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RESEARCH ARTICLE

Determinants of CO_2 emissions in the MERCOSUR: the role of economic growth, and renewable and non-renewable energy

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Abstract
The main objective of this study was to analyze the impact of energy consumption (divided into renewable and non-renewable sources) and income on CO_2 emissions within the environmental Kuznets curve (EKC) model for the Southern Common Market (MERCOSUR). To do so, the annual panel data collected during the 1990–2014 periods was used. The CO_2 variable, representing carbon dioxide emissions in metric tons per capita, was used as a proxy for the emission of pollutants. The annual data were obtained from the World Bank (World Development Indicators). The sample consisted of the five MERCOSUR member countries: Argentina, Brazil, Paraguay, Uruguay, and Venezuela, comprising a period of 25 consecutive years. The results showed that energy consumption from renewable sources had a negative impact on CO_2 emissions, while the energy consumption from non-renewable sources had a positive impact. The positive impact of economic development on CO_2 emissions was also seen. In addition, this study supports the validity of the EKC hypothesis for the MERCOSUR because GDP (real output) leads to environmental degradation while GDP^2 reduces the level of gas emissions.

Keywords CO_2 · EKC · Economic growth · Renewable energy · Non-renewable energy · MERCOSUR

Introduction

Due to large increases in greenhouse gas emissions (GHG) in recent decades, environmental pollution has become one of the most critical global issues. Many countries, including those of the European Union (EU), signed the Kyoto Protocol, which entailed specific target goals per country (Dogan and Seker 2016). This Protocol proposed a 5.2% reduction in GHG emissions, taking 1990 levels as a reference. Developed countries which subsequently ratified the Protocol committed themselves to reduced targets while developing countries were encouraged to reduce their emissions on a voluntary basis (United Nations 1998).

Irrespective of its commitment under the Kyoto Protocol, the EU adopted stricter environmental targets through binding legislation with the 2020 climate-energy package, which aims to make Europe a low-carbon economy and increase energy efficiency. The goal is a 20% reduction in greenhouse gas emissions and an increase of up to 20% in the use of renewable resources by 2020. Disengaging economic growth from carbon dioxide emissions has become an environmental ambition. Governments are committed to reducing their greenhouse gas emissions without undermining their economic development, based on the assumption that greater economic growth does not always lead to increased emissions. Italy ratified the Kyoto Protocol and has adopted European energy initiatives, such as the European Emissions Trading Scheme, the White Certificate Scheme in Italian legislation, financial incentives, and the legislative framework for increasing energy efficiency, in an attempt to meet their 2020 targets for CO_2 emissions (Bento and Moutinho 2016).

Several research studies have highlighted the relationship between CO2 emissions, GDP (or economic growth), and energy consumption (electricity). Other studies investigate the relationships between renewable energy, non-renewable energy, and economic growth, while a third group of studies

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analyzes the link between CO2 emissions, GDP, and energy consumption from renewable and non-renewable sources.

This research has mainly been carried out in Turkey (Halicioglu 2009; Ozturk and Acaravci 2010a; Say and Yücel 2006; Soytas and Sari 2009; Soytas et al. 2007), France (Ang 2007), Malaysia (Ang 2008), Central American countries (Apergis and Payne 2009), Central and Eastern Europe (Atici 2009), Albania, Bulgaria, Hungary, and Romania (Ozturk and Acaravci 2010b), BRICS countries (Cowan et al. 2014; Pao and Tsai 2011), China (Du et al. 2012; Jalil and Feridun 2011), Russia (Pao et al. 2011), Pakistan (Nasir and Ur Rehman 2011), panel of newly industrialized countries (Sharif Hossain 2011; Park and Hong 2013), MENA countries (Farhani and Shahbaz 2014; Omri 2013), Asia (Chandran and Tang 2013), Malaysia (Bölük and Mert 2014; Shahbaz et al. 2013; Farhani and Ozturk 2015; Shahbaz et al. 2014), Turkey (Bölük and Mert 2015; Dogan 2015; Seker et al. 2015; Yavuz 2014), G7 countries (Ajmi et al. 2015; Sadorsky 2009), Saudi Arabia (Alshehry and Belloumi 2015), European Union countries (Bengochea and Faet 2012; Kasman and Duman 2015; López-Menéndez et al. 2014), Canada, Denmark, Iceland, Finland, Norway, Sweden, USA (Baek 2015), 93 countries (Al-Mulali et al. 2015), Vietnam (Al-Mulali et al. 2015; Tang and Tan 2015), OECD countries (Apergis and Payne 2010a; Chiu and Chang 2009; Inglesi-Lotz 2015; Ben Jebli and Ben Youssef 2015; Apergis and Payne 2012b), emerging countries (Nicholas Apergis and Payne 2011a), Central America (Apergis and Payne 2012a; Apergis and Payne 2011b; Bhattacharya et al. 2016), Latin America (Al-mulali et al. 2014), Pakistan (Shahbaz et al. 2015a), France (Iwata et al. 2010), developed countries development panel (Apergis et al. 2010), USA, Japan, France, Korea, Spain, and Canada (Baek and Pride 2014), North Africa (Ben Jebli and Ben Youssef 2015), and South America (Apergis and Payne 2015).

