How Economic Growth, Renewable Electricity and Natural Resources Contribute to CO2 Emissions?

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Abstract: This study explores the relationship between economic growth and CO_2 emissions in the so-called European Union 5 (EU-5) countries (Germany, France, Italy, Spain, and the United Kingdom) for the 1985-2016 period. In doing so, we employ a carbon emission function to investigate the environmental Kuznets curve phenomenon, which describes a relationship between economic growth and environmental degradation. The empirical results confirm the existence of an N-shaped relationship between economic growth and CO_2 emissions in the EU-5 countries. We incorporate additional variables such as renewable electricity consumption, trade openness, natural resource abundance, and energy innovation to augment the carbon emission function. Renewable electricity consumption, natural resources, and energy innovation improve environmental quality, while trade openness and the interaction between economic growth and renewable electricity consumption exert a positive impact on CO_2 emissions. This study is novel in that it presents an interaction between economic growth and renewable electricity consumption. We also confirm the need for renewable energy regulations related to increasing renewable sources and promoting energy innovation to reduce the negative effects of energy and fossil energy resources on environmental degradation.

Keywords: Economic Growth, Renewable Electricity, Natural Resources, Environment

1. Introduction

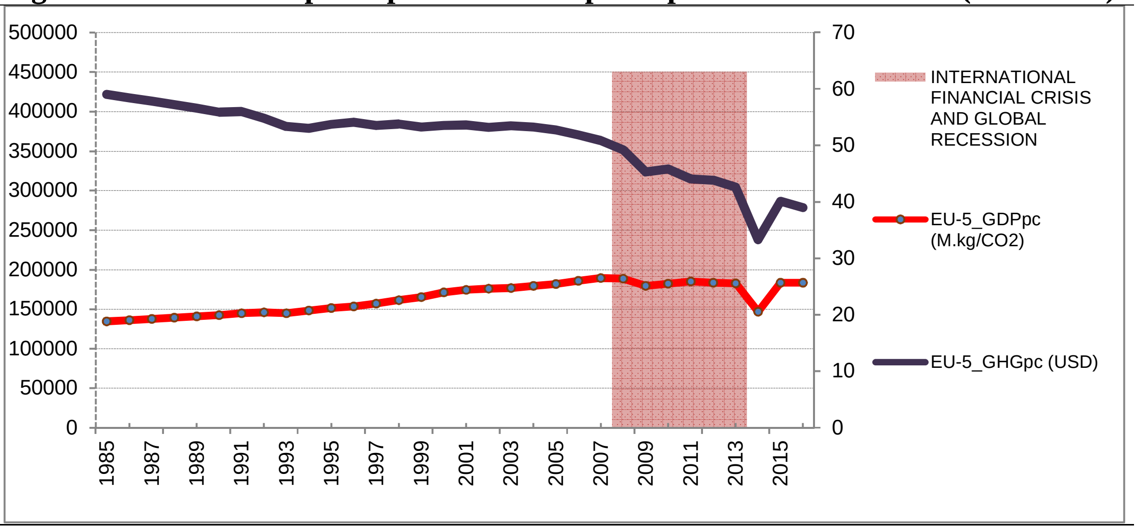
Over the last decades, climate change has become one of the most relevant environmental challenges.[1] According to a European Union (EU) Joint Research Centre (JRC) report, fossil fuel combustion accounts for 90% of total global CO_2 emissions (Oliver et al., 2012). Historically, developed countries have been responsible for a large percentage of worldwide emissions, but emissions in developing countries have been much higher in recent years (IEA, 2014). The US Energy Information Administration (EIA, 2012) considers renewable energy sources the fastest growing in terms of world energy, and their use will increase from 10% of total energy in 2008 to 14% by 2035. The existing literature indicates that renewable energy may help mend both energy security and climate change problems (Ristinen and Krushaar, 2006; Sims et al., 2007). Krewitt et al., (2007) determine that renewable energy sources could provide as much as half of the world's energy needs by 2050 in a target-oriented scenario to prevent dangerous anthropogenic interference with the climate system. Due to increasing concerns over the environmental consequences of greenhouse gas (GHG) emissions from fossil fuels, renewable energy has emerged as a substitute energy source, as any effort to reduce CO_2 emissions and control climate change must indubitably include the reorganization of the energy sector (Abulfotuh, 2007; Apergis and Payne, 2012). A few studies reveal that this expectation may be due to strong and high demand for energy in developing countries (Pao and Tsai, 2010; Alam et al., 2011; Wang et al., 2014). Other studies claim that it results from free trade policies, such that developed countries reduce their dirty goods production by taking advantage of globalization (Mehra and Das, 2008;

[1] The threats of global warming and climate change have been major concerns since the 1990s. The Intergovernmental Panel on Climate Change (IPCC) has reported that the average global temperature is estimated to rise between 1.1 and 6.4 ºC over the next 100 years (IPCC, 2007). According to the International Energy Agency (IEA), the total amount of air pollution emitted by the top 25 countries corresponded to 80% of worldwide emissions in 2012 (IEA, 2015). Furthermore, it is expected that developing countries will emit 80% of global emissions in the near future (Huwart and Verdier, 2013).

