

Studying the relationship between economic growth, CO₂ emissions, and the environmental Kuznets curve in Venezuela (1980-2025)

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Abstract

This work tries to determine whether it is possible to stabilize CO₂ emissions under a rapid increase of Gross Domestic Product in a medium term. The paper is an effort to study in detail how changes in the driving forces of the economy affect CO₂ emissions. We study the case of Venezuela for the period 1980-2025, using the methodology proposed by Robalino-López et al. [1, 2], which is based on an extension of the Kaya identity and on a GDP formation approach that includes the effect of renewable energies. We test the environmental Kuznets curve (EKC) [3] hypothesis in a coming future under different economic scenarios considering, therefore, not only past data but also projections for the coming years. We use cointegration techniques [4] and the Jaunky [5] specification to test the fulfillment of the EKC hypothesis in Venezuela. Our predictions show that Venezuela does not fulfill the EKC hypothesis, but however, the country could be on the way to achieve environmental stabilization in the medium term. This stabilization could be accomplished combining economic growth with increasing use of renewable energy, appropriated changes in the energy matrix, and in the productive sectoral structure.

Keywords: CO₂ emissions, environmental Kuznets curve, Venezuela

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1. Introduction

There are multiple factors that influence the level of CO₂ emissions, among them, economic development, population growth, technological change, resource endowments, institutional structures, transport models, lifestyles or international trade [6, 7]. Latest observations show that global CO₂ emissions are far from stabilizing and have experienced significant growth during the last century. Clearly, one factor behind this increase is the growth of economic activity. The identification of the kind of sources of Green House Gases (GHG) emissions and of its magnitude is essential information for economic planning, for decision makers and for environmental development. CO₂ is by far the main contributor to antropogenic GHG emissions; according to IPCC [8], CO₂ represents 76.7% of the GHG emissions (approximately 56.6% is from fossil fuels, 17.3% from deforestation, and 2.8% from other sources).

To address this issue the Intergovernmental Panel on Climate Change (IPCC) has developed several methods to estimate GHG emissions, such as the *Reference Method* [8, Vol 2, chap. 6]. This is a top-down technique that uses data from the country's energy supply to calculate CO₂ emissions, mainly from the burning of fossil fuels. This is a straightforward method that can be applied on the basis of the available energy supply statistics in mostly of the countries.

The adoption of environmentally sustainable technologies, improving energy efficiency, saving energy, forest conservation, reforestation, or water conservation are some of the most effective ways to address the climate change issue [9]. Furthermore, Chien and Hu [10], Robalino-López et al. [1, 2] show that increasing the use of renewable energy improves the CO₂ emission *efficiency* of the economy.

The economic growth has a direct impact on CO₂ emissions of a given country. Most of the literature suggests that the relationship between economic growth and CO₂ emissions is established through the energy use and influenced by the energy efficiency, the promotion of renewable energies, and by the productive sectoral structure. The detailed study of the later relationship will be one of the goals of this work. In particular, the relationship between GDP and emissions used to be considered as linear, but however, in certain cases this is no longer true. The environmental Kuznets

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curve (EKC) was firstly defined in the early 1990s almost simultaneously by Shafik and Bandyopadhyay [3], Panayotou [11], and Grossman and Krueger [12], who stated that EKC refers, by analogy, to the inverted U-shaped relationship between the level of economic development and the degree of income inequality [13]¹. According to the EKC hypothesis, the relationship between income per capita and some types of pollution is approximately an inverted *U*. This behavior states that as the GDP per capita grows, environmental damage increases, reaches a maximum, and then declines. The reason for this behavior is that when GDP reaches a certain threshold, the economy moves into a different regime, where the rate of emissions with respect to income can be reduced with respect to the initial regime. In the initial stage, as in the developing countries, CO₂ emissions scale with the *size of the economy* because the industries are relatively rudimentary, unproductive, and polluting. In the second stage, the impact of the economy in environmental degradation is reduced through the *structure and composition effect*, because the economy growth induces structural changes. In particular, that happens as an agricultural based economy shifts into a manufacturing services based economy. Finally, the third stage appears when *nations invest intensively in research and development and the dirty and obsolete technologies are replaced by clean ones*. At this point the pollution starts to decrease as a function of the GDP. The different phases of the EKC are depicted schematically in Fig. 1.

The proposal of the present work goes a step further, and intends to see under which conditions a given country could approach the fulfillment of the EKC hypothesis in the medium term. To this end we use a model which is based on an extension of the Kaya identity² [17] and on a GDP formation approach which links renewable energy and income [18]. The methodology was first presented by Robalino-López et al. [1, 2] and was applied to Ecuador, here it will be applied to Venezuela.

One of our aims is to estimate CO₂ emissions in Venezuela during the period 2011-2025, using a model already presented in Robalino-López et al. [1, 2], under four different scenarios which constrain GDP, productive sectoral structure, energy intensity, and energy matrix. Moreover, we will try to disentangle how these factors affect CO₂ emissions and to know whether and

¹Exhaustive surveys were made by Stern [14], Dinda [15], and more recently by Pasten and Figueroa [16].

²CO₂ emissions of a given country are broken down into the product of four factors: carbon intensity, energy intensity, economic rent, and population.

when EKC hypothesis could be accomplished in Venezuela in the medium term.

This study could serve as a guide for other oil-producing developing countries, because single country studies can help policy makers to create comprehensive policies to control environmental degradation.

The paper is structured as follows: Section 2 presents an overview of the literature, Section 3 provides an overview of the country, Section 4 introduces the model and the methodology, Section 5 is devoted to discussion of empirical results, and finally, Section 6 provides the summary, conclusions and policy implications.

2. Literature review

Nowadays, the analysis of the relationship between economic growth, energy consumption and CO₂ emissions is a very relevant topic in the literature on sustainable development. Pollution due to economic growth is one of the most important empirical relationships that have been tested and studied in the ecological literature for many countries, both developing and developed countries. The literature can be divided in three main lines of study: first, the study of the relationship GDP-energy consumption or GDP-energy-CO₂ emissions, including the study of the causality relationships; second, the study of the different aspects of the EKC hypothesis; and finally, the use of scenarios to be able to conduct forecast calculations of CO₂ emissions in a forthcoming period. In many works these lines of research overlap.

Regarding the first line of study, in [19] the authors studied the inequality in CO₂ emissions across countries and the relationship with the income inequality for the period 1971-1999. They concluded that inequality in CO₂ is mostly explained by the inequality in the per capita income. The relationship between energy consumption (electricity in this case) from renewable and non-renewable sources and economic growth for 18 Latin American countries during the period 1980-2010 was studied by Al-mulali et al. [20]. The authors used the Vector Error-Correction and found that renewable electricity consumption is more significant than non-renewable electricity consumption in promoting economic growth in the long and the short term. A similar study was carried out by Cowan et al. [21] for the BRICS countries during the period 1990-2010. The authors explored the relationship between electricity consumption, economic growth and CO₂ emissions and they found that the neutrality hypothesis holds for Brazil, India and China,

a feedback hypothesis for Russia exists, a one way Granger causality running from GDP to CO₂ in South Africa appears and a reverse relationship from CO₂ to GDP in Brazil is found. In [22] the author study the CO₂ emission flows and energy use in Argentina, Brazil, Colombia, Mexico and Venezuela from 1971 to 2001. Results showed that changes in CO₂ intensities are similar in all these countries, however the energy use slightly changes from country to country, leading to small differences in the evolution of CO₂ emissions. Herralá et al. [23] examine global CO₂ efficiency using a stochastic cost frontier analysis of 170 countries during the period 1997-2007. The estimates shown rather large differences in efficiency levels and efficiency changes across countries. In [24] the authors study the European Union countries from 1990 to 2008 using econometric models based on the Kaya identity. The authors defined a new environmental efficiency index.

The study of the EKC hypothesis goes a step further than above works, because, besides studying the GDP-CO₂ emissions relationship, it also considers the EKC fulfillment. In [25] carbon dioxide emissions and economic growth has been studied for a panel of developing countries (43 countries) in the period 1980-2004 and they found that in the 35% of the sample the CO₂ emissions diminished in the long run, which confirm that these countries approach the sloping down part of the EKC. A similar study was conducted for a panel of 69 countries by Ibrahim et al. [26] in the period 2000-2008 using the so-called generalized method of moments. The paper find evidences substantiating the presence of the EKC. Jaunky [5] tried to test the EKC hypothesis for 35 high-income countries for the period 1980-2005. He applied several panel data unit root and co-integration tests. The empirical tests provide evidences of an EKC for various countries. Esteve and Tamarit [27, 28] studied the EKC hypothesis for the case of Spain during the period 1857-2007. The authors found evidences pointing to the existence of the EKC in Spain. A review of the literature shows a long-run relationship linking income and emissions growth and recent research has assessed this relationship employing cointegration techniques. The empirical evidence suggests that GDP and pollution levels may be jointly determined, so that any constraint put on energy consumption to help the reduction of the emissions will have effects on economic growth. Some authors such as: Soytas et al. [29], Soytas and Sari [30], Lee [31], Lise [32], Chontanawat et al. [33], Halicioglu [34], Ozturk and Acaravci [35], Alam et al. [36], Fosten et al. [37], and Shahbaz et al. [39, 40], among others, use cointegration procedures to examine the relationship between CO₂ and income. All these

studies focused on the analysis of past evidences.