To date, there is no published research on the determinants of CO_2 emissions in the countries of the Southern Common Market (MERCOSUR). MERCOSUR was created in 1991 under the Treaty of Asunción, promoted by the then Brazilian President Fernando Collor de Mello and the Argentine President Carlos Menem. Its main objective was to create a common market between Argentina, Brazil, Paraguay, and Uruguay. This paper also considers Venezuela, which became an effective member in 2012. These countries together account for more than one third of all South American GDP. "Brazil, the main member of the above-mentioned economic bloc, is the 10th largest emitter of CO_2 in the world" (Olivier et al. 2016, p. 33). Based on the already-highlighted context and the reasons given, the proposed research problem is: "What are the relationships between renewable and non-renewable energy consumption, income and CO_2 emissions for MERCOSUR member countries?" In order to respond to this research problem, this study sets out to investigate the impact of energy consumption—both renewable and non-renewable—and income on CO_2 emissions within the environmental Kuznets curve (EKC) model.

This empirical study makes several contributions to environmental preservation—enriching the literature on the use of renewable and non-renewable energy—since most existing studies use aggregate energy consumption in their models and cannot therefore identify the effects of energy consumption by source (renewable and non-renewable), especially in emerging economies, such as the MERCOSUR member states. The primary objective of this study is to investigate, for the first time in the literature, the influence of real income, and the consumption of renewable and non-renewable energy on CO_2 emissions.

This research applies a cointegration modeling approach to empirically verify the validity of the Kuznets-proposed hypothesis, which when represented graphically takes the form of an inverted "U" and has been rationalized in terms of dualistic development models.

Economic growth, environment, and sustainability

For many years, the possibility of stagnation of the environment's capacity for Provisioning Services[1] was seen as the main limit to economic growth (Meadows et al. 1972). However, it has recently become clear that the threshold for growth may not be the limited amount of raw material that nature provides, but the Regulating Services[2] of the natural processes provided by nature (Brock and Taylor 2005; Duraiappah et al. 2005). In recent decades, for example, attractive alternatives to fossil fuel, which is non-renewable, have been increasingly used, such as energy, the sun, wind, hydroelectricity, biomass, and ethanol, etc. Parallel to the gradual change in the energy matrix is the increasing use of vehicles powered by electricity. They dispense with the use of fossil fuel, which, because of its finite nature, could impede development. Technology is also helping to produce food in ways never before imagined.

That is not to say that the question of the exhaustion of natural resources is not a cause for concern. It certainly is, but there are more critical concerns involving issues of pollution, industrial waste, and lack of potable water in a broader sense. And specifically, GHG emissions, which cause global

[1] Provisioning services—products obtained from ecosystems, including fresh water, food, fiber, genetic resources, biochemicals, natural medicines, and pharmaceuticals (Everett et al. 2010).

[2] Regulating services—benefits obtained from the regulation of natural processes, including air quality, climate, water/flood, erosion, water purification, disease and pest control, pollination, and buffering pollution (Everett et al. 2010).

warming, are surely increasing the temperature of the planet and negatively impacting the lives of all species.

These Regulating services have consequently received more attention from researchers, especially from the 1990s onwards. During this period, empirical research was undertaken with greater intensity and was only made possible by the measurement and monitoring of the environmental impact indicators. By means of the regulating services, nature dissipates polluted air, water pollution, and solid pollutants, and it also functions as a place of disposal for millions of tons of chemical and toxic waste. When the environment's capacity to dissipate or absorb waste is exceeded, environmental quality suffers and the response to this impaired quality can, in turn, limit economic growth (Brock and Taylor 2005), because reduced environmental quality requires more intensive measures to reduce emissions and clean up, all of which decrease returns on investment, and consequently affect economic performance.

In summary, on analyzing the literature on economic growth and the environment, it can be seen that, mainly from the 1970s onwards, there has been a change in focus. There are growing concerns about global warming and polluting emissions and not just about the depletion of oil or magnesium. This research, therefore, focuses on the determinants of emissions of CO_2, one of the main gases responsible for the greenhouse effect.

Policy developments in the field of energy-environment-economy in MERCOSUR

Climate scientists have shown that concentrations of carbon dioxide (CO_2) in the atmosphere have significantly increased over the past century and there is a clear influence of human activity on the climate system. Of the many human activities which produce greenhouse gases, energy consumption represents 68% of total emissions (International Energy Agency 2017, p.3). Consequently, it is important for this research to consider the composition of the energy matrix of the MERCOSUR countries.

Figure 1 shows that for all the MERCOSUR countries, with the exception of Argentina, the main source of energy generation is hydroelectricity, followed by thermoelectricity which is a considerable source of energy generation for countries, such as Argentina and Venezuela. When it comes to energy consumption from renewable energy sources, other than hydroelectric plants, Uruguay ranks first with 17%, followed by Brazil with 10%.

In many regions of the world, neighboring countries feel pressurized to take steps towards interconnecting their electric power systems (Pineau et al. 2004). Although the MERCOSUR countries present different levels of socio-economic development, as shown in Table 1, it is worth noting that interconnections already exist in the region's energy markets, for example, the Itaipu dam, between Brazil and Paraguay, with a capacity of 12,600 MW; the Yacyretá dam, between Argentina and Paraguay, with a capacity of 2700 MW; and the Salto Grande dam, between Argentina and Uruguay, with a capacity of 1890 MW. However, the physical link between these countries is a severe constraint on the possibilities for regional trading.

As energy markets become global and interdependent, issues affecting energy systems also increase in number and complexity. Accordingly, energy security in global markets is determined by various factors, such as economic growth, energy efficiency, pressure to reduce greenhouse gas emissions (GHG), development and implementation of new technologies as well as the social role in ensuring access to energy (Santos et al. 2017).