Carvalho et al., 2013; Shahbaz et al., 2013). Consequently, there is agreement regarding the need to encourage global energy measures that consider increasing the share of renewable sources in energy mix and the use of energy innovation to control environmental degradation (Arrow et al., 1996; Torras and Boyce, 1998; Andreoni and Levinson, 2001; Lorente and Álvarez-Herránz, 2016; Álvarez-Herránz et al., 2017).

This study analyses the effect of economic growth on CO_2 emissions in the EU-5 (France, Germany, Italy, Spain, and the United Kingdom) for the period 1985-2016. These countries have been the most influential members of the EU in the 21st century. The main reason for considering a panel of EU-5 countries is that they share a common 20/20/20 objective (European Commission (EC), 2012): that is, by 2020, the EU aims to reduce its GHG emissions by at least 20%, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of 20% or more. One of the main objectives of European energy policy has been the promotion of renewable energy, which is justified by concerns over oil prices volatility, dependency on foreign energy sources, and energy security for the sake of environmental quality. To promote renewable energy, different regulation measures have been applied, such as market-based and non-market-based promotion mechanisms (e.g., feed-in tariffs, premiums, quota-based green certificates, bidding incentives, incentives for investment, tax exemptions, and discounts) (EC, 2015). The EU strategy also includes a minimum 10% electricity interconnection for all member states by 2020, which the Commission hopes will put downward pressure on energy prices, reduce the need to build new power plants, reduce the risk of black-outs and other forms of electrical grid instability, improve the reliability of the renewable energy supply, and encourage market integration.[2] The EC has planned, in its *Renewable Energy Roadmap*, a binding target to increase the level of renewable energy in the EU's overall mix to 20% by 2020. On 19 March 2015, the European Council concluded that the EU is committed to building an Energy Union with forward-looking climate policy based on the Commission's framework with five priority dimensions—energy security, solidarity and trust, a fully integrated European energy market, energy efficiency—contributing to the moderation of demand and decarbonization of the economy, research, innovation, and competitiveness (EC, 2015).

Figure-1. Evolution of per capita GHG and per capita GDP in the EU-5 (1985-2016)



Source: IEA (2016).

Figure-1 illustrates the evolution of CO_2 emissions and gross domestic product (GDP) in the EU-5 countries over the period 1985-2016. Figure-1 also illustrates the potential correction

[2] Europe spent EUR 406 billion in 2011 and 545 billion in 2012 to import fossil fuels. In 2012, wind energy reduced fossil fuel costs by EUR 9.6 billion. The European Wind Energy Association recommends a binding renewable energy target to support the goal of replacing fossil fuels with wind energy in Europe by providing a stable regulatory framework.

of GHG levels in the selected countries. Per capita income exhibits an ascending trend despite the 2007 financial crisis. Therefore, the complementary evolution of these variables suggests the existence of an environmental Kuznets curve (EKC) in the sampled countries over the period 1985-2016. In this respect, numerous studies focus on the relationship between economic growth and environmental pollution, testing the validity of the so-called EKC hypothesis (Grossman and Krueger, 1991; Dinda, 2004; Stern, 2004). Moreover, the literature on the EKC has also considered the relationship between energy consumption and environmental degradation (Grossman and Krueger, 1991; Chen et al., 2007; Lean and Smyth, 2010; Farhani and Shahbaz, 2014; among others). This nexus implies that environmental degradation is an increasing function of economic activity until it reaches a critical level after which higher income leads to improved environmental quality (Grossman and Krueger, 1991; Selden and Song, 1994; Acaravci and Ozturk, 2010; Balsalobre-Lorente and Shahbaz, 2016; among others).

This study makes a three-fold contribution to the existing literature: (i) The relationship between economic growth and CO_2 emissions is investigated by testing the EKC hypothesis under an N-shaped framework for the period 1985-2016. (ii) Natural resource abundance is included as a determinant of CO_2 emissions along with renewable electricity consumption and trade openness in an augmented carbon emission function. Last but not the least, energy innovation is added to the carbon emissions function to examine its impact on technical and technical obsolescence. The empirical analysis indicates the presence of an N-shaped relationship between economic growth and CO_2 emissions in the EU-5 countries. Renewable electricity consumption, natural resource abundance, and energy innovation improve environmental quality. Trade openness and the interaction between economic growth and renewable electricity consumption decrease environmental quality by increasing CO_2 emissions.

The remainder of the paper is organized as follows: Section-2 reviews the literature on theoretical considerations and other relevant previous research endeavours. Section-3 presents the empirical model, data description, and methodology. Section-4 provides the empirical results and the discussion. The final section offers conclusions and new energy strategy guidelines.