In regard to the third branch of study, Bautista [41] conducted an scenario analysis for Venezuela up to 2050 paying special attention to sustainable scenarios. He showed that Venezuela has all the resources needed to achieve a sustainable development in the power generation sector and that the easiest way to reduce the emissions is to improve the energy efficiency. In [42] the authors developed a system dynamics model to describe the evolution of energy consumption and CO₂ emissions in the city of Beijing from 2005 to 2030. They conducted a sensitivity analysis showing that the economic growth and the increase of the population are the two main variables that modulate the value of CO₂ emissions. In [1] the authors developed a model based on the Kaya identity and on a formation of the GDP that depends on the use of renewable energies. The model was applied to Ecuador for the period 1980-2025. The authors carried out an scenario analysis and concluded that in order to control the CO₂ emission under scenarios of rapid growth of the GDP there are two complementary strategies, to improve the energy efficiency and/or to promote the use of renewable energy.

It deserves to be mentioned Ref. [2], because the authors study the EKC fulfillment not with past data, but in a forthcoming period. They studied Ecuador from 1980 to 2025, starting with the model proposed in [1]. The main conclusion of this work is that Ecuador will enter into the second stage of the EKC in the coming years if the country follows one of the scenarios where the energy efficiency and the renewable energies are promoted.

After this review, it is clear the lack in the literature of studies on the EKC hypothesis in a forthcoming period, in South America, in general, and in Venezuela, in particular.

Table 1: Summary of recent studies that analyzed the GDP growth-energy-CO₂ emissions relationship.

Author	Relationship	Region	Methodology	Period	Outcomes
Esteve and Tamarit [27, 28]	CO ₂ -GDP	Spain	EKC	1857-2007	Existence of EKC
Soytas and Sari [30]	Energy-GDP	Argentina	Causality relationship	1950-1990	Bi-directional causality
Alam et al. [36]	CO ₂ -Energy-GDP	India	Dynamic modeling & causal relationship	1960-1995	Bi-directional causality, energy-CO ₂ in the long-run but neither CO ₂ nor energy causes movements in income
Soytas et al. [29]	Energy-GDP	Turkey	Cointegration	1960-1995	Unidirectional causality, energy → GDP
Chontanawat et al. [33]	Energy-GDP	Central and South America, Turkey	Causality relationship	1960-2000	Mixed evidences
Halicioglu [34]	CO ₂ -Energy-GDP	Turkey	Causality relationship	1960-2005	Strong connection GDP-CO ₂
Kuntsi-Reunanen [45]	CO ₂ -Energy	Selected Latin American countries	CO ₂ emission flows	1970-2001	No significant changes
Padilla et al. [19]	CO ₂ -GDP	Groups of countries	Non-parametric estimations	1971-1999	GDP inequality → CO ₂ inequality
Shahbaz et al. [39]	CO ₂ -Energy-GDP	Pakistan	Cointegration, Granger causality & EKC analysis	1971-2009	Unidirectional causal relationship, GDP-CO ₂ . EKC hypothesis supported
Lee [31]	Energy-GDP	South America	Causality relationship	1975-2001	Relationship energy → GDP
Lise [32]	CO ₂ -Energy-GDP	Turkey	Decomposition analysis	1980-2003	Decoupling between CO ₂ emissions and economic growth
Narayan et al. [25]	CO ₂ -GDP	43 developing countries	EKC analysis	1980-2004	35% of the countries show EKC evidences
Jaunky [5]	CO ₂ -Energy-GDP	36 high-income countries	EKC analysis	1980-2005	GDP → CO ₂ EKC evidence found
Ozturk and Acaravci [35]	Energy-GDP	Albania, Bulgaria, Hungary, Romania	Causality relationship	1980-2006	Bi-directional causality in Hungary. No causal relationships for Albania, Bulgaria and Romania
Shahbaz et al. [40]	CO ₂ -Energy-GDP	Romania	Cointegration, EKC analysis	1980-2010	Long run relationship between economic growth, energy and CO ₂ . EKC evidence is found
Al-mulali et al. [20]	Energy-GDP	Latin America	Cointegration, Granger causality	1980-2010	Long run relationship between renewable energy and GDP growth
Robalino-López et al. [1]	CO ₂ -Energy-GDP	Ecuador	System Dynamics modeling & scenario analysis	1980-2025	Strong connection GDP-CO ₂
Robalino-López et al. [2]	CO ₂ -Energy-GDP	Ecuador	System Dynamics modeling & EKC analysis	1980-2025	EKC not fulfilled
Cicea et al. [24]	CO ₂ -GDP	European Union	Indicator analysis	1990-2008	Mixed evidences
Cowan et al. [21]	CO ₂ -Energy-GDP	BRICS countries	Granger causality	1990-2010	Evidences of GDP → CO ₂
Herrala et al. [23]	CO ₂ -GDP	170 countries	Stochastic cost analysis	1997-2007	Progress in global efficiency
İbrahim et al. [26]	CO ₂ -GDP	69 countries	GMM estimators	2000-2008	Mixed evidences
Feng et al. [42]	Energy, CO ₂	City of Beijing	System Dynamics modeling	2005-2030	Economic growth mainly modulate CO ₂ emissions

3. Overview of the study area

Venezuela has abundant energy resources that have played a key role in defining the nation's economic development road. The extraction of oil has formed the backbone of the Venezuelan economy since 1920s. The economy of Venezuela is largely based on petroleum and manufacturing sectors.

In 2010 revenue from petroleum exports accounted for approximately 18% of the country's GDP and roughly 93% of total exports [43]. Hence, the Venezuelan GDP is highly correlated with the price of the oil, therefore it suffers of large fluctuations; during the collapse of oil prices in the 1980s, the economy contracted, however it grew an average of 10.5% between 2004 and 2008, but shrank an average of 2.3% from 2009 to 2010. The country also has one of the highest inflation rates in the world, averaging 29.1% in 2010 [43]. According to Central Bank of Venezuela (BCV-Banco Central de Venezuela), the government received around 325 billion USD through oil production and exports from 1998 to 2008 [44].

Venezuela had the highest energy consumption per capita and the highest energy intensity in Latin America. According to IEA the primary energy use is about 20% higher than it would be without subsidies [45]. Venezuela has an oil production quota that cannot be exceeded because is an active member of OPEC; therefore, a high domestic consumption of oil penalizes the exports and the country revenues.

The other side of the high oil consumption is the high level of CO₂ emissions of the country: in 2009 Venezuela emitted 6.5 metric tons of CO₂ per capita. This makes Venezuela the largest CO₂ emitter per capita in Latin America, very far though from Qatar, the world's largest CO₂ emitter with 44 metric tons per capita. It is expected that present social and economic development in the region could significantly increase the Venezuelan level of emissions.

Since 2000, the annual average primary energy production of Latin America and the Caribbean reached 447 million tonnes of oil equivalent (Mtoe). This production was made of 70% of carbon fossil fuels (46% crude oil, 20% gas and 4% coal), the rest divided between biomass and garbage (18%), hydroelectricity (10%), nuclear (1%), and geothermic, solar and other renewable sources of energy (1%) [43]. The energy mix in Venezuela is different of this pattern, with a higher relative importance of carbon fossil fuels, which reached 89% of the total primary energy production (47% of oil and 42% of gas), with 10% of hydroelectricity and 1% of biomass and garbage by 2010 [43, 44].

The Venezuelan government has identified potential sources of renewable energy that would enable a reduction of the consumption of fossil fuel in the near future [38, 41]. At present, Venezuela has an hidro power complex at Caroí river with and annual energy production of 130 TWh, but the potential energy yield of this complex could reach 246 TWh. Regarding

wind and solar power, nowadays the installed power is negligible, but the potential resources are huge: 1038 TWh/year and 1465 TWh/year of wind and solar power, respectively. In summary, Venezuela has available renewable energetic resources that can significantly decrease the contribution of fossil energies to the energy matrix of the country [46].

