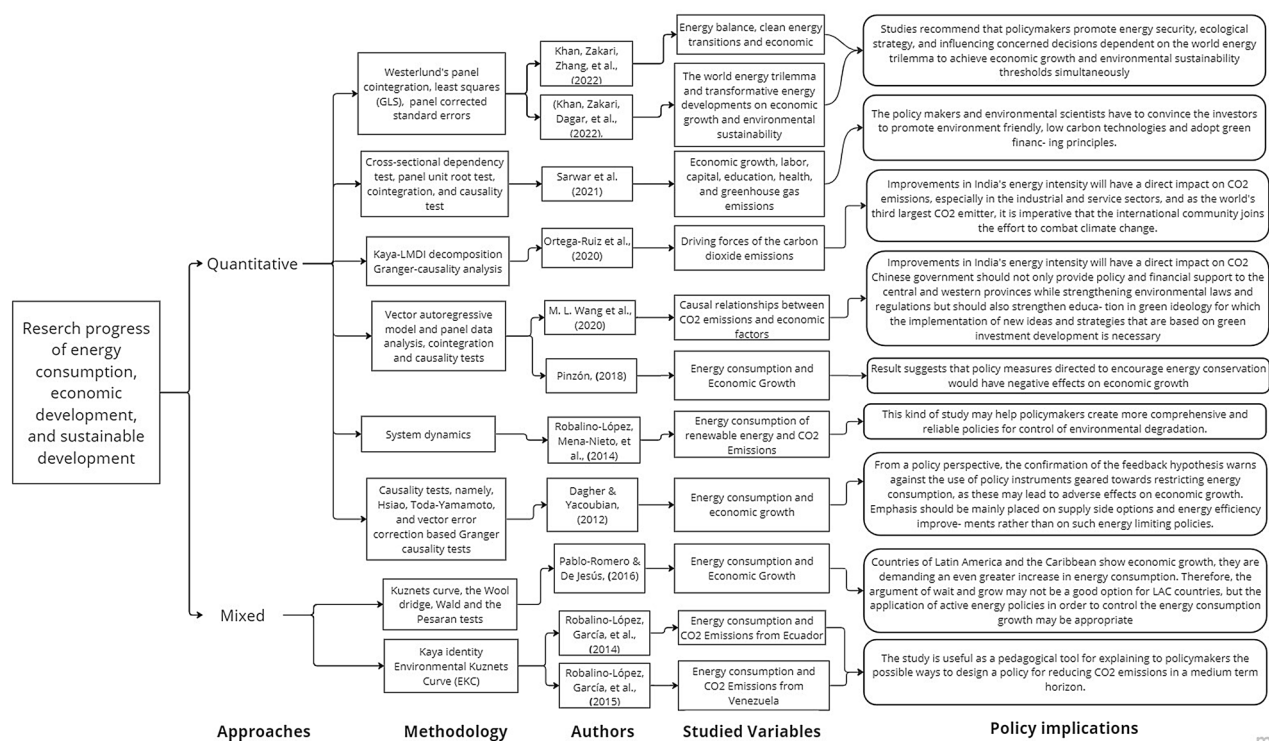


Fig. 1 Smart chart literature review

This paper aims to understand the statistical relationships between GDP, energy consumption and CO₂ emissions in the different economic sectors of Ecuador using a theoretical model to propose an empirical behaviour model that allows contextualising the state that sustains this country's current development. The following research questions (RQ) are raised:

- RQ1: What are the statistical relationships between GDP, energy consumption and CO₂ emissions in different sectors of Ecuador's economy, and how can these relationships inform improvement strategies?
- RQ2: How does Ecuador's economy fit into the Kuznets curve?

Therefore, this work contributes to the existing literature by providing a clearer view of the evolution of carbon emissions' driving forces over time and their relationships to Ecuador; based on an extension of Kaya Identity and the Granger causality study, this study provides critical indicators to design future mitigation policies for Ecuador.

Methodology

Data collected

Annual gross domestic product by economic activity at current prices in dollars was retrieved in the established time horizon (1990–2018) from CEPALSTAT (2019). Then, the energy consumption data were extracted from the database of the International Energy Agency World Energy Balances (2020). R Studio software was used to develop the study. Therefore, the primary analysis runs on 12 variables (sectoral GDP, sectoral energy consumption, sectoral carbon emissions), with a period of 29 years for a total of 348 observations.

The sectoral energy intensity, CO₂ emissions and CO₂ intensity calculations were performed, and the sectoral energy consumption databases and the IPCC emission factors table were consolidated. To complete the calculations focussed on the Kaya identity and the energy and environmental indicators analysis, correlational, cointegration and Granger Causality analysis were done. After all the studies were carried out, a deeper understanding was generated that has given way to the systematic modelling of the phenomenon through the conceptualisation of the system and the understanding of its relationships, which has resulted in an empirical model that explains the interaction of energy consumption, economic growth and CO₂ emissions by sectors in Ecuador (Fig. 2).

Modelling framework

The IPAT approach was also used as a proxy to understand the relationship of the study variables in a general way (Gutman and Gutman 2017) to determine the current behaviour (for 29 years from 1990 to 2018) of energy consumption by sectors in the Ecuadorian context. It is intended to comprehensively explain energy consumption patterns using a variation of the Kaya identity. This critical analysis allows one to consider the influence of five factors for the study of carbon emissions: global economic activities Q , the mix of economic activities by sector S_i , sectoral energy intensity EI_i , Energy Matrix M_{ij} and factors of CO₂ emission U_{ij} . In addition, two subcategories are also considered, corresponding to the economic sectors and the type of fuel (Robalino-López et al. 2014) (see Eq. 1):

$$C = \sum_{ij} C_{ij} = \sum_{ij} Q \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = \sum_{ij} Q \cdot S_i \cdot EI_i \cdot M_{ij} \cdot U_{ij}, \quad (1)$$

where C is the total CO₂ emissions, and C_{ij} is the CO₂ emissions from a type of fuel (j) in the economic sector (i). $S_i = Q_i/Q$; the ratio between sectoral GDP and total GDP, $EI_i = E_i/Q_i$; the ratio between sectoral energy consumption and sectoral GDP, $M_{ij} = E_{ij}/E_i$; the ratio between the energy consumption in ij (sector and type of energy) and the total energy consumption of the sector. i covers the four sectors: (1) agriculture, livestock, hunting, forestry and fishing sector; (2) industry sector; (3) transportation sector and (4) residential, commercial, and public services sector. j covers the type of energy: (1) natural gas; (2) renewables; (3) coal, peat and oil shale; (4) oil and its derivatives; (5) geothermal, solar, wind, heat, electricity, etc. $U_{ij} = C_{ij}/E_{ij}$; factors taken from IPCC (2006).

Each type of energy selected represents a group of fuels and the classification has been taken from energy balances (IEA 2020). According to the energy groups mentioned above, the environmental variable conversion factor has been determined, using the reference method of the 2006 IPCC Guidelines for National Greenhouse Gases Inventories (IPCC 2006), by averaging the group emission factors with a 95% confidence interval, taking the highest value of the fuels that emit carbon dioxide into the environment (natural gas, coal, peat and bituminous shale, oil and its derivatives). The units of kg/TJ were transformed into kg/ktOE. The group (renewable and geothermal, solar, wind, heat, electricity, etc.) does not emit CO₂ emission into the environment, following global energy balances (IEA 2020).