Energy security can be understood as "the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy" (APERC 2007). However, to analyze the concept of energy security, it is necessary to take the socio-economic status of countries into account. In terms of development and sustainability, developed countries focus almost exclusively on environmental issues, while for

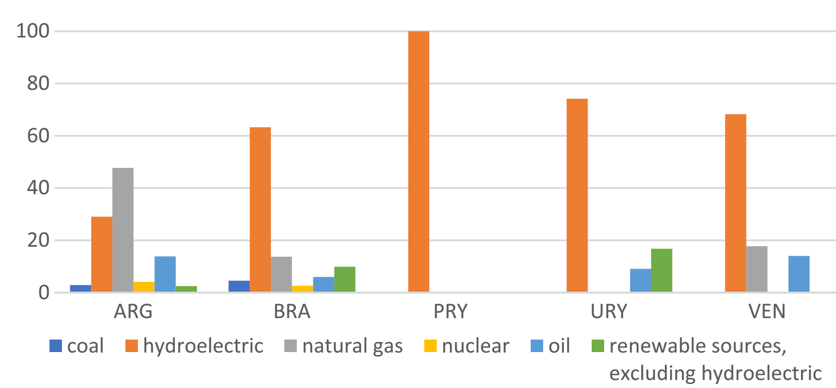

Fig. 1 Percent of total primary energy consumption by fuel type in MERCOSUR 2014; Data from World Bank Indicators

Table 1 Socio-economic indicators for MERCOSUR countries

Country	Area (km^2)	Population (millions inhab)	Urban population (%)	HDI	Gini index per capita (US$ 1)	GDP[1]	GDP at current price (US$ bi)
Argentina	2,766,889	41.4	91.5	0.8	0.42	10,323	610
Brazil	8,511,965	200.0	85.2	0.7	0.51	11,866	2246
Paraguay	406,752	6.8	59.2	0.7	0.51	3761	29
Uruguay	176,215	3.4	95.0	0.8	0.41	13,856	56
Venezuela	916,445	30.4	88.9	0.8	0.44	14,462	227

World Data Bank and ALADI Statistics; GDP[1] data for 2014, except for Venezuela, whose data are for 2013

developing countries, issues such as poverty and equity are top priority (APERC 2007; Santos et al. 2017). Table 2 shows how the concept of energy security changes from country to country in the MERCOSUR and summarizes overall policy developments in the field of energy-environment-economy.

As noted in Table 2, there are differences between MERCOSUR member countries as to how their regulatory systems are setup and run. These asymmetries and differences between partners, as well as historical distrust, appear as obstacles to creating a sense of cooperation. Macroeconomic uncertainties also inhibit the flow of investment in the energy sector.

Literature review and development of hypotheses

Relationships between CO_2 emissions, economic growth, and aggregate energy consumption have been the subject of studies in recent years, especially at international level. In general, these surveys can be divided into three groups, showing different results. The first research group highlighted the relationships between CO_2 emissions as a proxy for pollution, GDP (or economic growth), and aggregate energy consumption (Ajmi et al. 2015; Alshehry and Belloumi 2015; Ang 2007; Apergis and Payne 2009, 2015; Atici 2009; Baek 2015; Ben Jebli and Ben Youssef 2015; Chandran and Tang 2013; Cowan et al. 2014; Dogan and Seker 2016; Dogan and Turkekul 2016; Du et al. 2012; Farhani and Ozturk 2015; Halicioglu 2009; Jalil and Feridun 2011; Kasman and Duman 2015; Nasir and Ur Rehman 2011; Omri 2013; Ozturk and Acaravci 2010a, b; Pao et al. 2011; Pao and Tsai 2011; Park and Hong 2013; Say and Yücel 2006; Seker et al. 2015; Shahbaz et al. 2013, 2014, 2015b; Sharif Hossain 2011; Soytas and Sari 2009; Soytas et al. 2007; Tang and Tan 2015; Yavuz 2014).

Several studies are based on the EKC (Ajmi et al. 2015; Apergis and Payne 2009; Atici 2009; Baek 2015; Chandran

Table 2 Energy policy variables in MERCOSUR. Adapted from Santos et al. (2017)

Variable	Argentina	Brazil	Paraguay	Uruguay	Venezuela
Role of the STATE	Passive actor	Protectionist (a)	Nationalization of resources	Main actor (regulator)	Nationalization of resources
Private Initiative	Active	Yes	No	Regulated participation	No
Public-private partnerships (PPP)	Yes	Yes. Opening up of capital in 1995	No	Yes (under mediation of the executive power)	No
Focus on demand guarantee	Yes	Yes	Yes (PND 2030)	Yes	Yes (b)
Divides analysis into short and long term?	Yes	Yes (c)	Yes	Yes	Yes
Mention environmental issues	Yes	Yes, always in documents	Yes (d)	Yes	Yes
Mention regional integration	Yes	No	Yes (e)	Yes (with the countries of the bloc)	Yes (f)
Encourages renewable/alternative energies	Yes	Yes (g)	Yes (h)	Yes	Yes (i)
Focuses on non-renewable resources	Yes (l)	Yes (pre-salt reserve)	No	No	Yes (l)

Notes: (a) with a view to preserving national interest, according to Law 9478/1997; (b) despite facing serious internal crisis; (c) through short plans and PNE2030; (d) due to its essentially hydroelectric matrix; (e) with a view to selling the Itaipu surplus to other countries; (f) with LAC countries; (g) plans for hydroelectric, wind, and solar; (h) maintenance of hydroelectric plant only; (i) despite mentioning issue in regional and international organizations, internal practice is not observed; (l) maintenance of fossil matrix.