4. Model and methodology

4.1. Formulation of the model

The model to calculate CO₂ emissions from fossil energy corresponds to a nexus relationship, which is an extension of the original Kaya identity where we disaggregate in type of fuel and kind of industrial sector (see Refs. Robalino-López et al. [1, 2] for a complete description of the model). The amount of CO₂ emissions from industry and other energy uses may be studied quantifying the contributions of five different factors: scale of the economy, industry activity mix, sectoral energy intensity, sectoral energy mix, and CO₂ emission factors. Moreover, we consider different sub-categories concerning industrial sectors and fuel type. The CO₂ emissions can be written as,

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

where C is the total CO₂ emissions (in a given year); C_{ij} is the CO₂ emission arising from fuel type j in the productive sector i (note that the index i runs over four productive sectors and the index j over seven type of energy sources); Q is the total GDP of the country; Q_i is the GDP generated by the productive sector i ; E_i is the energy consumption in the industrial sector i ; E_{ij} is the consumption of fuel j in the industrial sector i ; S_i ($\frac{Q_i}{Q}$) is the share of sector i to the total GDP; the energy intensity of sector i is given by EI_i ($\frac{E_i}{Q_i}$); the energy matrix is given by M_{ij} ($\frac{E_{ij}}{E_i}$) and the CO₂ emission factor by U_{ij} ($\frac{C_{ij}}{E_{ij}}$)³. The definition of the productive sector division and the classification of type of fuels, comply the standard separation of the International Standard Industrial Classification [47] and the International Energy Agency [48], respectively.

³Throughout this paper, as a convention, we will always refer to the industrial sector with the i index and to the type of energy source with the j index.

It is also of interest to write up how to calculate the total energy in terms of the GDP,

$$E = \sum_{ij} E_{ij} = Q \sum_{ij} S_i \cdot EI_i \cdot M_{ij} \quad (2)$$

and the expended energy of every kind of fuel,

$$E_j = Q \sum_i S_i \cdot EI_i \cdot M_{ij}. \quad (3)$$

The subsequent data analysis and the pre-processing of the time series was performed using the Hodrick-Prescott (HP) filter [49], which allows isolation of outliers (economic crises, random behavior of markets, etc) of the time series under study. After that, it is possible to get the trend component of a time series and to perform estimations that are more appropriate. The smoothing parameter λ of the filter, which penalizes acceleration in the trend relative to cycle component, is taken equal to 100. Most of the business cycle literature uses this value for the λ parameter, as has been suggested by Hodrick and Prescott [49].

4.2. Economic submodel

This work presents as a key point the explicit inclusion of the effect of renewable energy on the GDP, allowing to establish a link between income and CO₂ emissions [50]. In this work we consider that renewable energy can increase GDP through import substitution of energy which has direct and indirect effects on increasing GDP and trade balance.

Closely following Chien and Hu [18] we use the expenditure approach to form the GDP,

$$Q = C_a + I + G + TB, \quad (4)$$

where C_a is the final household consumption expenditure, I the gross domestic capital formation, G is the general government final consumption expenditure, and TB the trade balance (exports minus imports).

On the other hand, according to Chien and Hu [18], the variable G should be removed from the model estimation to avoid multicollinearity. The system of theoretical GDP formation model is composed by the follow-

ing equations:

$$Q = a_1 \cdot I + a_2 \cdot TB + a_3 \cdot C_a + a_4 \cdot E_{imp} + a_5 \cdot RN + \epsilon_1 \quad (5)$$

$$I = b_1 \cdot RN + b_2 \cdot C_a + \epsilon_2 \quad (6)$$

$$TB = c_1 \cdot E_{imp} + c_2 \cdot RN + \epsilon_3 \quad (7)$$

$$E_{imp} = d_1 \cdot RN + \epsilon_4 \quad (8)$$

$$C_a = f_1 \cdot E_{imp} + f_2 \cdot TB + \epsilon_5 \quad (9)$$

where E_{imp} is the energy import, RN is the renewable energy and $\epsilon_1 \dots \epsilon_5$ are residuals. The coefficients a_i , b_i , c_i , d_i , and f_i appearing in these equations are determined using the Seemingly Unrelated Regression (SUR) with the smoothed dataset of the period 1980-2010. The data used to calibrate the model corresponds to the period 1980-2010 and was extracted from the official dataset of the country⁴. Table 2 shows the results after fitting the smoothed series of data.

In Eq. (5), GDP is positively influenced by capital formation, trade balance, and consumption (a_1 , a_2 , and a_3 are positive, as seen in Table 2). Chien and Hu [51] suggested that energy inputs may increase GDP, as such, energy imports and renewable energies are included as well in Eq. (5). In the case of Venezuela, our results confirm that the import of energy, E_{imp} , has a small, but positive influence ($a_4 > 0$) on the GDP, which is somehow surprising: a larger energy import implies a larger income. Finally, renewable energies also have a positive effect on the GDP ($a_5 > 0$), confirming the theory presented in Chien and Hu [51]. This is not a general property and strongly depends on the region under study. In particular, in the case of Ecuador $a_5 < 0$ (see Robalino-López et al. [1, 2]).

In Eq. (6) capital formation is influenced by renewable energy, thus increasing use of renewable energies will result in business expansion and thus capital could be accumulated in long term (b_1 and b_2 are positive in Table 2). In Eq. (7) a reduction of energy imports and an increase of the use of renewable energy have a positive influence in trade balance (c_1 is negative while c_2 positive in Table 2; note that $E_{imp} < 0$ for net energy exports, as it is the case of Venezuela). The theory proposed by Domac et al. [50] suggests that the use of renewable energy results in import substitution

⁴Data is from World Bank [43], and International Energy Agency [48]. Economic official data set used is given in constant 2005 PPP (purchasing power parity) international dollars [43]. In the rest of this paper GDP-PPP will be referred to only as GDP and 2005 PPP international dollars as USD, for brevity.

Table 2: Estimated coefficients for the GDP formation equations using the SUR technique (see Eqs. (5)-(9)).

Variable	Q ^a (a _i)	I (b _i)	TB (c _i)	E _{imp} (d _i)	C (f _i)
I ^a	1.49*** (152.06)				
TB ^a	0.88*** (22.66)				1.39*** (4.96)
C ^a	0.85*** (61.39)	3.29 10 ⁻² *** (0.39)			
E _{imp} ^b	6.16 10 ⁻⁵ *** (14.40)		-4.36 10 ⁻⁶ (-0.17)		-1.48 10 ⁻⁴ (-1.41)
RN ^b	2.19 10 ⁻³ *** (8.01)	6.45 10 ⁻³ *** (7.30)	4.04 10 ⁻³ *** (12.30)	-11.95*** (-8.83)	

^a Q, I, TB, C given in 10¹⁰ USD.

^b E_{imp} and RN given in 10³ ktoe.

*** represents significance at the 1% level and numbers in the parentheses are *t*-statistics.

and thus trade balance will increase with the use of renewable energies. This is particularly true in the case of Venezuela where oil extraction is limited due to the OPEC quota. Although Venezuela is a net exporter of fossil energy, their fossil energy consumption could be supplied by renewable energy, thus, diversifying its energy matrix and reducing the emissions. Hence, energy imports will be reduced by increasing the use of renewable energy (in Eq. (8) coefficient d_1 is negative which confirms this assumption). In Eq. (9), according to international trade theories, the domestic price of goods increases as the same kind of goods are exported, while it decreases as the same kind of goods are imported. Thus, trade balance ($f_1 > 0$) influences consumption through changes in domestic prices, as well as imports of energy ($f_2 < 0$) influence domestic energy prices and therefore increase the household consumption. As a result, consumption of energy-related products is also affected.

4.3. Energy consumption and productive sectoral structure submodel

Energy consumption refers to the use of primary energy before transformation into any other end-use energy, which is equal to the local production of energy plus imports and stock changes, minus the exports and the amount of fuel supplied to ships and aircrafts engaged in international transport. It is given in ktonnes of oil equivalent (ktoe). Energy intensity is defined as the ratio of energy consumption and GDP [43].

In this work we consider four sectors to define the productive sectoral structure which according to the International Standard Industrial Classification of all economic activities [47] are: 1) primary sector (Sector 1: agriculture, forestry, and fishing), 2) secondary sector-A (Sector 2: manufacturing), 3) secondary sector-B (Sector 3: mining, quarrying, electricity, gas, water supply, and construction), and 4) tertiary sector (Sector 4: services, trade, residential, and transportation). These are represented inside the model by their contribution to the country's economy (S_i), by their energy intensity (EI_i), and by their energy-fuel mix (M_{ij}). Index i runs over each sector of the productive sectoral structure, while index j runs over seven type of fuels: 1) natural gas, 2) liquefied petroleum gases (LPG), 3) motor gasoline, 4) gas/diesel oil, 5) fuel oil, 6) petroleum coke, and 7) renewable, alternative, and nuclear (not present in Venezuela) energy.