To complete the study, we prepared an analysis of the temporal evolution variables involved in energy consumption behaviour. Then, a correlational, cointegration and causal analysis of the variables was carried out for each economic and energy sector described for Ecuador. Following

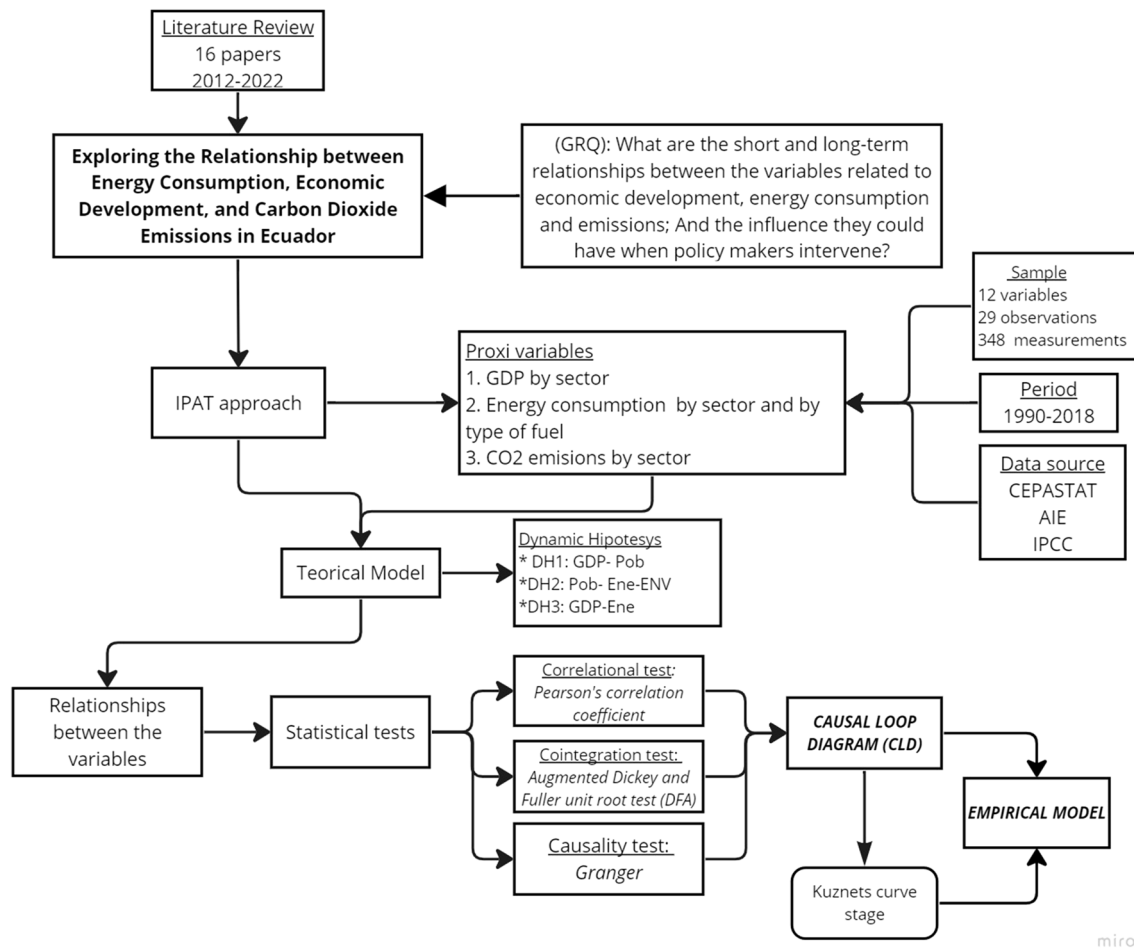


Fig. 2 Methodology chart

Robalino-López et al. (2014), the systemic approach is used. The energy consumption process is considered a development proxy for Ecuador in a study period from 1990 to 2018, considering the economic and energy consumption phenomena that have arisen in this time horizon.

The description of the process is given through the establishment of the dynamic hypotheses (DH):

- DH1: Economic development allows the population to obtain more and better goods and services that meet more sophisticated needs in pursuit of higher standards of living. Industries provide more products to meet these consumer demands, leading to an increase in energy consumption. Energy consumption stimulates economic development (GDP), and economic development (GDP) leads to increased energy consumption. It is reflected in the reinforcing loop “R1” (Chiu and Lee 2020; Malaquias et al. 2019; González-Eguino 2015; Jorgenson and Dietz 2015; Sadorsky 2010, 2011).
- DH2: Economic development and increased energy consumption negatively influence the population’s

life expectancy because new consumption habits have been promoted within society with a more significant environmental impact. Global warming caused by CO₂ emissions decreases the population growth rate. An economy with little technological capability and scarce human resources will not be able to take care of the environment, always subject to sustaining its growth through the intensive use of natural resources, which, together with cheap labour, are its source of international competitiveness. It is reflected in the “B” balance loop (Wang et al. 2020a, c; Alvarado et al. 2018; Vona et al. 2018; UN SDG 2002).

- DH3: Economic development increases the quality of life of the population. The increase in GDP positively impacts the population when it relates to good environmental practices and changes in the sectoral energy mix. Consequently, environmental degradation and GHG emissions are reduced. This guarantees adequate living conditions, so the population is not affected negatively. Economic development is enhanced. This is reflected in the reinforcing loop “R2” (Alsaedi et al. 2022; Alvarado

et al. 2018; Pablo-Romero and De Jesús 2016; Wang et al. 2020b, c)

Correlational test

The analysis through Pearson's correlation coefficient allows one to measure the linear association or line trend between two variables. It constitutes an overall measure of the degree to which the variation in one variable determines the variation in the other. However, this does not necessarily imply any cause–effect relationship (Gujarati and Porter 2010). This analysis is calculated from the scores obtained in a sample of two variables. Pearson's r coefficient can vary from: -1.00 = Perfect negative correlation to $+1.00$ = Perfect positive correlation (Hernández Sampieri et al. 2014), that is, if the correlation is negative, the relationship is inversely proportional, and if the correlation is positive, the relationship is directly proportional. Subsequently, the cointegration analysis is proposed through the Granger causality analysis between the variables $GDP \leftrightarrow EC$; $EC \leftrightarrow CO_2$ and $GDP \leftrightarrow CO_2$ to determine the relationship of the variables.

Cointegration tests

The cointegration test proposes the analysis of unit roots for which the logarithms of the variables have been taken. Cointegration analysis was performed using the Augmented Dickey and Fuller unit root test (DFA) (Pinzón 2018; Gujarati and Porter 2010). Cointegrating regressions of this type are estimated:

$$LGDP_t = \beta_1 + \beta_2 LECT_t + ut \quad (2)$$

$$LCO_2_t = \beta_1 + \beta_2 LECT_t + ut \quad (3)$$

$$LCO_2_t = \beta_1 + \beta_2 LGDP_t + ut, \quad (4)$$

where L stands for logarithm. β_1 is the regression intercept and β_2 the cointegrating parameter or coefficient of the regression. It is intended to verify that the residuals of regressions 1, 2 and 3 are stationary to prove cointegration. To prevent a spurious relationship, it is essential to mention that if the variables are non-stationary, then incorrect conclusions can be reached (Pinzón 2018; Gujarati and Porter 2010).

Using the R Studio software, the regression and residual models were obtained. The DFA test was applied, and for the residuals identified as non-stationary, the equation with the trend variable was re-estimated and verified using the DFA test. These tests were carried out to determine the long-term equilibrium relationship between the mentioned variables, which happens if the residuals are stationary, and there is cointegration.

The test has two hypotheses:

- H0: The errors of the series are non-stationary. Therefore, they are root-form processes and there is no cointegration.
- H1: The errors of the series are stationary. Therefore, they are not processed without unit roots and there is cointegration.