2. Literature Review

The relationship between income and income inequality, as stated by Kuznets (1955), has been re-interpreted in the environmental economics literature since the 1990s as the EKC. The EKC concept first emerged in 1991 in Grossman and Krueger's pioneering study of the potential impacts of the North American Free Trade Agreement. The first wave of EKC studies used basic EKC models, and both economic growth and its environmental impacts were estimated without any explanatory variables (Beckerman, 1992; Grossman and Krueger, 1991, 1995; Holtz-Eakin and Selden, 1995; Moomaw and Unruh, 1997; Schmalensee et al., 1998; Heil and Selden, 2001; etc.) to test the relationship between economic growth and environmental pollution using the EKC framework. The earlier literature analysed the relationship between economic growth and environmental degradation according to the EKC analytic scheme and proposed an inverted U-shaped relationship between economic growth and environmental degradation (Grossman and Krueger, 1991; Stern et al., 1996; Ekins, 1997; Gani, 2012). Subsequently, scholars started to review empirical EKC studies (Dinda, 2004; Stern, 2004). In their pioneering work, Grossman and

Krueger (1991) proposed an inverted U-shaped relationship between economic growth and environmental degradation.

The empirical EKC hypothesis suggests a direct relationship between economic growth and environmental quality, which changes after a threshold income level is attained (Panayotou, 1993; Selden and Song, 1994; Grossman and Krueger, 1991, 1995). In other words, income and CO_2 emissions per capita increase together until a certain *turning point* in income is reached, after which the growth of pollutants flattens and then reverses. Thus, an inverted U-shaped relationship between income and environmental pollution assumes a dynamic process of structural change connected to economic growth (Dinda, 2004). This behaviour also implies that economic growth affects environmental quality through three main channels: scale, composition, and technical effects (Grossman and Krueger, 1991). Consequently, environmental pollution is considered a process that results from scale, composition, and technical effects. Then, as an economy's income level increases, society will tend to demand cleaner policies aimed at protecting the environment.

This premise, under the EKC scheme, reflects the transition from agricultural production (primary sector) to industrial production (secondary sector) and, finally, to the tertiary sector. Panayotou (2003) suggests that the inverted U-shaped EKC reflects some mixture of scale, composition, and technical effects. First, when a society is at an early stage of development, the pre-industrialization phase, the development of rudimentary, inefficient industries result in *scale effects* and pollution. Second, there is a transition to industrial production and, finally, to the service sector, where *composition effects* reflect economic growth in sectors that pollute less. With higher income levels, industrial production is phased out in favour of more high-technology and service-oriented production (*technical effects*) (Hussen, 2005). This evolution implies that pollution levels may not increase to scale with economic growth if the output composition changes (Vukina et al., 1999). In other words, in the early stages of economic growth, environmental pollution levels rise until they reach a turning point beyond which economies experience reductions in pollution levels. Therefore, the EKC reflects the relative strength of the scale and technical effects (Brock and Taylor, 2005), where highly technological and effective production economic systems contribute to a decrease in pollution levels (Dinda, 2004). Under this hypothesis, the *technical effect* allows for the possibility that, as countries grow, cleaner technologies are substituted for dirtier ones in production processes (Hussen, 2005). In this view, economies will increase their innovation to avoid technical obsolescence in the energy sector. This, in agreement with increased scale returns, entails an elasticity of demand for a cleaner environment that exceeds unity (Dinda, 2004; Lorente and Álvarez-Herránz, 2016). When the total effect of the relationship between economic growth and environmental pollution is dissected, the *technical effect* is the main factor in environmental pollution reduction (Andreoni and Levinson, 2001). Finally, the *technical effect* includes the impact of transferred know-how and advanced technological production performance on the environment, since pollution increases unless environmental regulations are strengthened (Hettige et al., 2000).

On the other hand, an N-shaped EKC predicts an increase in the income-environmental pollution relationship over the long term (Shafik and Bandyopadhyay, 1992; Selden and Song, 1994; Grossman and Krueger, 1995; Moomaw and Unruh, 1997; Torras and Boyce, 1998). This expanded relationship appears when the connection between economic growth and environmental degradation is initially positive, but it becomes negative once a given income threshold is reached, before ultimately becoming positive again. This pattern assumes that environmental degradation increases (low-income) at initial stages of economic development and then decreases after an income turning point is reached. Finally, degradation begins to increase again in a third stage marked by high income but lower income growth rates, as *technical obsolescence* increases as the *scale effect* re-emerges and overcomes the *composition* and *technical effects* before the second turning point. In this regard, *technical obsolescence* will lead to the re-emergence of increasing pollution levels once the *scale effect* exceeds the *composition* and *technical effects* (Johansson and Kriström, 2007; Lorente and Álvarez-Herránz, 2016; Álvarez -Herránz et al., 2017).