4.4. CO₂ intensity and energy matrix submodel

CO₂ intensity ($CO2_{int}$) of a given country corresponds to the ratio of CO₂ emissions and the total consumed energy written in terms of mass of oil equivalent ($CO2_{int} = \sum_{ij} C_{ij} / \sum_{ij} E_{ij}$). The value of the $CO2_{int}$ in a given year depends on the particular energy mix during that year. M_{ij} gives the energy matrix, but it is more convenient to sum over the different sectors and aggregate the fossil fuel contributions, therefore, we define $M_j = \sum_i E_{ij} / \sum_{ij} E_{ij}$ for each type of fuel ($j = 1, \dots, 7$). Hence, $\sum_{j=1}^6 M_j$ is the share of expended fossil energy, while M_7 is the share of used renewable energy in the country.

In order to simplify the description, in this paper we assume that M_7 does not contribute to the CO₂ emissions. Following the methodology recommended by the IPCC, that is, the *Reference method*, the approach of the first level (*Tier 1*) for the fossil energy mix was used⁵.

⁵The emission factors, U_{ij} , are taken from the *IPCC* methodology to estimate CO₂ emission of each fuel [8].

4.5. Model equations and causal diagram

In the equations presented along this section we have seen how the model is split in two different parts: energy and productive sectoral submodel, Eqs. (2)-(3), and economic submodel, Eqs. (5)-(9). In the first case, the energy and, in particular, the amount of renewable energy, $E_{j=7}$, is calculated. In the second one, the value of the GDP is calculated in terms of its components, one of which is renewable energy. These two parts are coupled through the renewable energy term which generates a feedback mechanism that in the case of Venezuela is positive ($a_5 > 0$, see Table 2). In Fig. 2 we present the schematic view of the model, where the feedback mechanism is highlighted. This way of presenting the model is extremely useful because allows to see the driving forces of CO₂ emissions in a hierarchical way, showing the causality relationship between the different variables. It can be observed that the CO₂ emitted into the atmosphere has several connections with the variables of the model: economic growth, productive sectoral structure, energy consumption, and energy matrix.

A more quantitative way of presenting how the different variables are extrapolated is through the difference equations that should be solved:

$$Q(t) = a_1 I(t) + a_2 TB(t) + a_3 C_a(t) + a_4 E_{imp}(t) + a_5 RN(t-1), \quad (10)$$

$$E_j(t) = \sum_i S_i(t) \cdot EI_i(t) \cdot M_{ij}(t) \cdot GDP(t), \quad (11)$$

$$RN(t) = E_7(t), \quad (12)$$

$$y(t) = y(t-1) \cdot (1 + r_y), \quad (13)$$

where $S_i(t)$, $EI_i(t)$, $M_{ij}(t)$, $I(t)$, $TB(t)$, $C_a(t)$, and $E_{imp}(t)$ evolve following Eq. (13) while the parameters a_i have constant values. Note that index j runs over the type of energy sources, while i on the industrial sectors; $j = 7$ corresponds to renewable and alternative energy. $t = 0$ corresponds to the reference year 2010 and t is given in number of years since 2010. The value of r_y is fixed through the definition of the used scenario. In the case of the *BS* scenario one should use a value of r_y that depends on the time [52, 53]. In this case r_y roughly corresponds to the yearly average increase over the period 1980-2010.

The feedback mechanism is provided through the inclusion of $RN(t-1)$ in the calculation of the GDP (10). As $a_5 > 0$ (see Table 2) the feedback mechanism is positive. This fact induces an extra increase of the GDP for the *SC-3* and *SC-4* scenarios with respect to *SC-2* (see section 4.7) for increasing use of renewable energy. In general, any increase of the term

Variable	MAPE(%)
GDP	4.6 %
E _{fossil}	4.4 %
RN	4.4 %
E _{total}	4.1 %
CO ₂	4.2 %

Table 3: MAPE values for the main variables of the model.

$\sum_i S_i(t) \cdot EI_i(t) \cdot M_{ij}(t)$ for $j = 7$ will induce an increasing, though moderate, of the GDP.

4.6. Model validation and verification

The official dataset from 1980 to 2010 and the output of the model can be compared to test its robustness and reliability. This analysis can be carried out calculating the mean absolute percentage error (MAPE), which is defined as,

$$\text{MAPE}(\%) = \frac{1}{N} \sum_{i=1}^N \left| \frac{\text{Data}_i - \text{Model}_i}{\text{Data}_i} \right| \times 100, \quad (14)$$

where, Data_i , Model_i , and N are the real data, the calculated values, and the number of data, respectively. MAPE is commonly used to evaluate cross-sectional forecasts [54].

MAPE values for the main variables of the model are shown in table 4.6. The values are rather modest and therefore support the robustness of the model. To understand the differences between the real data and the output of the model for the historical period, one has to take into account that prior to use the data they are first smoothed through the HP filter. On the other hand, the description of the GDP implies a linear regression on smoothed time series. Finally, to calculate the CO₂ emissions we use generic emission factors, which generates additional discrepancies when comparing with real data (CO₂ inventory) that were computed using a fully disaggregated sum and specific emission factors for the country. Finally, note that in some cases part of the discrepancies are canceled out, in particular, the MAPE value for CO₂ is smaller than for GDP and E_{fossil}, but however CO₂ is calculated using both variables among other ingredients.

4.7. Scenarios

In this work we will calculate the value of CO₂ emissions in the medium term. As we have seen in previous sections, CO₂ emissions depend on several variables, therefore it is compulsory to define scenarios in which determine how GDP, sectoral structure, energy intensity, and energy mix will evolve in the coming years.

To define the scenarios we will use as a guide next goals: *Goal 1*, by 2025 GDP will be substantially higher than in 2010 through a process of industrialization and improvement of the productive sectoral structure of the country; *Goal 2*, in regard to *Goal 1*, the use of renewable energies will be twice the one in 2010; *Goal 3*, in regard to *Goal 1* and *Goal 2*, energy efficiency will increase with a reduction of the energy intensity (2% per year in each productive sector) and by changes in the productive sectoral structure.

Taking into account the latter goals, we propose four scenarios concerning the growth of GDP, the evolution of the energy matrix, of the productive sectoral structure, and the improvement of energy efficiency for the period 2011-2025.

1. *Baseline scenario (BS)*: GDP, energy matrix and productive sectoral structure will evolve through the smooth trend of the period 1980-2010, extrapolated to 2011-2025 using the geometric growth rate method.
2. *Doubling of the income (SC-2 scenario)*: GDP in 2025 will be more than double that of 2010. To generate this scenario a constant annual growth of the GDP formation components (I , TB , C , E_{imp}) of 4.7% per year between 2011 to 2025 is assumed and a structural change in the productive sectoral structure will be implemented through a stabilization of the share of primary sector (Sector 1) at 5%, a consolidation of the country's industrial sector (Sectors 2 and 3) increasing its share from 52% to 55% and a stabilization of the service sector (Sector 4) at 40%. The rest of variables will evolve as in the *BS scenario*. This scenario clearly corresponds to a situation where the economy is growing rapidly and no mitigation measurements to reduce CO₂ emissions are carried out.
3. *Doubling of the income and of the share of renewable energies (SC-3 scenario)*: The doubling of the GDP and the change of the productive

sectoral structure as in the *SC-2* scenario are considered, however the share of fossil energy, $\sum_{j=1}^6 M_j$, will be reduced approximately one point per year, passing from 88% in 2010 to around 76% in 2025 due to a constant annual growth of the renewable and alternative energy share. This scenario shows a first measure of environmental responsibility in order to try to reduce dependence on fossil energy.

4. *Doubling of income, doubling of renewable energy share and improvement in the efficiency of energy use (SC-4 scenario)*: The doubling of the GDP, the change in the productive sectoral structure and the change of the share of the fossil energy are the same as in the *SC-3 scenario*. Moreover, an improvement in the efficiency of energy use is implemented with a reduction in the sectoral energy intensity of 1% in each productive sector, relative to the *BS* scenario, which in practice supposes a 2% yearly reduction. This scenario improves the country's environmental responsibility and sustainable development by supporting energetic saving measures and energy efficiency.

It is important to note that the aim of this paper is not to perform a rigorous forecast of the GDP, energy consumption or energy intensity, but, we try to establish a baseline and other reasonable scenarios that could be useful as reference points for policy makers or further studies.