Then, the tau value and the critical value of each test are considered:

- Tau value < critical value rejects H0, accepts H1. Cointegrated variables
- Tau value > critical value rejects H1, accepts H0. Non-cointegrated variables

The values are tested at 1%, 5% and 10% confidence. If it is possible to establish stationarity, model 1 of cointegration is generated, which indicates that the variables are in equilibrium in the long term, going directly to model 3 of the error correction mechanism to couple the series to an equilibrium in the short term. If the series proves not to be stationary when performing the test, model 2 is generated adding the trend. It is necessary to estimate the equation again with the trend variable to create and apply the DFA test, verifying if it is possible to reach the stationarity of the series to confirm its cointegration.

The error correction mechanism (ECM) was carried out for the variables with long-term balance. This analysis seeks to correct the imbalance that may exist in the short term between the two variables (Liddle and Lung 2015). The error correction mechanism (ECM), first used by Sargan and later popularised by Engle and Granger, corrects the imbalance. An important theorem, the Granger representation theorem, states that if two variables, Y and X , are cointegrated, their relationship is expressed as MCE. Gujarati and Porter (2010) consider the following model:

$$\Delta LGDP_t = \alpha_0 + \alpha_1 \Delta LECT_t + \alpha_2 ut - 1 + \epsilon_t \quad (5)$$

$$\Delta LCO_2_t = \alpha_0 + \alpha_1 \Delta LECT_t + \alpha_2 ut - 1 + \epsilon_t \quad (6)$$

$$\Delta LCO_2_t = \alpha_0 + \alpha_1 \Delta LGDP_t + \alpha_2 ut - 1 + \epsilon_t, \quad (7)$$

where ϵ_t is a white noise error term, and $ut - 1$ is the lagged value of the error term of Eqs. (4), (5) and (6).

Equations (4), (5) and (6) establish a dependence on the variables and the term error. If the latter differs from zero, the model is not in equilibrium. Assume that $\Delta LECT$ is zero and that $ut - 1$ is positive. This means that $LGDP_t - 1$ is too high to be in equilibrium; that is, $LGDP_t - 1$ is above its equilibrium value ($\alpha_0 + \alpha_1 LECT - 1$). Since α_2

is expected to be negative, $\alpha_2 ut - 1$ is negative, and therefore, $\Delta LGDP_t$ will be negative to restore equilibrium. That is, if LEC_t is above its equilibrium value, it will begin to decrease in the following period to correct the equilibrium error, hence the name ECM. If $ut - 1$ is negative (that is, $LGDP_t$ is below its equilibrium value), $\alpha_2 ut - 1$ will be positive, which will cause $\Delta LGDP_t$ to be positive, which will cause $LGDP_t$ to increase in period t . Therefore, the absolute value of α_2 determines how quickly the equilibrium will be restored. In practice, $ut - 1$ is estimated by $\hat{u}t - 1 = (LGDP_t - \hat{\beta}_1 - \hat{\beta}_2 LEC_t - \hat{\beta}_3 t)$. The error correction coefficient α_2 is expected to be negative. This analysis seeks to determine the short-term balance of the variables and, therefore, the prediction of the behaviour of one over another (Alvarado and Toledo 2017; Liddle and Lung 2015; Engle and Granger 1987).

Granger causality test

Granger causality test has been carried out to determine the links and causal directions of the study variables, so that the question of whether the past values of a variable X can significantly explain the current values of another variable Y . If this is true, adding lagged values of X can improve the estimate of Y for future periods. Therefore, knowing that X Granger causes Y means that X helps significantly in predicting Y . The Granger test tests the null hypothesis of “Granger non-causality” (Pinzón 2018):

$$y_t = \alpha_0 + \alpha_1 y_{t-1} + \dots + \alpha_p y_{t-p} + \beta_1 x_{t-1} + \dots + \beta_p x_{t-p} + \varepsilon_t \quad (8)$$

$$x_t = \alpha_0 + \alpha_1 x_{t-1} + \dots + \alpha_p x_{t-p} + \beta_1 y_{t-1} + \dots + \beta_p y_{t-p} + \mu_t \quad (9)$$

Two hypotheses are raised:

- H_0 : (X) does not cause (Y)
- H_1 : (X) causes (Y)

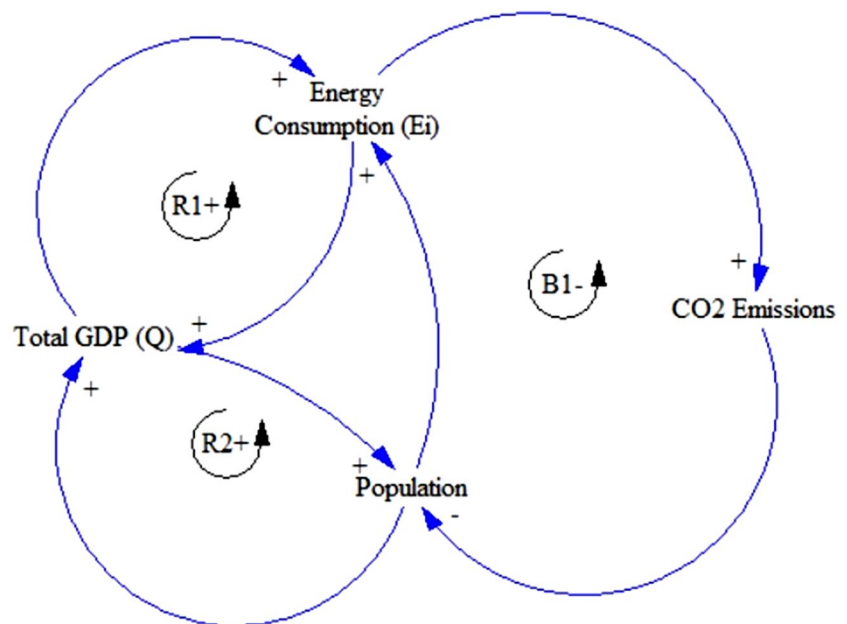
Finally, a comparative analysis is carried out between the theoretical model proposed through the System Dynamics methodology and the empirical model of the study.

Empirical results and discussion

Model context

In Ecuador, the sector with the highest contribution to GDP is the services sector, which has been increasing from the first study period 1990–1994 to the most recent 2015–2018. This is followed by the industry sector, which shows fluctuations and a not very accentuated growth during the study periods. For the third sector, we have the agriculture sector, which has a generalised tendency to decrease its participation in GDP, and the transportation sector, which shows minimal fluctuations without a significant change during the six study periods (see Fig. 3). Regarding energy consumption, the sector that occupies the most considerable amount of energy is the transportation sector, which accounts for more than 50% of total consumption. The agriculture sector has a minimum consumption of barely 3% (see Fig. 4). The sector with the

Fig. 3 Theoretical model adapted from Robalino-López et al. (2014) showing the relationship loops through dynamic hypotheses between the study variables



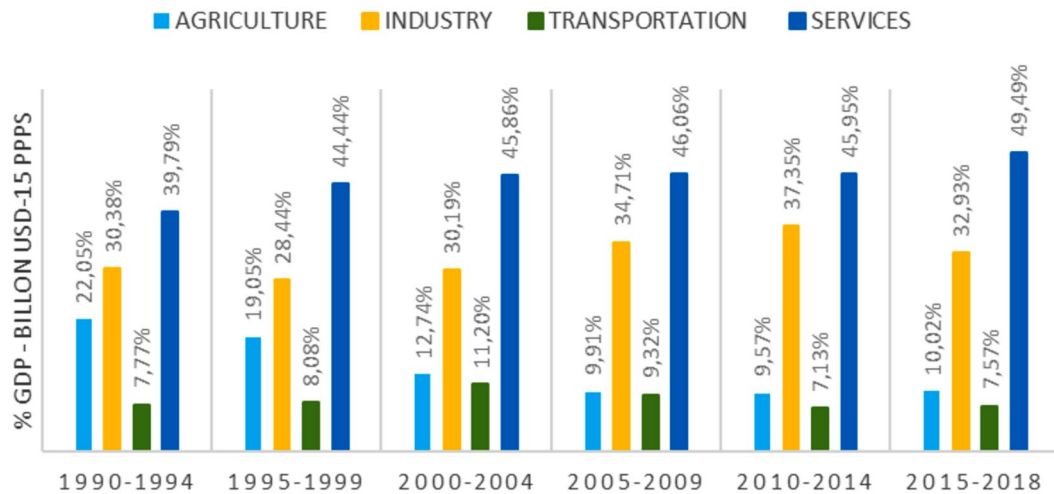


Fig. 4 Contribution to Ecuador's sectoral GDP (Billion USD, 2015 prices and PPPs). Data from CEPALSTAT (1990–2018)

highest energy intensity is the transportation sector, where the intensity shows a stable trend during the last study period (see Fig. 5).