While the inverted U-shaped EKC does not reflect the behaviour described above, the pattern suggests different behaviour that is better reflected by an N-shaped EKC model, where rising pollution levels return once an economy has achieved long-term high income. This, in turn, makes it possible to analyse the potential return to rising emissions once economies have achieved negative pollution rates and environmental technical obsolescence becomes possible (Lorente and Álvarez-Herránz, 2016). The N-shaped pattern helps illustrate how economies can correct technical obsolescence by implementing long-term energy regulation policies, making it possible to identify aspects related to *scale effects* and how these affect *technical effects* in the long term. Thus, innovation measures contribute to delays in a new ascending trend in pollution (He, 2006; Lorente and Álvarez-Herránz, 2016). To demonstrate the long-term appearance of *technical obsolescence*, it must be accepted that once an economy achieves a high income, society will demand a high-quality environment, which will require efforts in the form of environmental regulations to promote *technical effects* through more efficient and less polluting energy production actions (Bruvoll et al., 2003;

Turner and Hanley, 2011). Álvarez-Herránz et al. (2017) demonstrate the positive effect of energy innovation policies in lowering CO_2 emissions and how these measures help delay technical obsolescence. Additionally, other studies incorporate technological innovation in the nexus of clean energy, carbon emissions, and economic growth (Lee, 2013; Tang and Tan, 2013; Fei et al., 2014). Tang and Tan (2013) show that technological innovation is significant in mitigating the use of fossil fuels. Their results show a significant relationship between electricity consumption, economic growth, and technological innovation, which is in line with the applicability of endogenous growth theory to the energy sector. Fei et al. (2014) incorporate patenting activities to explore the causal relationship between technological innovation, CO_2 emissions, economic growth, and clean energy in New Zealand and Norway during the 1971–2010 period. Their results confirm that technological innovation plays a significant role in the clean energy–growth nexus.

Subsequently, we review the relevant theoretical aspects of the additional variables included in our empirical model. In recent research, EKC analyses have incorporated additional explanatory variables that enrich the relationship between economic growth and environmental degradation. Many studies have explored the dynamic relationship between economic growth and energy pollution (Akbostanci et al., 2009; Jalil and Mahmud, 2009; Narayan and Narayan, 2010; Jaunky 2011), while others focus on the relationship between economic growth, energy use, and environmental degradation (Soytas et al., 2007; Ang 2007, 2008; Apergis and Payne, 2009; Sadorsky, 2009; Apergis et al., 2010; Hatzigeorgiou et al., 2011; Hamit-Haggar, 2012; Ozcan, 2013). Numerous studies also indicate that energy use is the main contributor to carbon emissions (Shahbaz et al., 2013a, b, c, d; Farhani et al., 2014; Al-Mulali et al., 2015; Dogan and Turkekul, 2016). The relationship between energy use and economic growth has been presented as four main hypotheses. First, the *growth hypothesis* indicates that energy contributes to economic growth both directly in the production process and/or indirectly as a complement to labour and capital. On the one hand, policies aimed at energy conservation may have a negative impact on economic growth, and on the other hand, an increase in energy consumption might be detrimental to economic growth due to structural changes, such as shifting from energy- intensive towards less energy-intensive production. Second, the *conservation hypothesis* claims that energy conservation policies are aimed at reducing environmental pollution, improving efficiency, and managing waste. Third, the *feedback hypothesis* asserts that there is an interdependent relationship between economic growth and energy consumption. Fourth, the *neutrality hypothesis* assumes that energy consumption is a relatively minor component of real income and should thus have no significant impact on economic growth.

Many studies have focused on the causal relationships among *renewable and alternative energy use,* economic growth, and CO_2 emissions (Sadorsky, 2009; Apergis et al.; 2010; Menyah and Wolde-Rufael, 2010; AlFarra and Abu-Hijleh, 2012; Fadel et al., 2013; Lee, 2013 and Sbia et al., 2014). Ben Jebli et al. (2013) explore the effects of renewable energy use via its dynamic relationship with international trade, output, non-renewable energy consumption, and pollutant emissions for a panel of selected Organisation for Economic Co-operation and Development (OECD) countries and report inconclusive empirical results. Moreover, Soytas et al. (2007) found that in the long-run, economic growth positively affects energy consumption and carbon emissions. Apergis et al. (2010) examine the causal relationships between CO_2 emissions, renewable energy, and nuclear energy and economic growth for a group of 19 developed and non-developed countries during the 1984–2007 period. They conclude that there is a long-run and positive relationship between renewable energy consumption and CO_2 emissions. On the other hand, Balsalobre-Lorente and Shahbaz (2016) confirm that renewable energy consumption reduces CO_2 emissions. Vaona (2012) examines the energy consumption of non-renewable energy sources, and the results indicate that greater non-renewable energy consumption promotes economic growth but that an increase in output decreases the growth rate of non-renewable energy consumption, possibly be due to greater efficiency in energy use.

Furthermore, a significant body of literature analyses the relationships among electricity use, air pollution levels, and economic growth (Chandran et al., 2010; Silva et al., 2011; Bélaïd and Abderrahmani, 2013; Salim et al., 2014; Shahbaz et al., 2014; Khalid, 2015). Shahbaz et al. (2014) prove the existence of EKCs between economic growth, electricity consumption and CO_2 emissions. Silva et al. (2011) examine the causal relationships among economic growth, CO_2 emissions and renewable electricity output for a sample of four countries (Denmark, Portugal, Spain, the US) during the 1960–2004 period. These authors conclude that the increasing share of renewable energy sources initially has a negative impact on economic growth but a positive effect on CO_2 emissions reduction. Other studies reveal that renewable energy technologies have become more effective than regulation measures in reducing environmental pollution (Sebri and Ben-Salha, 2014; Balsalobre-Lorente and Shahbaz, 2016). To promote the environmental correction process, it is also necessary to increase the share of renewable sources in the energy mix to correct the negative effects of fossil fuel sources on carbon pollution when a society experiences economic growth that increases energy requirements. According to the role of renewable electricity consumption on CO_2 emissions and following Silva et al. (2011), Vaona (2012), and Balsalobre-Lorente and Shahbaz (2016), our study validates the negative relationship between renewable electricity consumption and CO_2 emissions. This process reduces the positive effect of renewable electricity consumption during environmental quality improvements.