4.8. *EKC hypothesis analysis*

To explore in a quantitative way the relationship between CO₂ and GDP, we follow Jaunky [5] specification for testing the EKC hypothesis in Venezuela. We consider the next simplified equation that relates CO₂ and GDP,

$$LCO2_t = \mu_0 + \mu_1 LGDP_t + \epsilon_t, \quad (15)$$

where, LCO₂ is the natural logarithm of the CO₂, while LGDP is the natural logarithm of GDP. μ_0 is a constant term, μ_1 estimates the CO₂-GDP elasticity, and ϵ is an error term. The use of the natural logarithm is needed to define in a proper way the elasticity in Eq. (15). The region of little environmental respect corresponds to $\mu_1 > 1$ and therefore to the stage 1 of Fig. 1. In this region a change in GDP induces a large change in CO₂ emissions, i.e., there is a high responsiveness. In general, countries stay in this phase in the early stage of its industrial development. If $0 < \mu_1 < 1$, then an increase in the income generates an increase less than proportionate in the emissions. The country enters in the second stage of the EKC with an

environmental stabilization. Finally, $\mu_1 < 0$ implies that any increase in the GDP brings a decrease in the CO₂ emissions. This is the final stage of the EKC and the country is moving into a situation of intensive use of sustainable technology and GDP increase is accompanied by reductions of CO₂ emissions.

5. Empirical results and discussion

Below, the empirical outcome of this study is presented. In particular, we provide estimations of GDP and CO₂ emissions till 2025, as well as the study of the EKC hypothesis. For completeness, some other projections are also shown. Besides we carry out a sensitivity analysis where we disentangle the factors that drive CO₂ emissions.

5.1. GDP

We depict in Fig. 3 the value of the GDP for the four considered scenarios. These values do not intend to be a detailed projection of the GDP but rather are a consequence of the definition of the scenarios. The starting point of our projection is the data of the GDP for 2010 which is 316 billion USD. In the case of the *BS* scenario the value of the projected GDP for 2025 is 484 billion USD, while the *SC-2* scenario reaches 643 billions USD, which is more than double that of 2010; *SC-3* and *SC-4* reach 673 and 672 billions USD, respectively. In the case of the *BS* scenario the yearly growth of the GDP corresponds to the average of the period 1980-2010. The other three scenarios have a annual growth of the GDP components of about 5% and the GDP in 2025 is roughly the double that in 2010. The differences in the value of the projected GDP between the three latest scenarios come from the presence of a positive feedback mechanism, which creates an additional growth of the GDP of about 4.7% in 2025 with respect to the *SC-2* scenario.

5.2. Energy

In this section we present the evolution of the energy consumption, disaggregating in fossil and renewable energy, for the four proposed scenarios. In Fig. 4 we depict the evolution of the energy consumption in the upper panel, the projection of the fossil energy consumption in the middle and the renewable energy in the lower panel.

The total energy consumption in 2025 in the *BS* scenario is around 102 Mtoe, while 130 Mtoe in the *SC-2*, 135 Mtoe in the *SC-3* and 113 Mtoe in the *SC-4* scenarios. Regarding the fossil energy consumption in 2025,

it corresponds to 90 Mtoe, 115 Mtoe, 105 Mtoe, and 88 Mtoe in the *BS*, *SC-2*, *SC-3*, and *SC-4* scenarios respectively. Therefore, renewable energy production is 12 Mtoe, 15 Mtoe, 30 Mtoe, and 25 Mtoe in 2025 for the *BS*, *SC-2*, *SC-3*, and *SC-4* scenarios, respectively. The contribution from renewable energy will allow to increase the oil exports in about 10-17 Mtoe when comparing the *SC-3* and *SC-4* with the *SC-2* scenario. The bigger renewable energy production in the *SC-2* scenario in comparison with the *BS* scenario is because the larger energy consumption due to larger economic growth in the *SC-2* scenario.

5.3. CO₂ emissions

In Fig. 5 we depict the value of CO₂ emissions during the period 2011-2025, under the four considered scenarios. In 2025 the highest emission corresponds to the *SC-2* scenario while the lowest to the *SC-4* scenario, though very close to the *BS* scenario, being the *SC-3* scenario in between these two extreme situations. The *SC-2* scenario does not implement any attenuation measure regarding CO₂ emission and moreover a rapid GDP increase is considered, therefore the larger value of the emissions is expected, reaching in 2025 a value of 306 Mtonnes, while the reference scenario only reaches 240 Mtonnes. In the *SC-3* scenario the share of renewable energy in the energy mix is increased and the emissions are reduced down to 280 Mtonnes. Finally, for the *SC-4* scenario besides the promotion of renewable energies a reduction of the energy intensity is implemented reducing, in this case, the emissions down to 234 Mtonnes. Therefore, there are two different strategies to reduce the emissions, either promote renewable energies, which achieves a reduction of 26 Mtonnes, or to improve the energy intensity, which accomplish a reduction of 46 Mtonnes. The combination of both strategies leads to a reduction of 72 Mtonnes with respect to the more polluted scenario, which corresponds to a reduction of 24% in 2025.

5.4. Sensitivity analysis

In this section we will present a sensitivity analysis based on the logarithmic mean Divisia index (LMDI) [55]. This analysis will allow us to determine the relative importance of each term appearing in the CO₂ emission formula (1). In fact, using this method it is possible to write down the increase of CO₂ emissions relative to the value of a given year, and to decompose it as the product of the factors corresponding to the different parts that make up the value of CO₂ emission. Therefore, we can write [55],

$$D_{tot} = D_{act} \times D_{str} \times D_{int} \times D_{mix} \times D_{emf} \quad (16)$$

where D_{tot} is the value of the CO₂ emission relative to a reference year, 2010 in our case, D_{act} account for the increase of the GDP relative to the reference year, D_{str} is the change of the structure term (the share of the different sectors to the GDP), D_{int} stands for the change of the intensity term that refers to energy consumption, and D_{mix} accounts the change in the energy mixing term⁶.

Table 4: Results of the CO₂ emission decomposition factors for the period 2010-2025.

Scenario	D_{tot}	D_{act}	D_{str}	D_{int}	D_{mix}
<i>BS</i>	1.33	1.48	1.02	0.88	0.99
<i>SC-2</i>	1.72	1.93	1.02	0.87	0.99
<i>SC-3</i>	1.57	2.02	1.02	0.87	0.88
<i>SC-4</i>	1.31	1.99	1.02	0.74	0.88

This analysis shows that CO₂ emissions increase 33% by 2025 ($D_{tot}=1.33$) in the *BS* scenario, mainly due to the increase of the income, $D_{act} = 1.48$, although the energy intensity is reduced to $D_{int} = 0.88$. In the *SC-2* scenario the emissions increase 72% with respect to 2010, mainly forced by the strong increase of the GDP, $D_{act} = 1.93$, which is partially compensated by the reduction of the energy intensity term, $D_{int} = 0.88$. *SC-3* scenario supposes an improvement with respect to *SC-2* scenario, $D_{tot} = 1.57$, due to the reduction of the mixing term in a 11%. Finally, *SC-4* scenario has an increase of CO₂ emissions even smaller than the *BS* scenario, $D_{tot} = 1.31$, which origin is the small value of the energy intensity, $D_{int} = 0.74$. The coefficients of the LDMI analysis are summarized in Table 4.

It is important to note that the reduction in the global CO_{2int} is twofold, on one hand, it is due to the use of a more efficient fossil fuel technology (lower energy intensity) and, on the other hand, due to the reduction of the share of fossil energy to the energy matrix. Both contributions are equally important. The period 2011-2025 presents a reduction of the global CO_{2int} from 2.4 to 2.1 ktCO₂/ktoe in *SC-3* and *SC-4* scenarios.

5.5. EKC verification

CO₂ emissions and GDP are strongly correlated in most of cases and the relationship between both variables is expected to be monotonously increas-

⁶Note that there is an extra factor, D_{emf} , the emission factor, which remains unchanged and equal to one.

ing. The EKC suggests that the almost linearly increasing relationship between CO₂ emissions and GDP can be broken under certain circumstances as was explained in section 1. To face this problem we first depict CO₂ versus GDP, as it is shown in Fig. 6. In this figure we plot the raw and the smoothed data for the period 1980-2010, as well as the results for the extrapolated period, 2011-2025, under the four considered scenarios. The black full line that corresponds to the *BS* scenario shows a moderated raising with a steadily increase of the GDP, showing a clear linear tendency for GDP larger than 250 billion USD. The red dashed curve that stands for the *SC-2* scenario presents a more rapid growth of the GDP and once more a linear relationship with the CO₂ is fulfilled. Finally, green and blue lines correspond to the *SC-3* and *SC-4* scenarios, respectively, and both show a rapid increase of the GDP, even faster than in the *SC-2* scenario, due to the feedback mechanism, but the slope of the curves is smaller than in the *BS* and *SC-2* scenarios. This suggests that the latest scenarios can be on the way to achieve a more sustainable sounding situation. In the *SC-2* scenario the GDP grows substantially and no attenuation measures are carried out, that is why the slope is the same than in the *BS* scenario. In the *SC-3* scenario the use of renewable energy is promoted and in the *SC-4* scenario, moreover, the energy intensity is reduced, explaining the change in slope with respect to *BS* and *SC-2* scenarios. We also mark in Fig. 6 the year of the turning point into the second stage of the EKC for the different scenarios, as explained below in this section.