The behaviour of sectoral emissions has maintained its pattern from 1990 to 2018, and the sector with the highest emissions is the transport sector (see Fig. 6).

Carbon intensity is directly related to the energy matrix. To verify how polluting the energy consumed is, the behaviour of carbon intensity has kept its pattern from 1990 to 2018, so the sector with the highest carbon intensity is the transportation sector, and the lowest is the services sector (see Fig. 7).

Statistical analysis results

Correlational test

The correlation analysis shows that all correlations are positive. They are directly proportional relationships, which show that if one variable increases, the other will also increase, and if they decrease, both will decrease proportionally (Fig. 8).

The agriculture sector has very weak positive correlations between GDP and EC and GDP and CO₂, which implies that the variation in GDP does not determine the variation in EC

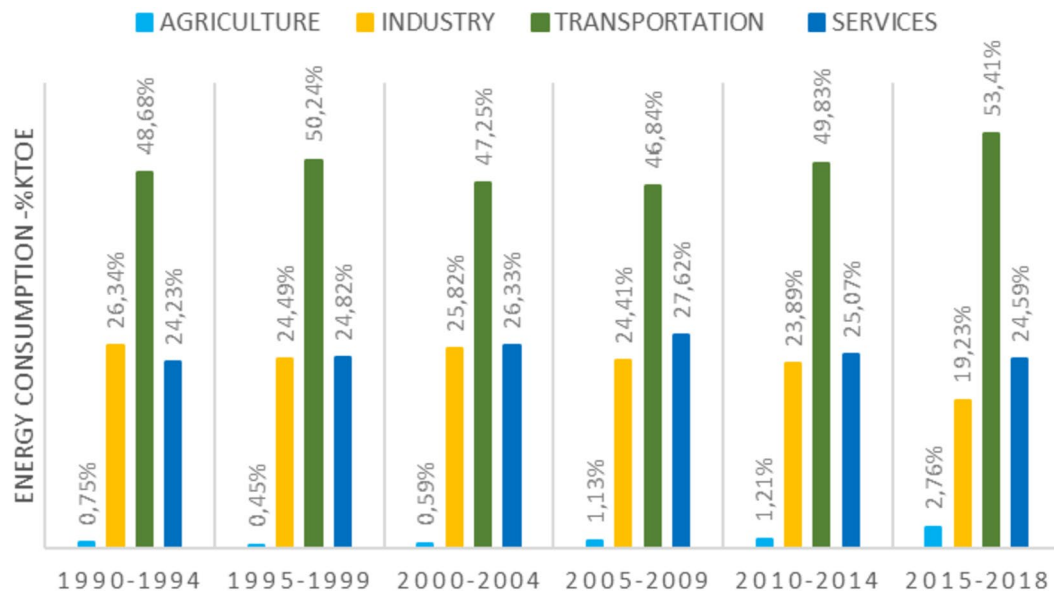


Fig. 5 Sectoral energy consumption in Ecuador (% Ktoe). Data World Energy Balances (1990–2018)

Fig. 6 Energy intensity (ktoe/GDP Billion USD, 2015 prices and PPPs) by sectors in Ecuador. The ratio of energy demand (consumption) per unit of economic output

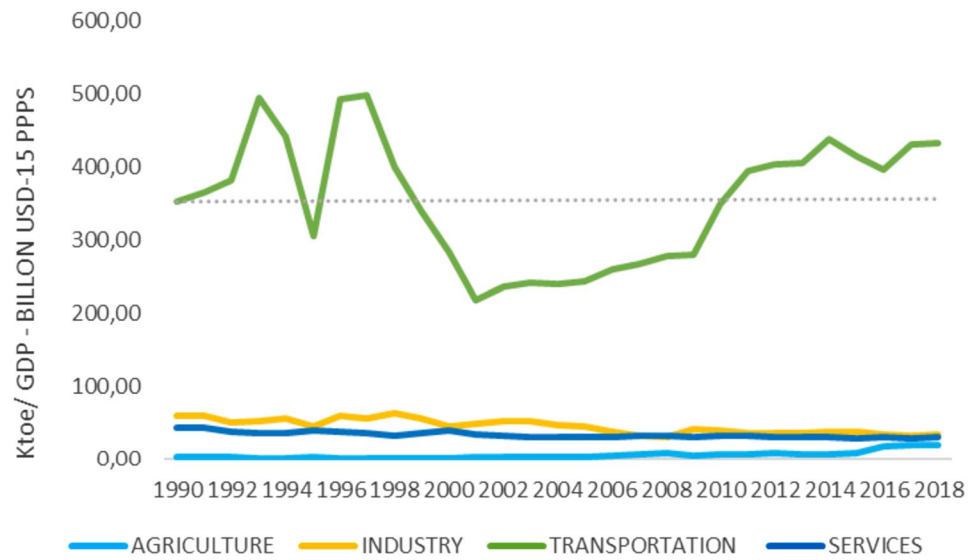


Fig. 7 Kilotons CO₂ emissions by sectors in Ecuador (Kt-CO₂). Kaya identity was applied to get the results (1990–2018)

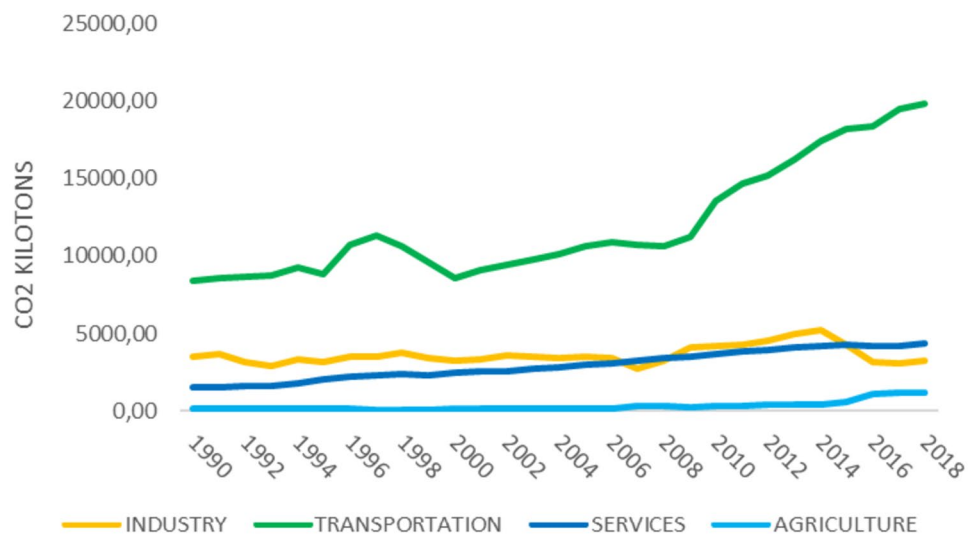
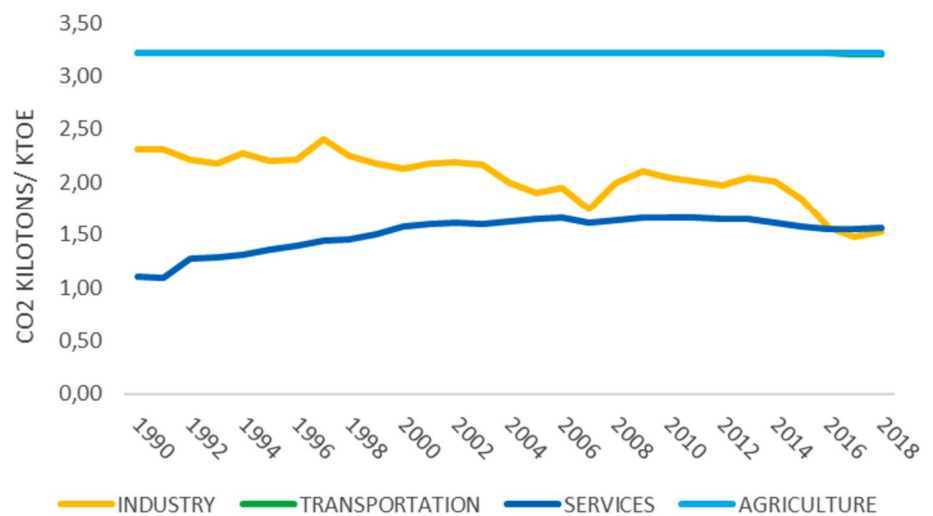