Trade openness is also considered a relevant variable in the evolution of environmental pollution. Numerous studies incorporate trade openness in the relationships among environmental pollution, economic growth, and energy use (Ang, 2007; Apergis and Payne, 2009; Acaravci and Ozturk, 2010; Nasir and Rehman, 2011; Jayanthakumaran et al. 2012; Shahbaz et al., 2013; Kasman and Duman, 2015; Dogan and Turkekul 2016). Trade openness effects have been linked with output, non-renewable energy use, and pollutant emissions, and they are considered an effective determinant of carbon emissions (Esty, 2001; Mukhopadhyay, 2009). Ahmed et al. (2016) prove that trade liberalization contributes to economic growth, which implies an increase in environmental pollution. Farhani et al. (2014) show that the environmental impact of trade openness can be positive or negative depending on the magnitudes of the *scale, technical* and *composition effects*. These controversial results on the net effect of trade openness can be explained by the *pollution haven hypothesis* (Kukla-Gryz, 2009; Guo et al., 2010), which suggests that residents of developing countries have fewer environmental concerns than those in developed countries, whereas the former group cares more about increases in income and welfare (Tang, 2015). Hence, the *pollution haven hypothesis* implies that the impact of trade openness on the environment depends on the net *scale, composition*, and *technical* effects (Grossman and Krueger, 1993, 1995; Heil and Selden, 2001). Thus, the net effect of trade openness on environmental degradation links *scale effects* with economic growth (Antweiler et al., 2001, Farhani et al., 2014). Moreover, under increasing income levels, trade openness leads to higher rates of carbon emissions because of increased production and energy consumption. On the other hand, free trade and higher incomes can provide environmental improvements at higher development levels. The composition effect argues that countries modify their production composition based on their comparative advantage. If the demand for traded goods produced by polluting methods increases, then countries tend to produce these goods. In practice, this process operates in favour of developed countries. Otherwise, the evidence of trade openness effects on environmental degradation for individual countries varies by income, possibly due to policy differences, economic structure, level of economic openness, and country-specific variations (Baek et al., 2009; Wiebe et al., 2012; Mudakkar et al., 2013; Ozturk, 2015; Khan et al., 2016). Our study pays attention, through the analysis of the inflection points between the first and second points in the N-shaped EKC, to the argument that implies that *trade liberalization* supports the efficient use of resources while sustainable growth essentially contributes to environmental quality (Ahmed et al., 2016).

Traditionally, one of the most robust variables in cross-country growth regressions, deem natural displaying a significantly negative correlation with economic growth is natural resource abundance (Sachs and Warner, 1995, 1997; Sala-i-Martin, 1997; Sala-i-Martin et al., 2004). Numerous studies have found a correlation between resource abundance and political instability (Alstine and Neumayer, 2010). Thus, some approaches to the resource curse blame low institutional quality for a lack of incentives (Robinson et al., 2006). Other studies consider that, in the early stages of environmental movement, natural resource availability could be compatible with sustained economic growth (Meadows et al., 1972). However, a more recent debate has centred on non-renewable resource abundance (Beckerman, 1992; Lomborg, 2001; Meadows et al., 1992, 2004). Neumayer (2004) postulates that it is necessary to consider how technical change can work to overcome apparent scarcity of limits[3]. Shahabadi and Feyziand (2016) probed the association with natural resource abundance by including foreign direct investment in an augmented carbon emissions function. Their results indicate that natural resource abundance attracts foreign direct investment, which improves environmental quality in developed countries due to the adoption of energy-efficient technologies.

3. Model Construction and Data

This study explores the linkages among economic growth, trade openness, renewable electricity consumption, energy innovation, natural resource abundance, and CO_2 emissions to determine whether the patterns found in the literature apply to the EU-5 countries. Consequently, we construct an econometrical model based on the empirical EKC model for 1985-2016 for the selected EU-5 countries. We present the empirical model, which indicates an N-shaped EKC and the incorporation of additional explanatory variables. Since the seminal study of Grossman and Krueger (1991), numerous studies have considered the link between economic growth and environmental degradation (Shafik and Bandyopadhyay, 1992; Panayotou, 1993; Selden and Song, 1994; Shafik, 1994), although some evidence suggests that increased economic activity does not always ensure environmental quality (Halkos and Tzeremes, 2009). The N-shaped relationship between economic growth and energy pollution has also been thoroughly discussed in the EKC framework, where environmental degradation initially increases with the level of per capita income, reaches a