Table 5: Ng-Perron tests^a for unit root.

Variable	$\overline{MZ}_\alpha^{GLS}$	\overline{MZ}_t^{GLS}	\overline{MSB}^{GLS}	\overline{MPT}^{GLS}
$LGDP_t$	-1.458	-0.497	0.341	30.493
$LCO2_t$	0.361	0.297	0.823	144.345
Critical values	$\overline{MZ}_\alpha^{GLS}$	\overline{MZ}_t^{GLS}	\overline{MSB}^{GLS}	\overline{MPT}^{GLS}
10%	-14.2	0.185	-2.62	6.67
5%	-17.3	0.168	-2.91	5.48
1%	-23.8	0.143	-3.42	4.03

^a The *Modified Akaike Information Criteria (MAIC)* are used to select the autoregressive truncation lag, k , as proposed in Perron and Ng [56]. The critical values are taken from Ng and Perron [57, table 1].

Prior to a more quantitative analysis it is compulsory to test the order of integration of both variables $LGDP_t$ and $LCO2_t$ using the tests of Ng and Perron [57]⁷. The results in Table 5 show that the null hypothesis of no stationarity cannot be rejected, independently of the statistic used, for both series, $LGDP_t$ and $LCO2_t$. Accordingly, both series would be concluded to be I(1).

Once the order of integration of the series is analyzed, we will analyze the long-run regression model [5] using the Dynamic Ordinary Least Squares (DOLS)⁸ estimation method of Stock and Watson [4] following the methodology proposed by Shin [58]⁹. This approach is similar to the KPSS¹⁰ tests, which are implemented in two stages for the case of cointegration.

We will estimate the coefficients of a long-run dynamic equation [5] including leads and lags of the explanatory variables (GDP in our case) in the long-run regression model, *i.e.* the so-called DOLS regression:

$$LCO2_t = \mu_0 + \mu_1 LGDP_t + \sum_{j=-q}^q \mu_j \Delta LGDP_{t-j} + \epsilon_j. \quad (17)$$

Moreover we use the statistic C_μ ¹¹, a LM-type test designed by Shin [58], to test the null hypothesis of cointegration against the alternative of no cointegration in a DOLS regression. In Table 6 we report the estimates from the DOLS regression and the results from Shin [58] test. Results show evidence of linear cointegration between CO₂ emissions and GDP, because we cannot reject the null hypothesis of cointegration. The estimated value of the CO₂-GDP elasticity for the dataset period is $\mu_1 = 1.178$, which denotes little environmental responsibility, *i.e.*, Venezuela in the year 2010 is still in the first stage of the EKC.

⁷These authors proposed using test statistics, which are modified versions of Phillip-Perron and ADF tests. Such modifications improve the tests with regard to both size distortions and power.

⁸Least squares estimation of equation might suffer two problems: endogeneity bias in the explanatory variables and nuisance parameter dependencies due to serial correlation in the residuals.

⁹In order to overcome the problem of the low power of the classical cointegration tests in the presence of persistent roots in the residuals of the cointegration regression, Shin [58] suggests a new test where the null hypothesis is that of cointegration.

¹⁰These tests are called Kwiatkowski et al. [59] tests, and assume the null hypothesis of stationarity.

¹¹ C_μ is the test statistic for deterministic cointegration, *i.e.*, when no trend is present in the regression.

Table 6: Stock-Watson-Shin's DOLS ^{a,b,c,d} estimation of linear cointegration.

Parameter	data	BS	SC-2	SC-3	SC-4
estimates	1980-2010	1980-2025	1980-2025	1980-2025	1980-2025
μ_0	5.506*** (0.023)	7.515*** (0.1777)	7.095*** (0.247)	7.799*** (0.366)	8.878*** (0.513)
μ_1	1.178*** (0.047)	0.764*** (0.038)	0.862*** (0.052)	0.723*** (0.076)	0.509*** (0.107)
R^2	0.998	0.991	0.994	0.987	0.962
Test: C_μ^c	0.152	0.144	0.187	0.194	0.193
σ^2	0.011	0.028	0.027	0.040	0.057

^a Standard errors (in brackets) are adjusted for long-run variance. The long-run variance of the cointegrating regression residual is estimated using the Barlett window which is approximately equal to $\text{INT}(T^{1/2})$ as proposed by Newey and West [60].

^b We choose $q=\text{INT}(T^{1/3})$ as proposed by Stock and Watson [4].

^c C_μ is a LM statistic for cointegration using the DOLS residuals from deterministic cointegration, as proposed by Shin [58]. *, ** and *** denote significance at the 10%, 5% and 1% level, respectively.

^d The critical values are taken from Shin [58, Table 1, m=1]: $C_\mu = 0.231$ (10%), $C_\mu = 0.314$ (5%), $C_\mu = 0.533$ (1%).

Our main goal is to study the EKC of Venezuela as a function of the time, in the medium term, up to 2025. To carry out this study, we perform the same process described above using the projected series provided by our model. Results are shown in Table 6. As it can be seen, for all the scenarios $\mu_1 < 1$ which proves that Venezuela is on the way to enter in the second stage of the EKC. In the case of the *BS* scenario, the elasticity goes from $\mu_1 = 1.178$ in 2010 to 0.764 in 2025, while in the *SC-2*, *SC-3*, and *SC-4* scenarios it moves till 0.862, 0.723, and 0.509 in 2025, respectively. In Fig. 7 we show the evolution of the CO₂-GDP elasticity as a function of the year for the period 2000-2025. This figure shows a very stable value of the elasticity for the reference period, up to 2010, and then a down sloping tendency in all the considered scenarios, which means that Venezuela is moving into the second stage of the EKC. In the *BS* scenario the elasticity goes rapidly below 1 (turning point in 2014) but remains stable for the rest of the period. To understand this fact we have to take into account that the data concerning energy intensity in Venezuela, which shows a quite erratic evolution in the

reference period in all the industrial sectors, leads to a down sloping smooth projection for the period 2011-2025. This reduction of the energy intensity is the origin of the reduction of the elasticity. The same argument holds in the *SC-2* scenario, because for this scenario the energy intensity has the same evolution than in the *BS* scenario. In this case the entrance in the second phase of the EKC happens latter, turning point in 2016. The behavior of the *SC-3* scenario is very similar to *SC-2* scenario, although in this case renewable energy is promoted. The turning point of the *SC-3* scenario also happens in 2016. Finally in the *SC-4* the faster decreasing of the elasticity is obtained, showing the turning point in 2014. Besides having the different scenarios different turning points, they also have a different asymptotic behavior. *BS* and *SC-2* scenarios seem to converge to a constant value, around $\mu_1 = 0.76$, while in *SC-3* and *SC-4* scenarios the elasticity continues decreasing all the time. We can extract as a conclusion that although it is possible to reduce the rate of emissions even without implementing any sustainable goal, rapidly the country gets a saturation value. However, undergoing the appropriate sustainable measures the country can steadily reduce the CO₂ emission rate and eventually reduce CO₂ emissions. The obtained results are not general and depend very much on the country, i.e., of the reference data set. Indeed, in a previous work for Ecuador [2] the evolution of the value of the elasticity is quite different to Venezuela.

Changes made in the *SC-4* scenario (promotion of renewable energy and increase of the energy efficiency in the productive sectors) help to create a more favorable future scenario in terms of sustainable development. Undergoing the goals of this scenario, the country could be able to enter the area of environmental stability in the medium term.

6. Summary, conclusions and policy implications

In this paper we have estimated the value of the GDP, the energy consumption and the CO₂ emissions in Venezuela in the medium term, from 2011 to 2025. The model was based on a nexus relationship which is a variation of the Kaya identity and on a GDP formation which includes the effect of renewable energy. This model was first presented by Robalino-López et al. [1, 2] and applied to Ecuador. The official data set for the period 1980-2010 was used to calibrate the model, while in the period 2011-2025, an estimation of different variables, including CO₂ emissions and sectoral energy consumption, was carried out. On the other hand, different scenarios that represent the evolution of GDP, energy matrix and productive

sectoral structure have been defined. One of the key points of the model is the direct influence of renewable energies on the GDP [18], which creates a feedback mechanism between income and CO₂ emissions. The relationship between CO₂ emissions and GDP is studied on the light of the environmental Kuznets curve (EKC) and the value of the CO₂-GDP elasticity is calculated as a function of the time. It is found that Venezuela will enter into the second phase of the EKC in the coming years.