Fig. 8 Carbon intensity by sectors in Ecuador. Kaya identity applied to get the results Kt-CO₂/Ktoe (1990–2018)



or CO₂ emissions. The perfect positive correlation between EC and CO₂ indicates that the variation of EC strongly impacts the variation of CO₂ emissions.

The industry sector has three types of correlations: a very strong positive correlation between GDP and EC, where the variation of GDP has a high impact on the variation of EC. There is a considerable positive correlation between EC and CO₂, where the degree to which EC impacts CO₂ emissions is considerable, and a medium positive correlation between GDP and CO₂, where the degree of variation of one variable on the other is medium.

The transport sector has a medium positive correlation between GDP and EC and GDP and CO₂, where the degree of variation of GDP has a medium impact on EC and CO₂ emissions. It has a very strong positive correlation between EC and CO₂, where the degree of variation in EC strongly impacts CO₂ emissions.

The service sector has three very strong positive correlations, which indicates that the degree of variation of GDP determines a high degree of variation of both EC and CO₂ emissions, just as the EC variable determines the degree of variation of CO₂ emissions (Table 1).

Cointegration test

The agriculture sector has only one cointegration relationship proven from model 1, which is generated between the EC and CO₂ emissions variables. This indicates that these variables have a long-term equilibrium, i.e. they grow or decline in synchronicity. The industry sector has two cointegration relationships from model 1 between the variables GDP–EC and GDP–CO₂, showing equilibrium both in the long and short term for these variables. The transportation

sector has two cointegration relationships between the variables GDP–EC and GDP–CO₂, which are generated by performing the cointegrating regression with the trend variable, where the relationship was obtained both in the long term and in the short term. Finally, the services sector has the three cointegrating relationships GDP–EC and EC–CO₂ that are generated in model 1 of cointegrating regression and GDP–CO₂, which is generated in model 2 of cointegrating regression by adding the trend variable. Cointegration is identified in all the relationships of the sector. There is an equilibrium in the long term; however, equilibrium is not identified in the short term because the residual generated is positive (Table 2).

Granger causality test

The Granger causality analysis does not show causal relationships in any sense for the agriculture sector as well as for the transport sector. However, unidirectional causal relationships in the industry sector have been found. When the alternative hypotheses H1 are accepted, EC causes GDP, and CO₂ emissions cause GDP. When alternative hypotheses H1 are accepted in the services sector, GDP causes CO₂ emissions, and EC causes CO₂.

Granger causality is related to the predictive ability of one variable over another, indicating that past values of one variable, X , can significantly explain the current values of another variable Y (Gujarati and Porter 2010). The analysis shows that none of the relationships studied has a predictive capacity for the transport sector. For the industry and services sector, there are unidirectional predictive relationships (Table 3).

Table 1 Pearson correlational test

	GDP-A	GDP-I	GDP-T	GDP-S	EC-A	EC-I	EC-T	EC-S	CO ₂ -A	CO ₂ -I	CO ₂ -T	CO ₂ -S
GDP-A	1				0.17				0.17			
GDP-I		1				0.90				0.53		
GDP-T			1				0.61				0.61	
GDP-S				1				0.99				0.98
EC-A	0.17				1				1			
EC-I		0.90				1				0.78		
EC-T			0.61				1				0.99	
EC-S				0.99				1				0.98
CO ₂ -A	0.17				1				1			
CO ₂ -I		0.53				0.78				1		
CO ₂ -T			0.61				0.99				1	
CO ₂ -S				0.98				0.98				1

GDP-A gross domestic product agriculture, *GDP-I* gross domestic product industry, *GDP-T* gross domestic product transportation, *GDP-S* gross domestic product services, *EC-A* energy consumption agriculture, *EC-I* energy consumption industry, *EC-T* energy consumption transportation, *EC-S* energy consumption services, *CO₂-A* CO₂ emissions agriculture, *CO₂-I* CO₂ emissions industry, *CO₂-T* CO₂ emissions transportation, *CO₂-S* CO₂ emissions services. Blanks are omitted correlations not required for the analysis

Table 2 Cointegration test

Productive sector	Dickey and Fuller test	Variables	<i>t</i> statistic value	Critical values tau			Conclusion	Model 1	Model 2 with trend	Model error correction mechanism
				1%	5%	10%				
Agriculture	Test regression trend	GDP-A à EC-A	- 1.2202	- 4.15	- 3.5	- 3.18	No Cointegrated variables	N/A	N/A	N/A
		GDP-A à CO ₂ -A	- 1.2202	- 4.15	- 3.5	- 3.18	No Cointegrated variables	N/A	N/A	N/A
		EC-A à CO ₂ -A	- 4.2770	- 4.15	- 3.5	- 3.18	Cointegrated variables	LEC-A = -1.169e + 1.000eLCO ₂ -A	N/A	LEC = - 5.34e-17 + 1.0eLCO ₂ -A - 0.13e-01res
Industry	Test regression trend	GDP-I à EC-I	- 3.2979	- 4.15	- 3.5	- 3.18	Cointegrated variables	LGDPI = - 9.7383 + 1.7968LEC-I	N/A	LGDPI = 0.032 + 0.04LEC-I - 0.18res
		GDP-I à CO ₂ -I	- 3.3156	- 4.15	- 3.5	- 3.18	Cointegrated variables	LGDPI = - 5.185 + 1.084CO ₂ -I	N/A	LGDPI = 0.032 + 0.0024LCO ₂ -I - 0.18res
		EC-I à CO ₂ -I	- 1.9800	- 4.15	- 3.5	- 3.18	No Cointegrated variables	N/A	N/A	N/A
Transport	Test regression trend	GDP-T à EC-T	- 1.5945	- 4.15	- 3.5	- 3.18	No Cointegrated variables	N/A	LEC-T = 8.67 + (0.05485) + 0.87344LGDPI-T	LEC-T = 0.05 - 0.65LGDPI-T - 0.17res
		GDP-T à CO ₂ -T	- 1.5962	- 4.15	- 3.5	- 3.18	No Cointegrated variables	N/A	LCO ₂ -T = 9.71 + (0.054868) - 0.876199LGDPI-T	LCO ₂ -T = 0.045 - 0.65LGDPI-T - 0.17res
		EC-T à CO ₂ -T	- 2.9400	- 4.15	- 3.5	- 3.18	No Cointegrated variables	N/A	N/A	N/A
Services	Test regression trend	GDP-S à EC-S	- 4.4800	- 4.15	- 3.5	- 3.18	Cointegrated variables	LGDPI-S = - 6.15.725 + 1.35LEC-S	N/A	LGDPI-S = 0.03 + 0.50LEC-S + 0.07res
		GDP-S à CO ₂ -S	- 2.8095	- 4.15	- 3.5	- 3.18	No Cointegrated variables	N/A	LCO ₂ -S = 1.795 + (0.0314) + 0.2210LGDPI-S	LGDPI-S = 0.023 + 0.42LCO ₂ -S + 0.07res
		EC-S à CO ₂ -S	- 3.6532	- 4.15	- 3.5	- 3.18	Cointegrated variables	LEC-S = - 1.89 + 0.71LCO ₂ -S	N/A	LEC = - 0.001 + 0.68LCO ₂ -S + 0.019res