and Tang 2013), while many others do not investigate the presence of the EKC hypothesis. Those who examined the validity of the EKC hypothesis found greatly diverging results, even for the same countries and regions. This is the case of Turkey, as some studies point to the validity of the EKC (Seker et al. 2015; Yavuz 2014) while others did not find any substantial evidence that the EKC model could be applied to the same country (Halicioglu 2009; Ozturk and Acaravci 2010a). No support for the EKC hypothesis has been found for the UK, Italy, or Japan (Ajmi et al. 2015), while for the Arctic countries (Canada, Finland, Denmark, Iceland, Norway, Russia, Sweden, and the USA (Alaska)), little evidence has been found (Baek 2015).

As regards trade openness, normally used as a control variable, researchers, such as ATICI (2009), did not find statistical significance in this relationship. On the other hand, Jalil and Feridun (2011) and Nasir and Ur Rehman (2011) show that trade openness contributes to increased pollution levels, while Dogan and Turkekul (2016) and Sharif Hossain (2011) indicate that trade liberalization mitigates pollution.

Trade openness can impact carbon emissions through composition, scale, and technique effects (Farhani et al. 2014). Scale effects mean that increases in trade can lead to higher GDP, higher energy consumption, and higher pollution. Composition effects imply that a country specializes in the production of certain goods with respect to comparative advantage, and accordingly increases in trade could lead to higher or lower pollution depending on whether the goods the country produces are in energy-intensive-polluted sectors or not. Lastly, the technique effect refers to technology spillover through trade flows between countries, and thus, the adoption of environmentally friendly technologies in producing goods could lead to environmental improvements (Dogan and Seker 2016). The net effect of trade openness on the environment can be either positive or negative depending on which effect is predominant.

The studies of the first group present consensus in regard to the influence of energy consumption on CO_2 emissions for the countries and regions analyzed. These include the most recent studies (Ajmi et al. 2015; Alshehry and Belloumi 2015; Apergis and Payne 2015; Baek 2015; Ben Jebli and Ben Youssef 2015; Chandran and Tang 2013; Cowan et al. 2014; Dogan and Seker 2016; Dogan and Turkekul 2016; Farhani and Ozturk 2015; Jalil and Feridun 2011; Kasman and Duman 2015; Nasir and Ur Rehman 2011; Omri 2013; Ozturk and Acaravci 2010a, b; Pao et al. 2011; Pao and Tsai 2011; Park and Hong 2013; Seker et al. 2015; Shahbaz et al. 2013, 2014, 2015b; Sharif Hossain 2011; Tang and Tan 2015; Yavuz 2014), although they report different directions of causality between carbon emissions, energy consumption, real income, and trade openness.

There is bi-directional causality between GDP and energy consumption for Japan, unidirectional causality of GDP for energy consumption for Italy and the UK, and one-way causality of energy consumption for GDP for Canada. On the other hand, there is bi-directional causality between energy consumption and CO_2 emissions for the USA and France (Ajmi et al. 2015). In Saudi Arabia, there is one-way causality between energy consumption for economic growth and CO_2 emissions, the long-term unidirectional causality between energy consumption for economic growth and CO_2 emissions. In the short term, there is one-way causality that stems from CO_2 emissions for energy consumption and GDP (Alshehry and Belloumi 2015).

Ang (2007) shows that economic growth exerts a causal influence on energy consumption, and that both positively impact the emission of CO_2 in France (Ang 2007; Apergis and Payne 2009) and the Arctic countries (Canada, Finland, Denmark (Greenland), Iceland, Norway, Russia, Sweden, and the USA (Alaska)) (Baek 2015). For Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Suriname, Uruguay, and Venezuela, there is a positive relationship with real GDP per capita, per capita CO_2 emissions, and real oil prices (Apergis and Payne 2015). For Bulgaria, Hungary, Romania, and Turkey, the results confirm the existence of EKC, so that per capita CO_2 emissions decrease over time as GDP per capita increases (Atici 2009).

In the long term, bi-directional causality between economic growth and CO_2 emissions were detected in Indonesia and Thailand, and unidirectional causality of GDP for emissions of Romania in Malaysia (Chandran and Tang 2013). In turn, there is no evidence of causality between GDP and CO_2 emissions in India or China, while energy consumption causes CO_2 emissions in India (Cowan et al. 2014).

The second group investigates the relationships between renewable, non-renewable energy, and economic growth in a multivariate framework in which most studies use capital and labor as additional variables (Al-mulali et al. 2014; Apergis and Payne 2012a; Apergis and Payne 2010a, b, 2011a, b, 2012a; Bhattacharya et al. 2016; Dogan 2015; Fang 2011; Inglesi-Lotz 2015; Kula 2014; Shahbaz et al. 2015a).

Since renewable and non-renewable energies can have a different impact on economic growth (GDP), the second group decomposes aggregate energy consumption by source and then analyzes the energy and economic growth nexus for several countries and regions. They find a unidirectional causality between renewable energy and economic growth (Dogan 2015; Kula 2014), while others show bi-directional causality, including Al-Mulali et al. 2014; Shahbaz et al. 2015a.