[3]Khalid et al. (2016) use a production function to examine the relationship between natural resources abundance and economic growth. They note that natural resource abundance is a contributing factor to domestic production.

turning point, and then declines with further increases in per capita income per the EKC hypothesis (Grossman and Krueger, 1995; Torras and Boyce, 1998). For our empirical study, we begin with the general theoretical framework (equation-1) to identify different relationship between economic growth and environmental degradation (Grossman and Krueger, 1995):

$$GHGpc_{it} = \alpha_{it} + \beta_1\ GDPpc_{it} + \beta_2\ GDPpc_{it}^2 + \beta_3 GDPpc_{it}^3 + \beta_4 Z_{it} + \varepsilon_{it}, \qquad (1)$$

where CO_2 emissions per capita refers to pollution or environmental degradation, *GDPpc* is the level of income per capita, and Z_{it} indicates other influences on environmental quality. From equation 1, depending on the value allocated to coefficients β_1, β_2, and β_3, the EKC can adopt the cubic form, which shows that an economy that reaches a certain level of income (highest point) also experiences decreasing environmental pollution with continued growth in income, finally accelerating the environmental degradation process, with high-income levels but low growth rates. This behaviour considers that economies might follow a path of increasing pollution due to *scale effects*, which overcome *composition* and *technology effects* when the margin for continuous improvement in the distribution is exhausted or when diminishing returns to technological change reduce contamination through technology depletion. This viewpoint raises the possibility that, once technology improvement cannot continue or becomes too expensive, net environmental degradation results from increased income (Opschoor and Vos, 1989). Therefore, adequate environmental regulation could effectively accelerate technology changes capable of reducing pollution (Torras and Boyce, 1998). Many studies have demonstrated that changes in the energy-mix pattern and the promotion of renewable energy sources have a direct impact on reducing CO_2 emissions (Balsalobre et al., 2015).

To validate our main hypothesis (a negative relationship between renewable electricity output and environmental degradation), we develop some of the most important aspects of the theoretical EKC model. Equation 2 is an extension of equation 1, including additional variables and using a panel least squares (PLS) model with correction for heteroscedasticity for the EU-5 during the 1985-2016 period:

$$GHGpc_{it} = \alpha_{it} + \beta_1\, GDPpc_{it} + \beta_2\, GDPpc_{it}^2 + \beta_3 GDPpc_{it}^3 + \beta_4 RNWELECT_{it} + \beta_5 RNWELECT * GDPpc_{it} + \beta_6\, TO_{it} + \beta_7 NRA_{it} + \beta_8\, ENERG\_INNOV_{it} + \varepsilon_{it}, \quad (2)$$

where $GHGpc_{it}$ is environmental degradation measured as CO_2 emissions in millions of kilograms of CO_2 per capita in country *i* in year *t* (OECD, CD-ROM), $GDPpc_{it}$ is economic growth shared by the level of income per capita measured in millions of US$ in current prices and current purchasing power parities (PPPs) for country *i* in year *t* (OECD, CD-ROM). $RNWELECT_{it}$ is renewable energy use, as measured by renewable electricity consumption (Gw/h) (IEA, 2016). $RNWELECT*GDPpc_{it}$ is an interaction term between economic growth and renewable electricity consumption. The interaction between renewable electricity consumption and economic growth is added to carbon emissions function to examine whether growing economies meet increased energy requirements by reducing the share of renewable energies in their energy mix and increasing the share of non-renewables. With higher economic growth, the use of more non-renewable energy nullifies the positive effect of renewable energy on environmental quality and increases carbon emissions. The coefficient β_5 measures the interaction effect that GDPpcit has on the causal effect of the independent or exogenous variable $RNWELECT_{it}$ and the dependent or endogenous variable $GHGpc_{it}$. Values of $\beta_5 > 0$ reveal that the usage of non-renewable energy sources with increasing economic growth reduces environmental quality, and vice versa. Further, this interaction reflects that a causal relationship can be established between $RNWELECT_{it}$ and $GHGpc_{it}$. We also must consider the potential role of other variables, such as $GDPpc_{it}$. TO_{it} is the trade openness of country *i* in year *t*. $ENERG\_INNOV_{it}$ is energy innovation in terms of the shared public budget for renewable energy in millions of USD for country *i* in year *t* (OECD, CD-ROM). NRA_{it} indicates the abundance of natural resources expressed as the GDP share of natural resources.