*tau value < critical value rejects H0, accepts H1. Cointegrated variables *tau value > critical value rejects H1, accepts H0. Non-cointegrated variables

GDP-A gross domestic product agriculture, GDP-I gross domestic product industry, GDP-T gross domestic product transportation, GDP-S gross domestic product services, EC-A energy consumption agriculture, EC-I energy consumption industry, EC-T energy consumption transportation, EC-S energy consumption services, CO₂-A CO₂ emissions agriculture, CO₂-I CO₂ emissions industry, CO₂-T CO₂ emissions transportation, CO₂-S CO₂ emissions services

Table 3 Granger causality test

Lag 2				
Variables	<i>F</i> test	Chi ² test	RV-test	Wald test
Agriculture sector				
GDP→EC	<i>p</i> =0.6653	<i>p</i> =0.6008	<i>p</i> =0.6065	<i>p</i> =0.6653
EC→GDP	<i>p</i> =0.8369	<i>p</i> =0.8022	<i>p</i> =0.8037	<i>p</i> =0.8369
GDP→CO ₂	<i>p</i> =0.6653	<i>p</i> =0.6008	<i>p</i> =0.6065	<i>p</i> =0.6653
CO ₂ →GDP	<i>p</i> =0.8369	<i>p</i> =0.8022	<i>p</i> =0.8037	<i>p</i> =0.8369
EC→CO ₂	<i>p</i> =1.0000	<i>p</i> =1.0000	<i>p</i> =1.0000	<i>p</i> =0.0000
CO ₂ →EC	<i>p</i> =1.0000	<i>p</i> =1.0000	<i>p</i> =1.0000	<i>p</i> =0.0000
Industry sector				
GDP→EC	<i>p</i> =0.9409	<i>p</i> =0.9278	<i>p</i> =0.9280	<i>p</i> =0.9280
EC→GDP	<i>p</i> =0.0038	<i>p</i> =0.0001	<i>p</i> =0.0011	<i>p</i> =0.0038
GDP→CO ₂	<i>p</i> =0.9356	<i>p</i> =0.9213	<i>p</i> =0.9216	<i>p</i> =0.9356
CO ₂ →GDP	<i>p</i> =0.0433	<i>p</i> =0.0116	<i>p</i> =0.0212	<i>p</i> =0.0433
EC→CO ₂	<i>p</i> =0.0922	<i>p</i> =0.0382	<i>p</i> =0.0537	<i>p</i> =0.0922
CO ₂ →EC	<i>p</i> =0.4393	<i>p</i> =0.3506	<i>p</i> =0.3644	<i>p</i> =0.4393
Transportation sector				
GDP→EC	<i>p</i> =0.4037	<i>p</i> =0.3133	<i>p</i> =0.3285	<i>p</i> =0.4037
EC→PIB	<i>p</i> =0.3756	<i>p</i> =0.2845	<i>p</i> =0.3007	<i>p</i> =0.3756
GDP→CO ₂	<i>p</i> =0.4041	<i>p</i> =0.3138	<i>p</i> =0.3289	<i>p</i> =0.4041
CO ₂ →GDP	<i>p</i> =0.3755	<i>p</i> =0.4066	<i>p</i> =0.3006	<i>p</i> =0.3755
EC→CO ₂	<i>p</i> =0.4879	<i>p</i> =0.4025	<i>p</i> =0.4145	<i>p</i> =0.4879
CO ₂ →EC	<i>p</i> =0.4917	<i>p</i> =0.4066	<i>p</i> =0.4184	<i>p</i> =0.4917
Services sector				
GDP→EC	<i>p</i> =0.0670	<i>p</i> =0.0233	<i>p</i> =0.0362	<i>p</i> =0.0670
EC→GDP	<i>p</i> =0.1111	<i>p</i> =0.0505	<i>p</i> =0.0674	<i>p</i> =0.1111
GDP→CO ₂	<i>p</i> =0.0075	<i>p</i> =0.0005	<i>p</i> =0.0025	<i>p</i> =0.0075
CO ₂ →GDP	<i>p</i> =0.2249	<i>p</i> =0.1407	<i>p</i> =0.1602	<i>p</i> =0.2249
EC→CO ₂	<i>p</i> =0.0122	<i>p</i> =0.0013	<i>p</i> =0.0045	<i>p</i> =0.0122
CO ₂ →EC	<i>p</i> =0.4530	<i>p</i> =0.3651	<i>p</i> =0.3784	<i>p</i> =0.4530

Reference values: *p* value less than 0.05 to reject H0 and accept H1 in all tests

GDP gross domestic product, *EC* energy consumption, *CO₂* CO₂ emissions

For simplification, the empirical model integrates the demographic variable with the economic one and considers the rest of the relationships proposed for the comparison. In the 1990–2018-time horizon, the variables have been disaggregated by economic sectors studied through the balance energy and a variant of the Kaya identity as quantification technologies of the phenomenon. From the analysis of the demand, the variables that feed this section of the energy balance have been considered by sector. The total GDP is positively fed by the sectoral GDP (*Q_i*) composition, the EC breaks down into sectors, and the type of fuel feeds the total EC. Sectoral emissions are part of the country's total emissions.

The statistical relationships represented in the empirical model show that the most influential sectors are the

industry sector and the service sector since they have the most significant number of relationships and are the sectors in which it has been possible to determine unidirectional causal relationships, in addition to being the sectors with the most significant contribution to economic development (GDP) (Fig. 9).

The agriculture sector shows that, of the study variables, the GDP weakly determines the degree of variation in EC and CO₂ emissions. However, the variation in EC would strongly imply the variation in CO₂ emissions, mainly linked to the type of energy matrix handled in this sector; 100% of it is centred on oil from 1990 to 2018. The variables that have a balance in the long term are also EC and emissions, which would indicate that the two may have a synchronous growth or fall without implying that there is a predictive capacity for this sector since no causal relationships are established. According to this analysis, the diversification of the energy matrix, focussing on using biofertilisers for the sector, is proposed as a management improvement strategy, considering that the direct influence occurs in the EC–CO₂. Evidence shows that using a biodigester in rural areas allows one to reduce monthly energy expenditure and make a tangible difference to the standard of living of rural households due to certain economic costs. State intervention is suggested in search of broader benefits for the entire economy (Smith et al. 2014), and it is important to mention that mitigating the environmental impact in this sector does not have the same effect as in other productive sectors since EC is minimal and, therefore, it is an insignificant CO₂ emitter (Araujo and Robalino-López 2019).