A third group of studies looked at the link between CO_2 emissions, GDP, and energy consumption by source (i.e., renewable and non-renewable energy) (Al-Mulali et al. 2015; Apergis and Payne 2014; Apergis et al. 2010; Baek and Pride 2014; Bengochea and Faet 2012; Bölük and Mert 2014, 2015; Chiu and Chang 2009; Dogan and Seker 2016; Farhani and

Shahbaz 2014; Iwata et al. 2010; Jebli et al. 2016; López-Menéndez et al. 2014; Menyah and Wolde-Rufael 2010; Sadorsky 2009; Shafiei and Salim 2014).

There is a long-term cointegrated relationship between per capita renewable energy consumption, real GDP per capita, per capita carbon emissions, real coal, and real oil prices with their respective positive and statistically significant coefficients (Apergis and Payne 2014). In addition, renewable energy consumption contributes about 1/2 or less per unit of energy consumed than fossil energy consumption in terms of greenhouse gas emissions in EU countries. This implies that a shift in the mix of energy consumption to alternative renewable energy technologies can reduce GHG emissions (Bölük and Mert 2014), as the coefficient of electricity production from renewable sources in relation to emissions of CO_2 is negative and significant in the long run (Bölük and Mert 2015), and also highlights that nuclear energy tends to reduce CO_2 emissions (Baek and Pride 2014).

Existing studies, in general, show that renewable energy mitigates CO_2 emissions (Al-Mulali et al. 2015; Apergis and Payne 2014; Baek and Pride 2014; Bengochea and Faet 2012; Bölük and Mert 2014, 2015; Dogan and Seker 2016; Farhani and Shahbaz 2014; Jebli et al. 2016; López-Menéndez et al. 2014; Shafiei and Salim 2014), with the exception of Apergis et al. (2010) and Bölük and Mert (2014). Of these, several recent studies use trade openness as an additional variable to deal with the bias of the omitted variable but produce conflicting results for the net effect of trade on carbon emissions. In other words, the net effect of trade openness is statistically insignificant (Iwata et al. 2010), while in other cases, trade reduces emission levels (Jebli et al. 2016; Mouselli et al. 2013). On the other hand, the studies in the third group show different types of causal directions between CO_2 emissions, real income, renewable and non-renewable energy, and trade openness. The results of studies on the relationships between CO_2 emissions, energy consumption, and income do not always converge. Thus, given this scenario and the lack of studies on MERCOSUR member countries, the following research hypotheses are formulated:

- H_1 There is a positive and significant relationship between income and emission of pollutants in MERCOSUR countries;
- H_2 There is a negative and significant relationship between consumption of renewable energy and emission of pollutants in MERCOSUR countries;
- H_3 There is a positive and significant relationship between consumption of non-renewable energy and emission of pollutants in MERCOSUR countries;
- H_4 There is a quadratic relationship between income and emission of pollutants, showing the validity of the EKC hypothesis for MERCOSUR.

Model and data

This research used annual panel data for the 1990–2014 periods. The variable CO_2 was used as a proxy for emission of pollutants, which represents carbon dioxide emissions in metric tons per capita. The data were obtained from the World Bank (World Development Indicators), whose database is available on the http://data.worldbank.org website. The sample comprises the five MERCOSUR countries: Argentina, Brazil, Paraguay, Uruguay, and Venezuela, covering a period of 25 consecutive years, with 125 observations per variable. The period cannot be extended because data on renewable energy consumption (REC), a crucial variable for the model, are only available from the year 1990.

To study the influence of renewable and non-renewable energies on carbon dioxide (CO_2) emissions as a proxy for greenhouse gases, this study uses the well-known and frequently used environmental Kuznets curve (EKC), which basically states that an increase in gross domestic product (GDP) contributes to a certain extent to carbon emissions and then reduces the level of emissions as GDP continues to grow (Stern 2004).

The EKC model assumes that pollution increases with income in the early stages of economic growth, but that after a turning point, increased income leads to environmental improvement (Grossman and Krueger 1991). In other words, the EKC hypothesis presupposes a quadratic relationship between economic growth and environmental pollution. Furthermore, Stern (2004) also presents an assumption that the elasticity of CO_2 emissions relative to GDP is the same in all countries, although carbon emissions can vary between economies at any real income level.

Thus, to test the association between GHG emission and renewable energy production, non-renewable energy, and GDP, the following model was used:

$$\mathrm{CO}_{2it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 REC_{it} + \beta_3 NREC_{it} + \varepsilon_{it} \quad (1)$$

where

- CO_{2it} carbon dioxide emissions in metric tons per capita of country i in year t;
- GDP_{it} real value of GDP per capita, constant in US$ for the year 2010, of country i, in year t;
- REC_{it} consumption of renewable energy including hydroelectric, wind, solar, and biomass, measured as a percentage of the total energy consumption of country i in year t;
- NREC_{it} consumption of non-renewable energy such as thermal, oil, and natural gas, measured as a percentage of the country's total energy consumption of country i in year t.

In addition to the energy from renewable and non-renewable sources and GDP variables, some research emphasizes the importance of trade openness (TR) in the determination of CO_2 emissions (Dogan 2015; Halicioglu 2009; Jebli et al. 2016). By inserting trade openness into the basic framework as an additional variable, the modified EKC model, according to Dogan and Seker (2016), can be shown as in Eqs. 2, 3, and 4:

$$CO_{2it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 REC_{it} + \beta_3 NREC_{it} + \beta_4 TR_{it} + \beta_5 FD_{it} + \beta_6 URB_{it} + \varepsilon_{it} \quad (2)$$

$$CO_{2it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 REC_{it} + \beta_4 NREC_{it} + \varepsilon_{it} \quad (3)$$

$$CO_{2it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 REC_{it} + \beta_4 NREC_{it} + \beta_5 TR_{it} + \beta_6 FD_{it} + \beta_7 URB_{it} + \varepsilon_{it} \quad (4)$$

where

TR_{it} trade openness measured by the sum of imports and exports as a ratio of the total GDP of country i in year t;

FD_{it} financial development of country i in year t; measured by the amount of domestic credit provided by the financial sector in relation to GDP;

URB_{it} percentage of urban population as a ratio of the total population of country i, in year t.