To verify the role of the public budget devoted to renewable energy research, development, and demonstration (RD&D) in every country as a measure of technological innovation, we compare equations 2 and 3 to identify this effect by omitting the renewable innovation measures:

$$\begin{aligned} GHGpc_{it} = \alpha_{it} + \beta_1\, GDPpc_{it} + \beta_2\, GDPpc_{it}^2 + \beta_3 GDPpc_{it}^3 + \beta_4 RNWELECT_{it} \\ + \beta_5 RNWELECT * GDPpc_{it} + \beta_6\, TO_{it} + \beta_8\, NRA_{it} \\ + \varepsilon_{it}. \end{aligned} \tag{3}$$

The empirical model indicates that pollution levels increase as a country develops, but they begin to decrease as rising income passes a turning point. Both Model 2 (equation 2) and

Model 3 (equation 3) employ *PLS with correction for heteroscedasticity*. Across all models and time periods, the goal of the model estimation process is to determine the existence of an EKC for per capita CO_2 emissions in the selected EU-5 countries. Positive coefficients for $GDPpc_{it}$ and $GDPpc_{it}^3$ and negative coefficients for $GDPpc_{it}^2$ indicate an N-shaped relationship between economic growth and CO_2 emissions. Equations 2 and 3 include additional explanatory variables to better describe this relationship.

4. Empirical Results and Discussion

The descriptive statistics and pairwise correlations are reported in Table-1. We find that volatility in trade openness is high compare to renewable electricity consumption and real GDP per capita measure of economic growth. Natural resources are less volatile than CO_2 emissions and energy innovation. The correlation analysis reveals a positive correlation between economic growth and carbon emissions and a negative correlation between renewable electricity consumption and carbon emissions. Trade openness is positively correlated with CO_2 emissions. Natural resources and energy innovation are inversely associated with carbon emissions, whereas renewable electricity consumption and trade openness are positively correlated with economic growth. The correlation between natural resources and economic growth (renewable electricity consumption) is negative. Energy innovation is positively (negatively) associated with economic growth, renewable electricity consumption and trade openness (natural resources). Natural resources are negatively (positively) linked with economic growth and renewable electricity consumption (trade openness). Trade openness is positively correlated with renewable electricity consumption. The correlation analysis indicates the absence of multi-colinearity among the variables.

Table-1. Descriptive Statistics and Correlation Matrix

Variable	GHG_PCKG	GDPPC_PPP	RNWELECT	TO	NRA	ENERGY_RDD
Mean	10.2751	33038.97	52401.52	1.00E+12	0.2389	600.4665
Median	9.6620	33152.04	46223.00	8.09E+11	0.0979	493.4560
Maximum	17.3733	44935.10	194984.2	3.55E+12	1.2404	1578.402
Minimum	5.9824	22916.44	4142.857	1.16E+11	0.0306	67.64600
Std. Dev.	2.4844	4814.646	37482.03	7.14E+11	0.3054	418.9320
Skewness	0.7183	-0.1350	1.1538	1.5804	1.6993	0.5728
Kurtosis	2.8890	2.6404	4.5300	5.5466	4.4303	2.3583
Sum	1633.751	5253196.	8331841.	1.59E+14	37.9911	95474.17
Sum Sq. Dev.	975.2661	3.66E+09	2.22E+11	8.06E+25	14.7393	27729636
GHG_PCKG	1.0000					
GDPPC_PPP	0.0029	1.0000				
RNWELECT	-0.3028	0.2609	1.0000			
TO	0.0716	0.2405	0.2368	1.0000		
NRA	-0.2906	-0.0661	-0.3223	0.0527	1.0000	
ENERGY_RDD	-0.02251	0.2305	0.2801	0.2509	-0.2205	1.0000

Table-2. Panel Unit Root Analysis

	(A)	(B)		
Variable	LLC-test*	IPS-test	ADF-Fisher Chi-square	PP-Fisher Chi-square
GHGPC	2.06052	3.59657	4.89452	5.33418
	(0.9803)	(0.9998)	(0.8981)	(0.8678)
GPDPC	-1.84778	0.65558	5.65255	5.06444
	(0.0323)	(0.7440)	(0.8436)	(0.8868)
GDPPC^2	-1.48174	0.89939	4.94055	4.35687
	(0.0692)	(0.8158)	(0.8951)	(0.9298)
GDPPC^3	-1.23502	1.09692	4.49770	3.87922
	(0.1084)	(0.8637)	(0.9221)	(0.9526)
RNWELECT	8.24096	8.36632	0.93035	3.07962
	(1.0000)	(1.0000)	(0.9999)	(0.9795)
TO	0.32324	2.95804	1.00172	0.47677
	(0.6267)	(0.9985)	(0.9998)	(1.0000)
NRA	-0.75526	-1.03492	8.2040	3.5060
	(0.2250)	(0.1510)	(0.1000)	(0.9509)
ENERGY_INNOV	1.28049	1.01423	7.76163	14.4022
	(0.8998)	(0.8448)	(0.6521)	(0.1554)
ΔGHGpc	-4.10204	-3.24585	29.2747	72.6110
	(0.0021)	(0.0006)	(0.0011)	(0.0000)
ΔGPDPC	-4.52560	-4.35560	38.8112	52.9608
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ΔGDPPC^2	-5.03096	-4.54102	40.2923	(48.6548
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ΔGDPPC^3	-5.31185	-4.71928	41.7385	45.6092
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Δ RNWELECT	-6.2030	-1.65345	29.6774	59.8976
	(0.0000)	(0.0491)	(0.0010)	(0.0000)
ΔTO	-7.87431	-7.26744	64.3415	89.2615
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ΔNRA	-7.30320	-8.29272	74.1162	144.583
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
ΔENERGY_INNOV	-4.01249	-5.40351	48.8828	122.946
	(0.0000)	(0.0000)	(0.0000)	(0.0000)

Notes: (A): Null: Unit root (assumes a common unit root process); (B): Null: Unit root (assumes an individual unit root process); Probabilities are given in ( ).