The EC and CO₂ emissions of the industry sector cause the GDP of the sector, that is, the past values of the sector's EC and its CO₂ emissions can explain the current GDP values, so there is predictive capacity. In addition, in the sector, the variation in EC determines the variation in GDP very strongly. The variation in CO₂ moderately determines the variation in GDP, and the variation in EC greatly determines CO₂ emissions, considering that the energy matrix of the sector is much more diversified and has the participation of various sources but continues to maintain 65.12% in fossil energies and a clean energy share of 34.6%. The cointegration analysis indicates a long-term balance between GDP and EC and between GDP and CO₂ emissions, which shows that there can be a synchronous growth or fall in the relationships of the variables in this sector. The causal relationships found in the sector allow the proposal of a management improvement strategy linked to the use of non-conventional energies, increasing the use of solar energy by 4.6% per year. This value is taken from the average world growth from 2014 to 2018 for the industry sector with the type of solar, wind and other energy (IEA 2020).

The agri-food subsector of Ecuador consumes 71% of the total energy destined for this sector (Jácome et al. 2019).

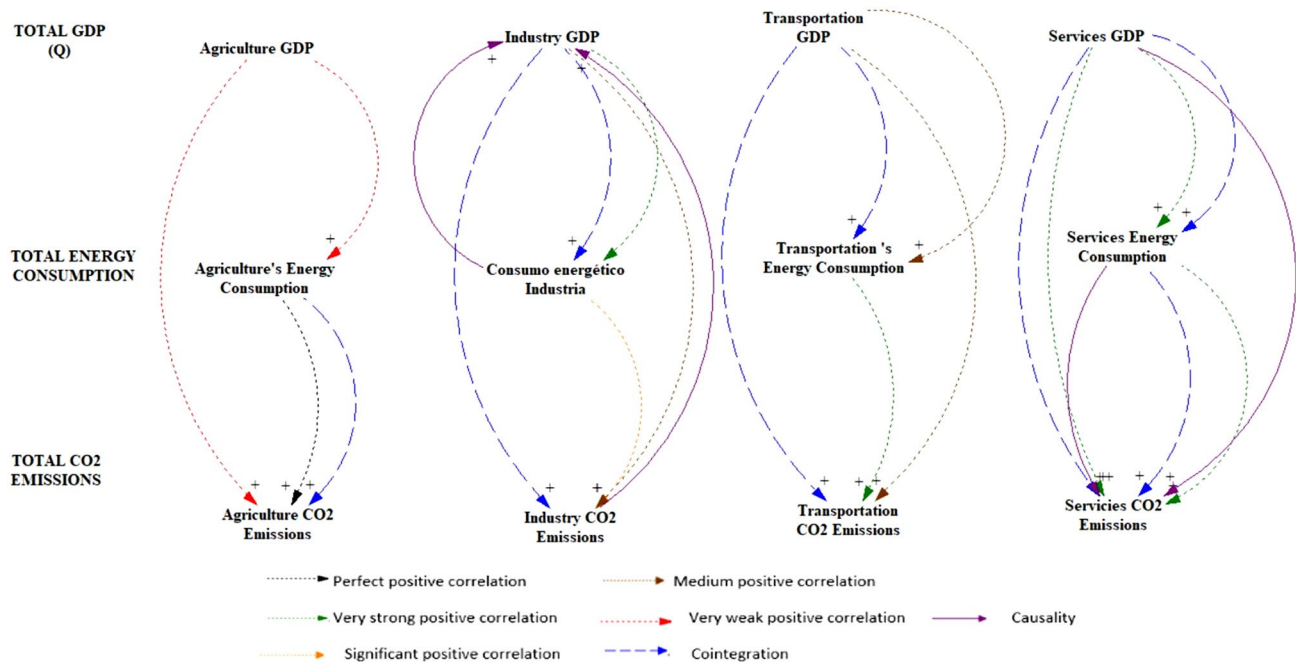


Fig. 9 Empirical model—causal loop diagram. Cointegration test *tau value < critical value rejects H0, accepts H1. Cointegrated variables *tau value > critical value rejects H1, accepts H0. Non-cointe-

grated variables. Granger causality test: *Reference values: p value less than 0.05 to reject H0 and accept H1 in all tests

Using this strategy, CO₂ emissions would be directly impacted, and GDP would allow more sustainable development. There is evidence that solar technology can be an essential factor in the diversification of the Ecuadorian energy matrix, with the participation of local industry that allows the improvement of costs in using this type of technology. It is worth mentioning that developing countries are paying more attention to the use of solar energy in this sector by focussing on public policies to encourage this technology, as it is important to provide access to resources in the form of knowledge, financing and legitimacy from abroad (Gil Perez and Hansen 2020; Jácome et al. 2019; Robalino-López 2015).

The transport sector does not manage relationships that show the predictive capacity of one variable over the other; that is, the past values of one variable cannot significantly explain the current values of the other in the relationships studied. This sector has, in its variables, a behaviour in which the variation of GDP moderately determines the variation of EC and CO₂ emissions, and the variation of EC would strongly imply the variation of CO₂ emissions. This is linked to the energy mix of the sector, with its energy matrix centred on oil at 99.96%. The cointegrating relationships indicate a long-term equilibrium relationship with GDP, EC and CO₂ emissions, implying a synchronous growth or fall of the variables studied. As an improvement strategy, it is proposed to increase the use of biofuels by 3.62% per year

through policies that focus on public transport, which is the sector in which the state can have influence. This strategy would have a direct impact on CO₂ emissions from the country. The percentage value of the system is taken from the average growth that Colombia reflects from 2014 to 2018 in biofuels for the transport sector (IEA 2020).

In the services sector, the variation in GDP determines the variation in EC and CO₂ emissions, in addition to the fact that energy consumption determines the variation in CO₂ emission in a very strong, positive way. The energy mix of the sector indicates that it uses 46.01% fossil energy and 51.13% clean energy. As the cointegration of the variables is found in the three relationships, it can be determined that there is a balance in the long term and that the variables in the sector will grow or decline in a synchronised way. The causal relationships are unidirectional from the GDP of services to CO₂ emissions and from EC to CO₂ emissions. The improvement strategy must focus on reducing CO₂ emissions, for which it is proposed to use energy efficiency, especially in homes, through targeted subsidy policies, which gradually eliminate subsidies for petroleum derivatives and increase energy efficiency. It is worth mentioning that for this sector, Ecuador has managed efficiency plans linked to the substitution of elements with high energy consumption for more efficient ones: RENOVA plan 2012–2016, change of refrigerators, efficient lighting plan 2008–2014, use of higher efficiency lamps and efficient cooking plan

2014–2018 with the change of kitchens that use liquefied petroleum gas for those of induction. However, these plans have not had the expected impact since the correct approach has not been taken towards the transformation of behaviour since the understanding of energy consumption has not been generated (Araujo and Robalino-López 2019).

The comparison of the theoretical model with the empirical model shows that there are differences regarding the loops that are formed by sector:

DH1: indicates the presence of a reinforcing loop between GDP and energy consumption. This reinforcing causal loop is not reflected in any of the sectors studied. However, in the industry sector, it creates a causal relationship in the direction of energy consumption to GDP, so it could only be true that consumption is encouraging the sector's economic development and not that economic development generates an increase in energy consumption. The causal link in this direction indicates that through economic development, consumers could buy more and better goods and services that satisfy more sophisticated needs in search of higher living standards. Industries would provide more products to meet these needs. Consumer demands lead to an increase in energy consumption (Sadorsky 2010, 2011).