The control variables were inserted into the model in order to give greater robustness to the results. The variables and their measurements are summarized and justified in Table 3.

Results

This study examines the relationships between carbon dioxide emissions, income, renewable energy consumption, non-renewable energy consumption, trade openness, financial development, and urbanization for MERCOSUR member countries, in the 1990–2014 periods.

The descriptive statistics of the variables presented in Table 4 show that Venezuela emits most CO_2, with an average of 6.25 metric tons per capita, followed by Argentina and Brazil, with 4 and 1.86 metric tons per capita, respectively. Paraguay stands out as a country with a cleaner energy matrix, since out of its total energy consumption, 0.6854 metric tons are, on average, from renewable sources. It is followed by Brazil and Uruguay with 0.4567 and 0.4272, respectively. In terms of wealth generation, Venezuela ranked first with an average per capita GDP of \$12,697, followed by Uruguay and Brazil, with averages of \$9550 and \$9472, respectively.

For the other analyses, all variables were converted into their natural logarithms. The Levin, Lin, and Chu (LLC) and Im, Pesaram, and Shin (IPS) unit root tests were performed. Both tests, presented in Table 5, show that the variables are stationary in the first difference.

Table 6 presents the correlation coefficients of the pairs of variables. The (unreported) tests show that no prediction variable produces a variance inflation factor (VIF) greater than or

Table 3 Summary of variables

Variable	Justification
GDP	Economic growth, measured by gross domestic product, leads to emissions of pollutants, especially CO_2 (Ang 2007; Apergis and Payne 2015; Apergis and Payne 2009; Baek 2015). There are positive and significant relationships between economic growth and CO_2 emissions.
REC	Renewable energy consumption contributes about 1/2 or less per unit of energy consumed than fossil energy consumption in terms of GHG emissions. This implies that a shift in the mix of energy consumption to alternative renewable energy technologies can reduce GHG emissions (Bölük and Mert 2014). Greater use of clean energy leads to lower CO_2 emissions. In this way, renewable energy mitigates CO_2 emissions, resulting in a negative impact (Al-Mulali et al. 2015; Apergis and Payne 2014; Baek and Pride 2014; Bengochea and Faet 2012; Bölük and Mert 2014, 2015; Farhani and Shahbaz 2014; Jebli et al. 2016; López-Menéndez et al. 2014; Shafiei and Salim 2014).
NREC	There is a direct relationship between non-renewable energy consumption and CO_2 emissions. An increase in the consumption of non-renewable energy leads to greater emissions of pollutants (Dogan and Seker 2016). Therefore, a positive relationship between the variables is expected.
TR	Greater trade openness leads to less pollution as expanded trading involving international trade reduces emissions (Jebli et al. 2016; Mouselli et al. 2013). Therefore, a negative relationship between the variables is expected.
FD	Countries that are more financially developed have lower financial costs, better financing networks, thereby enabling companies to make more investments, acquire new machinery and equipment, which results in higher energy consumption and CO_2 emissions. Financial development also leads to lower credit rates, thereby increasing consumption, which stimulates production, energy consumption, and the emission of gases (Dogan and Turkekul 2016; Tamazian et al. 2009).
URB	Growth in urban populations results in an increase in industrial production, transportation, energy consumption and, consequently, the emission of gases (Martínez-Zarzoso and Maruotti 2011; Kasman and Duman 2015). Therefore, a positive relationship between the variables is expected.

Table 4 Descriptive statistics of the variables for the countries analyzed

Country	Variable	Mean	Median	St Deviation	Min.	Max.
Argentina	CO_2	4.00	3.86	0.46	3.29	4.75
	FD	31.92	30.38	9.08	21.96	62.42
	NREC	88.21	88.65	1.26	85.80	90.65
	GDPPC	8567.45	8339.89	1374.79	5939.76	10,780.02
	REC	10.18	10.19	1.43	7.61	13.29
	TD	28.38	28.41	9.86	13.75	41.75
	URB	89.47	89.52	1.39	86.98	91.60
Brazil	CO_2	1.86	1.84	0.31	1.40	2.59
	FD	86.26	84.57	25.73	54.93	180.04
	NREC	54.97	54.61	2.42	51.22	59.12
	GDPPC	9472.98	8910.86	1340.83	7796.84	11,912.15
	REC	45.67	45.47	2.47	41.48	49.86
	TD	22.41	22.64	4.51	15.16	29.68
	URB	80.94	81.88	3.52	73.92	85.43
Paraguay	CO_2	0.74	0.74	0.11	0.49	0.88
	FD	26.17	26.93	7.48	13.79	40.78
	NREC	29.52	30.11	3.52	20.14	33.82
	GDPPC	2915.38	2814.77	308.99	2569.69	3761.91
	REC	68.54	67.44	4.40	62.68	79.15
	TD	98.81	97.46	10.81	80.74	123.08
	URB	55.34	56.60	3.34	48.69	59.42
Uruguay	CO_2	1.78	1.70	0.38	1.27	2.56
	FD	41.03	33.77	17.04	25.03	99.92
	NREC	60.32	60.72	5.46	46.84	70.25
	GDPPC	9550.65	9068.24	2012.74	6877.29	13,856.70
	REC	42.72	42.76	5.29	33.30	55.43
	TD	46.69	41.63	9.84	33.39	65.21
	URB	92.38	92.57	1.92	88.97	95.15
Venezuela	CO_2	6.25	6.15	0.61	5.10	7.61
	FD	25.68	20.06	12.82	10.51	61.93
	NREC	88.69	88.88	1.05	86.43	90.49
	GDPPC	12,697.54	12,628.13	1236.70	9710.27	14,652.18
	REC	13.53	13.50	1.08	11.44	16.52
	TD	51.41	51.54	5.93	38.52	60.13
	URB	87.58	88.44	1.48	84.28	88.94