We have carried out the projection of CO₂ emissions under four different scenarios. First, in the *BS* scenario (baseline scenario), the variables of the model were taken accordingly to the observed tendency in the reference period 1980-2010. For this scenario the emissions in 2025 are 33% higher than in 2010. Similarly, the second scenario, *SC-2*, is characterized by the doubling of income in 2025 relative to 2010. In this case the emissions are 72% higher than in 2010. In the third scenario, *SC-3*, besides assuming the doubling of the GDP, we impose a decrease of the fossil energy share down to 76%, reaching, CO₂ emissions at the end of the period 57% higher than in 2010. Finally, in the fourth scenario, *SC-4*, we also include changes in the productive sectoral structure to achieve a reduction of energy intensity, which supposes a decreasing of the CO₂ intensity. In this case, the emissions are even lower than in the *BS* scenario, only 31% higher than in 2010. In the *SC-3* scenario the increasing use of renewable energy allows to reduce CO₂ emissions 15% with respect to *SC-2* scenario. Finally, in the *SC-4* scenario an improvement of the energy intensity is implemented, reaching a reduction of 41% with respect to the *SC-2* scenario. Therefore, we can conclude that the reduction of CO₂ emissions can be accomplished using two different strategies: improving the energy intensity and increasing the share of renewable energies to the total energy consumption. Because of the lack in the literature of projections of CO₂ emissions for Venezuela, we cannot directly compare our results with any other, although one can find in the bibliography some reference points with which to check the model and the scenarios. On one hand, our estimations of CO₂ emissions are larger than the target proposed by the National Electricity Corporation of Venezuela for 2050, which corresponds to half the emissions in 1999 [41]. This target is based on the renewable energy resources available in Venezuela and not yet used. Therefore the CO₂ emissions for the *SC-3* and *SC-4* scenarios could be even lower if the share of renewable energy to the energy matrix is increased more than in the proposed scenarios. On the other hand, in [23] it is shown that the *CO₂ efficiency* of Venezuela increased from 1997

to 2007, which suggests that *SC-3* and *SC-4* are probably rather realistic scenarios.

Concerning the analysis of the EKC hypothesis we conclude that Venezuela do not fulfill this hypothesis under any of the considered scenarios, i.e., in the medium term the CO₂-GDP elasticity is always positive. Our results show that Venezuela in 2010 is still in the first stage of the EKC and that under the *BS* scenario can only slightly reduce the value of the elasticity and it will remain with a rather stable value if no attenuation measures are implemented in the near future. Very much the same situation happens under the *SC-2* scenario, which only differs of the *BS* scenario in the rapid increase of the GDP. Although the country enters into second stage of the EKC relatively soon, in 2014 and 2016 for the *BS* and *SC-2* scenarios, respectively, the elasticity moves into a constant value, $\mu_1 \approx 0.76$, in the medium term and therefore the country will move towards a dead end, concerning environmental sustainability. In *SC-3* and *SC-4* scenarios different environmentally sounding measures are implemented and, once more, the country enters very rapidly into second stage of the EKC, also in the years 2016 and 2014 for the *SC-3* and *SC-4* scenario, respectively. However, in this case the trend of the elasticity is clearly down sloping and it could be expected to reach a negative value in the medium term, especially in the *SC-4* scenario. The diversification of energy sources and the reduction of the energy intensity is essential to reach a sustainable development. Fossil fuel substitution has been proven to be a successful way to reduce emissions by moving energy consumption into forms with lower carbon intensity and improving energy efficiency. Our results are in agreement with Narayan et al. [25] who found that Venezuela for the period 1980-2004 showed evidences of the fulfillment of the EKC, with a long-run elasticity of 0.29, much smaller than the short-run one, 1.57, which is a hint of the accomplishment of the EKC hypothesis.

The methodology presented in this paper can be useful to estimate CO₂ emissions of a given country and to understand the driving forces that guide this process, such as economic growth, energy use, energy mix structure, and fuel use in the productive sectors. Moreover, it can serve as a pedagogical tool for explaining to policymakers the possible ways to design a policy for reducing CO₂ emissions in a medium term horizon. As was stated by Robalino-López et al. [1, 2], the presented methodology is transferable to other period of time or region.

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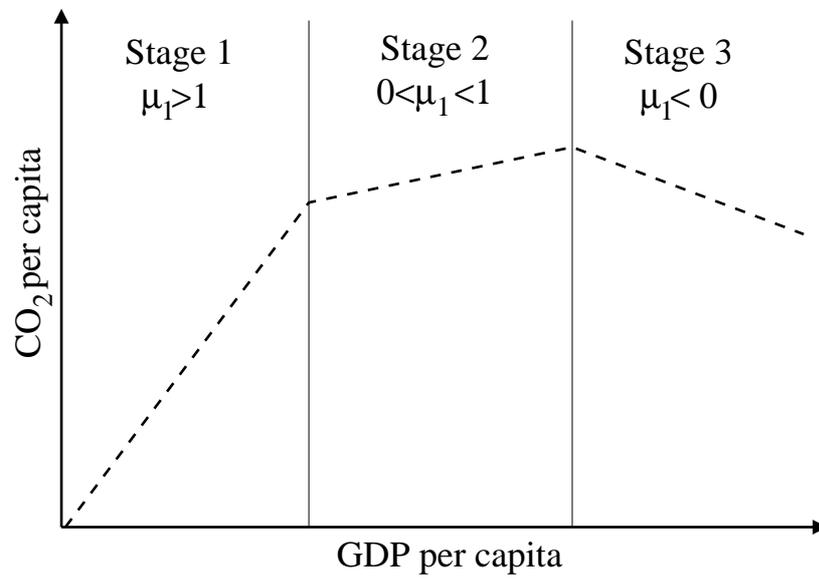


Figure 1: Schematic plot of the U inverted relationship between GDP per capita and CO₂ emission per capita: stage 1 corresponds to a rapid growth of the emission, stage 2 to the stabilization phase, and stage 3 to the reduction of the CO₂ emission as the income increases.

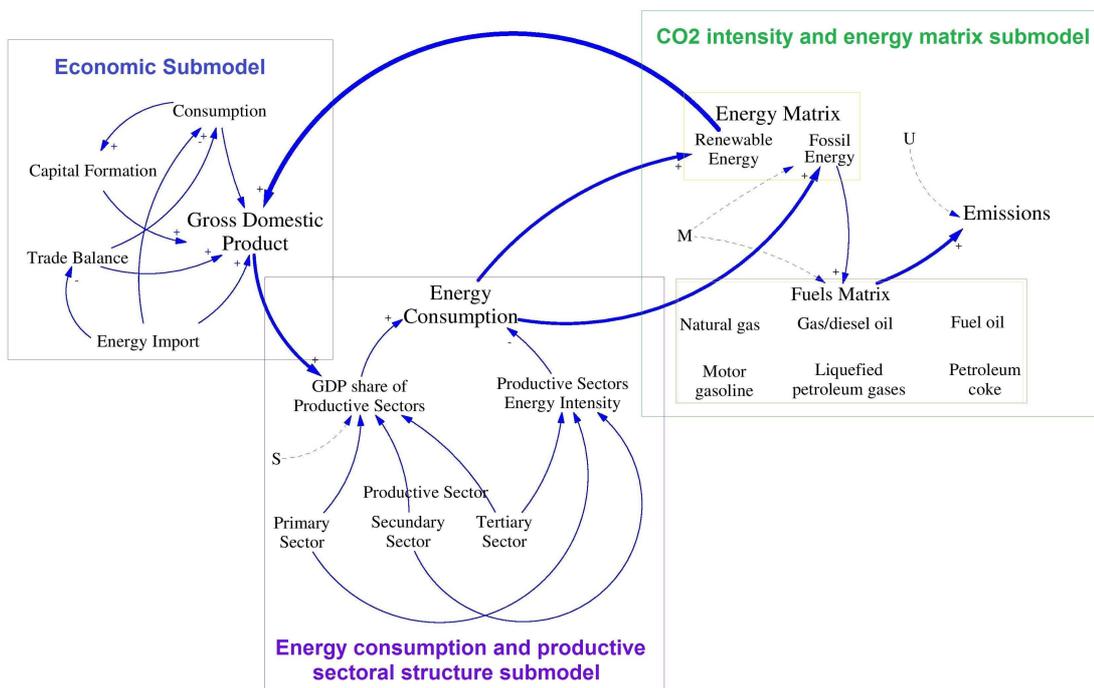


Figure 2: Causal diagram of the model. Continuous lines stand for the relationship between variables, while dashed ones correspond to control terms (S: *productive sectoral structure*, M: *energy matrix*, U: *emission factors*). Bold line represents a feedback mechanism.