DH2 indicates that economic development and increased energy consumption negatively influence the population's life expectancy. This is because new consumption habits have been promoted within society with more significant environmental impact. Global warming is caused by CO₂ emissions, leading to a decrease in the population growth rate. This theoretical balance loop is different in the empirical model since when using a variation of the KAYA identity, the population was not considered. However, the causal relationships are clear from the emissions of CO₂ to GDP in the industry sector and from GDP to CO₂ emissions in the services sector, in addition to the relationship in which energy consumption is causing CO₂ emissions.

DH3 is rejected because the model groups the demographic and economic variables. After all, a variation of the identity is used as an approximation of the quantification technology to understand this complex phenomenon. Therefore, the dynamic model would highlight that the country is in the initial stage of the Kuznets curve, where CO₂ emissions cause the GDP of the services sector. In turn, the reinforcement of the loop is given by the industry sector in that it is indicated that the emissions produced are causing the GDP of the system. The two sectors are the most economically representative of Ecuador. According to the EKC hypothesis, the relationship between per capita income and pollution is an inverted U. The behaviour establishes that as the GDP per capita grows, the environmental damage increases. When it reaches its highest stage, it begins to decrease. At this point, pollution starts to decline as a function of GDP (Salari et al. 2021; Pablo-Romero and De Jesús

2016; Robalino-López et al. 2014, 2015). In fact, according to the theoretical bases discussed, it can be established that the country still has a low degree of industrial sophistication; the energy matrix is found with a strong dependence on oil, which is why it is polluting, which reaffirms the results obtained qualitatively through historical analysis and quantitatively through data processing, the study of indices and statistical analysis.

In a scenario proposed by Robalino-López et al. (2014), Ecuador would be ready to enter the area of stability of the Kuznets curve in the medium term in 2019–2021. To obtain this goal, it is essential to implement policies that diversify energy resources and increase energy efficiency in productive sectors for sustainable development. However, according to the information presented in the historical context of qualitative information and with the energy, carbon intensity and other quantitative analysis, it can be observed that Ecuador has not made a great effort to increase energy efficiency in the productive sectors. It maintains a constant energy intensity in all sectors, which indicates that its energy efficiency has not been improved, and diversification in energy resources for the transport and agriculture sectors has not been generated.

Policy implications

Long-term equilibrium relationships are established in the four sectors analysed in Ecuador. However, the results obtained are different. The GDP–EC relationship is present in the industry, services and transportation sectors; for these findings, it is recommended that policymakers take actions regarding energy efficiency in the sectors to reduce their energy intensity, taking into account that in the long term, they seek the advancement of economies and decoupling between economic growth and energy consumption. The EC–CO₂ emissions relationship is found in the agriculture and services sector, so the implementation of cleaner technologies is suggested to reduce emissions without sacrificing energy consumption. Moreover, there is a GDP–CO₂ relationship in the industry sector, so policies that promote sustainable development, green technologies and renewable energy are suggested to break the link between growth and emissions.

Short-term relationships are found in the GDP–EC variables for the industry and transport sectors, the GDP–CO₂ relationship in the industry and transport sectors and the EC–CO₂ relationship in the agriculture sector. Based on those findings, it is recommended that the decision-makers adopt cleaner technologies and changes in the composition of the energy mix.

The focus of the improvement strategies has been linked to the use of non-conventional renewable energies in search

of sustainable development through the diversification of the energy matrix so that the country continues moving towards the achievement of the seventh sustainable development goal of the United Nations, which is to “Guarantee access to affordable, safe, sustainable and modern energy” and the thirteenth development goal, which is Climate Action (Eisenmenger et al. 2020). It is important to emphasise that Latin America is considered a leader in renewable energy mainly due to the use of hydroelectric power; however, this source has been decreasing in recent years, which is why the importance of incurring new types of non-conventional renewable energies such as solar energy, biomass or wind energy is increased. These proposals for improving sector management seek to improve environmental conditions without impacting economic development.

Conclusions

This research reveals that Ecuador maintains its profile as an energy exporter, with a strong economic and energy dependence on oil, which has kept it vulnerable to external economic shocks. The sectoral energy matrix and energy consumption were maintained from 1990 to 2018.

The previous works of the authors and the modelling of the complex system through System Dynamics have been taken as the starting point. Based on this premise, dynamic hypotheses have been proposed to explain the behaviour of the complex system. The empirical model (CLD) allows a better understanding of the behaviour of the variables within each analysed sector, as meaningful relationships have been found that help explain and better understand the system's behaviour. The statistical relationships studied for the agriculture sector show that there is no greater management capacity in the relation of GDP–EC and GDP–CO₂. Still, if it were possible to diversify the sectoral energy matrix, the variation in energy consumption would cause the sector's emissions to vary enormously since the EC–CO₂ ratio is vital. This relationship also tends to balance in the long term, and the variables would have a synchronous increase or decrease. It would not be seeking to affect the amount of energy consumed, which for the sector is minimal, but rather in its quality so that CO₂ emissions can be reduced.

The industry sector has statistical relations of unidirectional causality that allow us to understand its behaviour much more clearly. This sector's causal links are energy consumption to GDP and CO₂ emissions to GDP. The result makes sense because the industrial sector is the sector that contributes directly to GDP. Emissions are linked to their opting for polluting technologies due to using fossil fuels (Alvarado et al. 2018; Vona et al. 2018; Wang et al. 2017). The difficulty of reducing energy consumption is evident in the sector since it would directly impact GDP (economic

development). The improvement strategy has been linked to promoting the use of solar energy to increase the use of non-conventional alternative energies; for example, the historical evolution of Malaysia's energy policies and initiatives indicate the importance of being designed to secure diverse sources of energy and avoiding excessive reliance on fossil fuels (Yatim et al. 2016). In the transport sector, causal relationships cannot be established, which would indicate that none of the variables studied can explain the current values of its related variable through their past values, so there is no predictive capacity within the sector (Mena-Nieto et al. 2023). However, the relationship with the most significant possibility of variation of one over the other is GDP to CO₂; therefore, a proposal is made to improve management linked to the possibility of using biofuels in the sector, considering that 99% of the sources of energy consumption are oil. Various studies show that the transport sector is considered a key sector because it promotes socioeconomic development while being the largest contributor to carbon emissions, which becomes an obstacle to developing fewer polluting systems. Although eco-driving policies, electric vehicles and use of alternative fuels are alternatives that significantly reduce emissions, considerable progress is still needed in this sector to reduce further emissions, constituting a challenge for most countries (Amin et al. 2020; Matak and Krajačić, 2020; Miškić et al. 2022). The services sector manages unidirectional causal links from GDP to CO₂ emissions and energy consumption to CO₂ emissions. The results adhere to statistical data processing since it is the sector with the most significant contribution to GDP. Despite having the most diverse energy matrix of all sectors, oil and its derivatives continue to be the most demanded source, which would indicate that development is being sustained through the intensive use of resources, which is to say the economy still has little technological capability and scarce human resources, thereby finding in natural resources and cheap labour a source to sustain international competitiveness (Vona et al. 2018). The improvement strategy proposed for the sector is linked to keep and increase the use of hydroelectricity, in such a way that it directly impacts energy consumption by generating variations in emissions that do not affect GDP because a policy of lower energy consumption should not be encouraged since the sector contributes strongly to the economic development of the country. It is advisable to make changes that only impact emissions using fewer polluting technologies.

Globally, the sectors that form a reinforcement loop are the industry sector, from emissions to GDP, and the services sector, from GDP to emissions. These relationships clearly show Ecuador as an economy that is in the initial part of the Kuznets curve since, being a developing country, emissions increase with the size of the economy since industries are still relatively rudimentary, unproductive and

polluting (Salari et al. 2021; Pablo-Romero and De Jesús 2016; Robalino-López et al. 2015).

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Declarations

Conflict of interest The authors declare that they have no relevant financial or non-financial interests to disclose.

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