equal to 10, corroborating that multicollinearity is not a problem for the estimation of Eqs. 1 and 2. The most significant correlations were verified between the variables LURB and LGDP (0.91), LREC and LNREC (− 0.89), and LURB and LNREC (0.87), which, in general, indicates low correlations between the model variables.

The other basic assumptions, namely, residue normality, homoscedasticity, and autocorrelations, were also analyzed. For residual normality, the Jarque-Bera test was performed, which indicated that the residuals did not follow a normal distribution. However, the central limit theorem based on Gujarati and Porter (2011) was used as a support, in which for samples greater than 100 observations, the normal distribution is presumed, i.e., the assumption of normality is restricted to those samples which contain less than 100 observations.

To verify if there were residual autocorrelations, the Durbin-Watson test was used. It presented a value of 2.1411, which shows the non-existence of autocorrelations. For the assumption of homoscedasticity of the residuals, the Breusch-Pagan-Godfrey test was used, and showed the non-existence of heteroscedasticity.

In addition, the Breusch-Pagan test and the F (Chow) test were used to detect the best model. The results showed the existence of the group and time effects, so regression was performed with these two effects.

Table 5 Unit root test

	LLC			IPS		
	Level	Δ		Level	Δ	
LCO_2	− 0.47087	− 8.49042	*	− 0.17509	− 8.06086	*
LFD	3.50714	− 10.927	*	0.9729	− 8.3249	*
LGDP ($LGDP^2$)	1.37189	− 4.90542	*	2.60823	− 3.84735	*
LNREC	− 1.63286	− 5.83053	*	− 1.55197	− 5.16223	*
LREC	− 0.90298	− 8.88137	*	− 1.3965	− 8.26172	*
LTR	− 0.81435	− 7.21885	*	− 0.94411	− 7.4228	*
LURB	− 0.48644	− 1.65841	**	− 0.3338	− 2.12232	**

*denotes significance at 1% level

**denotes significance at 5% level

Δ is the first difference term

Table 7 shows the OLS regression results. Estimation of Eq. 1 confirmed hypotheses 2 and 3. A negative relationship between the use of renewable energy (REC) and CO_2 emission was found. This result allows one to infer that a 1% increase in the consumption of renewable energy had a negative impact of 2.7% on CO_2 emissions. As for non-renewable energy consumption (NREC), it had a strong impact on environmental degradation. The elasticity of NREC in relation to CO_2 showed that a 1% increase in the consumption of non-renewable energy positively impacts CO_2 emissions by 8.86%.

These results, showing a direct relationship with the consumption of non-renewable energy and the opposite with the consumption of renewable energy, converge with previous studies (Al-Mulali et al. 2015; Apergis and Payne 2014; Baek and Pride 2014; Bengochea and Faet 2012; Bölük and Mert 2014; Dogan and Seker 2016; Farhani and Ozturk 2015; Farhani and Shahbaz 2014; Jebli et al. 2016; López-Menéndez et al. 2014; Shafiei and Salim 2014) in other countries, sustaining the idea that renewable energy consumption mitigates CO_2 emissions.

On the other hand, these findings differ from those of Apergis et al. (2010) and Bölük and Mert (2014). It was not possible to confirm hypothesis 1 with the estimation of Eq. 1, as the coefficient of GDP was not statistically significant, 0.3814 (0.7039).

With the inclusion of the control variables according to Eq. 2, there is a negative relationship between trade openness (TR) and emission of pollutants. The other control variables (FD and URB) were not significant. These results converge with those found by Jebli et al. (2016) and Mouselli et al. (2013), and it can be inferred that trade openness reduces emission levels.

In Eq. 3, the model tests the validity of EKC for MERCOSUR countries. The EKC model assumes that the level of pollution increases with the level of income up to a turning point, after which environmental degradation tends to decrease as the economy continues to grow. Thus, by observing the results of model 3 in Table 7, the validity of the EKC for the countries in question is confirmed, since the GDP coefficient is positive and GDP^2 is negative, both at a 5% significance level. In this way, it is possible to confirm hypotheses 1 and 4.