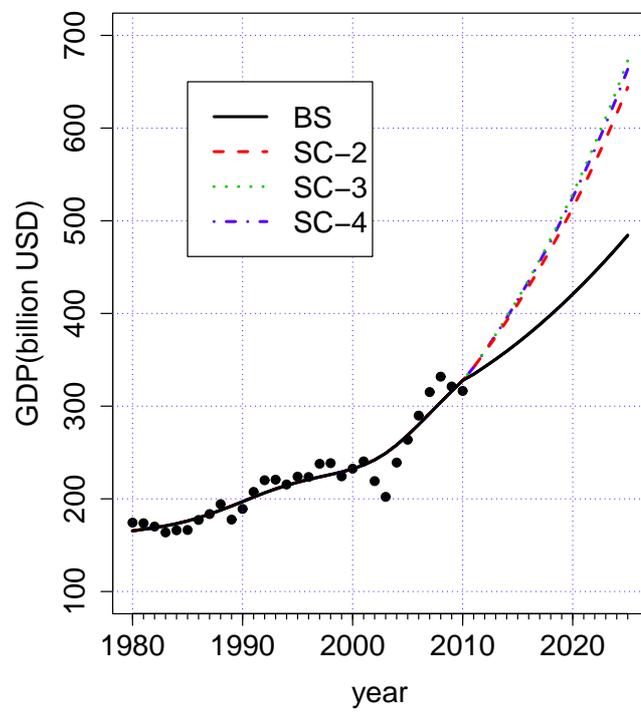


Figure 3: GDP of Venezuela for the period 1980-2025. Dots correspond to the official dataset.

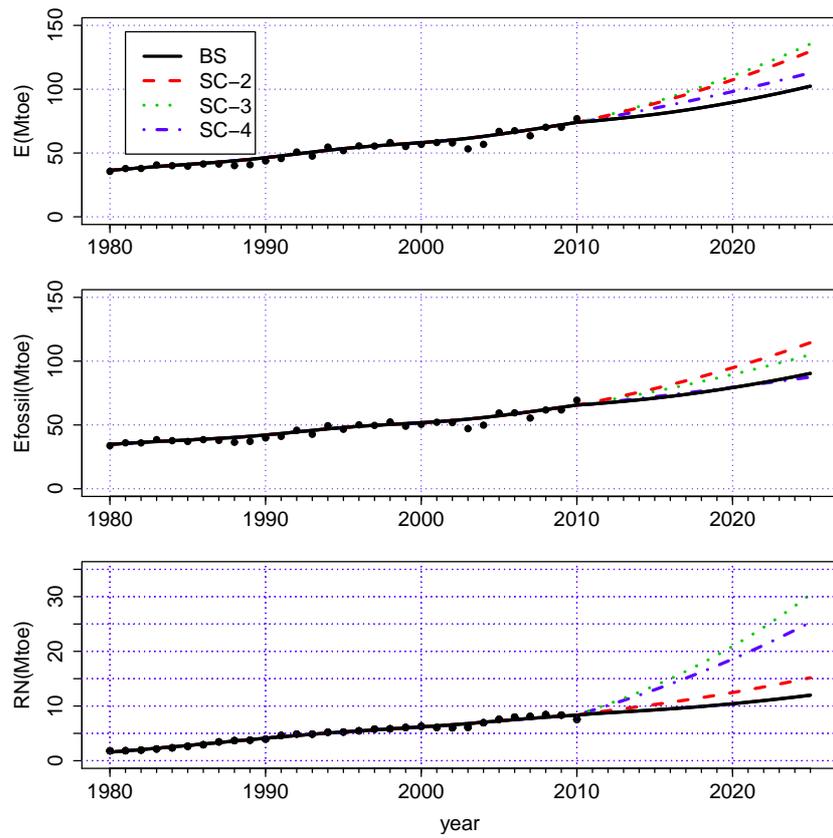


Figure 4: Energy consumption of Venezuela for the period 1980-2025. Top panel: total energy consumption. Mid panel: fossil energy consumption. Bottom panel: renewable energy consumption. Dots correspond to the official dataset.

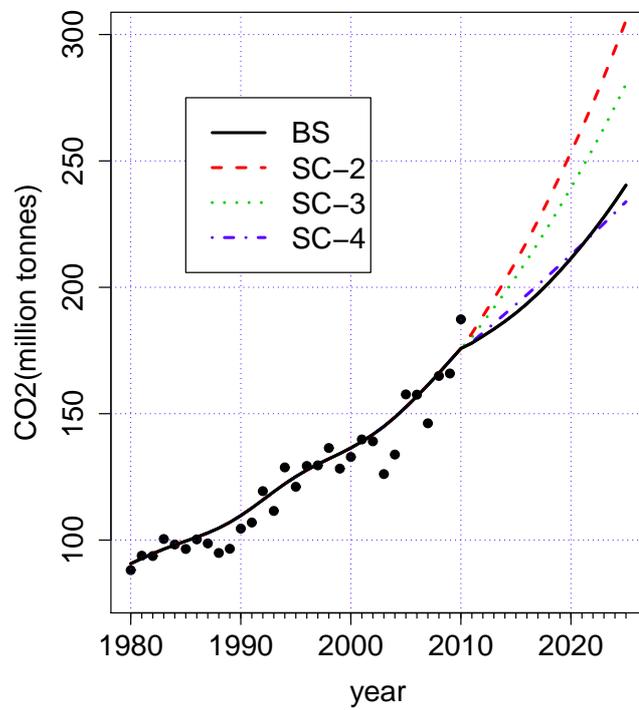


Figure 5: CO₂ emissions of Venezuela for the period 1980-2025. Dots correspond to the official dataset.

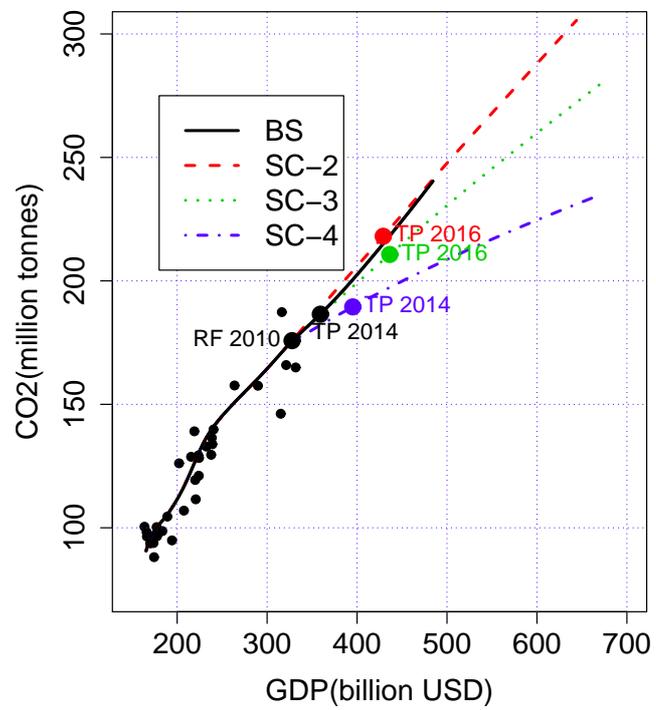


Figure 6: Venezuela GDP vs CO₂ emissions for the period 1980-2025. Dots correspond to the official data, *RF* stands for *Reference year* and *TP* for *Turning point*.

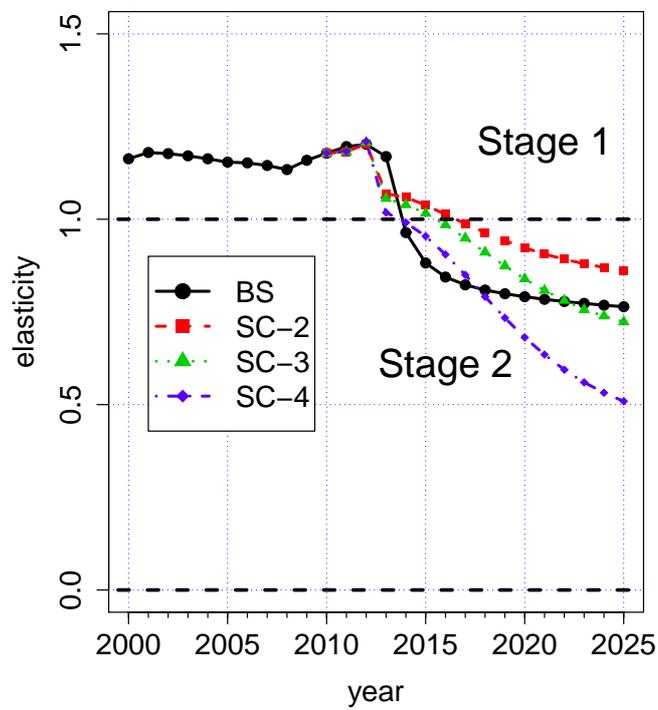


Figure 7: Evolution of Venezuelan CO₂-GDP elasticity for the period 2000-2025.