In terms of economic growth, it was seen that there was a positive relationship between real GDP and CO_2 emissions. This is in accordance with the previous literature in France (Ang 2007; Apergis and Payne 2009), in the Arctic countries (Canada, Finland, Denmark (Greenland), Iceland, Norway, Russia, Sweden, and USA (Baek 2015)) and in Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Suriname, Uruguay, and Venezuela (Apergis and Payne 2015). Considering the validity of the EKC hypothesis, the

Table 6 Analysis of correlations of variables

	LCO_2	LFD	LGDP	LNREC	LREC	LTR	LURB
LCO_2	1						
LFD	− 0.1862	1					
LGDP	0.82054	0.19713	1				
LNREC	0.94055	− 0.0594	0.83441	1			
LREC	− 0.8972	0.30292	− 0.5688	− 0.8933	1		
LTR	− 0.3851	− 0.5089	− 0.5387	− 0.5449	0.36655	1	
LURB	0.75137	0.15433	0.90848	0.87496	− 0.6129	− 0.5925	1

Table 7 Panel results for CO_2

Variables Dependent variable: CO_2	Model 1 *t* value (sig)	Model 2 *t* value (sig)	Model 3 *t* value (sig)	Model 4 *t* value (sig)	Model 5 *t* value (sig)
C	1.8965	0.9326	1.9465	0.0989	3.4984
	(0.6120)	(0.3537)	(0.0548)	(0.9215)	(0.0000)
GDP	0.3814	0.2033	2.2222	2.3257	
	(0.7039)	(0.8394)	(0.0296)	(0.0225)	
GDP^2	–	–	− 2.1910	− 2.3171	
	–	–	(0.0311)	(0.023)	
REC	− 2.7008	− 2.4387	− 2.6377	− 2.4150	
	(0.0083)	(0.0000)	(0.0099)	(0.0179)	
NREC	8.8571	8.9019	8.7906	8.6662	
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	
TR		− 1.6849		− 1.6447	
		(0.0957)		(0.1038)	
FD		0.5707		0.7981	
		(0.5697)		(0.4271)	
URB		− 0.2115		0.6531	
		(0.833)		(0.5155)	
LFD*LTR					− 0.2029 (0.0000)
Effects	Fixed	Fixed	Fixed	Fixed	Fixed
R^2	0.717814	0.728796	0.73257	0.745273	0.9872
R^2 adjusted	0.621614	0.622252	0.637279	0.640928	0.9830
F	7.461693	6.840302	7.687693	7.142338	237.5
(sig)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)

results of this research agree with Ajmi et al.(2015), Apergis and Payne (2009), Atici (2009), and Chandran and Tang (2013). The level of emissions increases in the early years of economic growth, and after reaching a turning point, it decreases in the context of continued economic growth.

The insertion of control variables, when tested by the EKC hypothesis, demonstrated in model 4 of Table 7, did not significantly impact the result presented without the control variables. Only the trade openness variable, which presented little significant relationship, stands out. But, when taken together, the financial development and trade openness (model 5 of Table 7) variables have a negative effect on CO_2 emissions. This implies that the intensification of trade liberalization contributes to reducing environmental degradation in the region and justifies the use of these moderator variables in the empirical model.

Conclusions and policy implications

The objective of this research was to investigate the impact of energy consumption—both renewable and non-renewable—and income on CO_2 emissions within the environmental Kuznets curve (EKC) model for MERCOSUR countries.

Four hypotheses were raised: H1—there is a positive and significant relationship between income and emission of pollutants in MERCOSUR countries; H2—there is a negative and significant relationship between consumption of renewable energy and emission of pollutants in MERCOSUR countries; H3—there are positive and significant relationships between consumption of non-renewable energy and emission of pollutants in MERCOSUR countries; and H4—there is a quadratic relationship between income and emission of pollutants, as in the EKC hypothesis.

On the basis of the results presented, it was possible to confirm the four hypotheses of the research. With the estimation of Eqs. 1 and 2, hypotheses 3 and 4 were confirmed, as the consumption of renewable and non-renewable energy, respectively, negatively and positively impact CO_2 emissions.

With the estimation of Eqs. 3 and 4, it was possible to confirm hypothesis 1 and 4, in addition to hypotheses 2 and 3, thereby confirming the positive impact of economic development, measured by GDP, on CO_2 emissions, and also confirming the hypothesis of EKC.

Empirical results reported in this research are robust and reliable due to the use of appropriate estimation techniques. The elasticities found imply major economic policy implications for MERCOSUR. Policy measures which constrain energy consumption slow down economic growth. When the economy grows, demand for energy also increases. However, this path is energy-saving and reduces the share of non-renewable energy and increases the share of renewable energy for the lower levels of CO_2 emissions. Policymakers should focus more on public awareness of renewable energy and environmental quality, mainly in solar and wind power, whose sources of generation are abundant in MERCOSUR countries.

The results of the research imply how crucial renewable energies, such as biogas, solar, and wind, are for the control of CO_2 emissions in MERCOSUR. A shift in the energy mix to cleaner energies (renewable energy technologies) is vital to achieving environmental goals as well as the sustainable development of the country. The findings also highlight that regulations in support of renewable sources would yield reductions in per capita emissions. An increase in the use of electricity produced from renewable sources will help mitigate energy dependency and guarantee energy security.

Moreover, the existence of EKC was found for the MERCOSUR as the elasticity of CO_2 emissions with respect to GDP and GDP^2 is positive and negative, respectively. Increases in GDP, in general, lead to environmental improvements after MERCOSUR member states pass the threshold level.

As seen in the literature review, the net effect of trade openness on the environment can be positive or negative depending on which effect predominates. The result of this research indicates that the net environmental impact of trade openness (− 1.68) reduces environmental deterioration given that the technique and composition effects dominate the scale effect. That makes sense as in recent decades MERCOSUR countries, in particular, have made progress in inventing new technologies (mainly in agribusiness) and the trade bloc seems to benefit from the technology spillover through trade.

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