To examine the unit root properties of the variables, we have applied LLC, IPS, ADF-Fisher and PP-Fisher unit root tests whose results are reported in Table-2. The LLC unit root test indicates that all the variables contain unit root processes in levels with intercepts and trends. After taking the first differences, the variables are found to be stationary. This shows that the variables are integrated of order one, I(1). The IPS, IPS, ADF-Fisher and PP-Fisher unit root tests also confirm the empirical findings of the LLC unit root test, which shows the reliability and consistency of the unit root analysis.

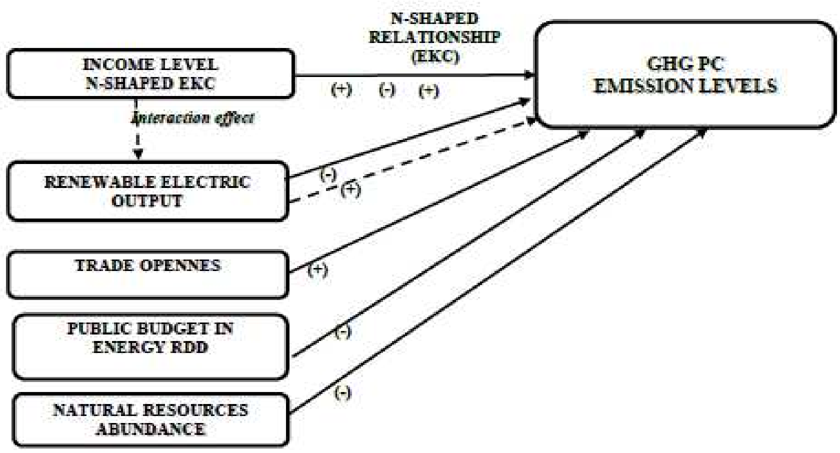
Table-3. PLS with Correction for Heteroscedasticity (1985-2016)

Dependent variable: GHG_PC			
Variable	**Model 1 (Equation 1)**	**Model 2 (Equation 2)**	**Model 3 (Equation 3)**
C	−108.040	−208.646	−199.407
	[−2.9245]*	[−8.3989]*	[−7.5320]*
GDPPC	0.0110704	0.020169	0.0192932
	[3.1094]*	[8.3225]*	[7.4812]*
GDPPC^2	−3.30627e-07	−6.03132e-07	−5.75711e-07
	[−3.2704]*	[−7.6946]*	[−6.9321]*
GDPPC^3	3.12101e-012	5.91134e-012	5.62913e-012
	[3.2309]*	[6.9908]*	[6.3326]*
RNWELECT		−0.000138533	−0.00014953
		[−3.6118]*	[−4.9881]*
RNWELECT*GDPPC		2.16888e-09	2.45163e-09
		1.9163]***	[2.7032]*
TO		1.54165e-012	1.82236e-012
		[3.7775]*	[4.6733]*
NRA		−1.55742	−1.56603
		[−3.7707]*	[−4.4381]*
ENERGY_INNOV		-	−0.000674383
		-	[−2.1551]**
Effects specification: cross-section fixed (dummy variables)			
R-squared	0.638039	0.837874	0.889554
Adjusted R-squared	0.540132	0.828174	0.881372
F-statistic	80.170076	86.37995	108.7313
p-value	0.000054	3.28e-43	4.44e-48
S.E. of regression	1.350011	1.120147	1.141053

*Notes: t-statistics and p-values are given in [ ]; *, **, and *** show significance at the 1%, 5%, and 10% levels, respectively.*

In Table-3, we present the main results from our estimation (1985-2016). Our main model proposes an empirical EKC that regresses GHGpc on GDPpc, incorporating auxiliary variables to verify whether the income–environmental quality relationship fits an N-shaped pattern. First, we estimate Model 1 (equation 1) in order to test for the existence of the hypothesized N-shaped EKC. The results validate the existence of N-shaped behaviour for the selected countries between 1985 and 2016[4]. Table-3 shows that all variables are also significant for the proposed models. The R^2 values for models 1, 2 and 3 are 63.80%, 83.78% and 88.95%, respectively, after correcting for heteroscedasticity. This result indicates that all models are explained well by the independent variables. The F-statistic is statistically and highly significant, which implies adequate specification of the empirical models.

Figure-2. Causal Model Diagram



Source: Prepared by the authors.

For the values of the coefficients in Model 2 (equation 2), first, the estimates show that $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$ correspond to an N-shaped EKC (Figure-2). This scenario identifies the behaviour of GHGpc emissions with respect to GDPpc, where a first tier of per capita income produces an increase in the pollution level until an income level of X(1) = US$ 29,531.45 is

[4] In Model 1 (equation 1), the first turning point is X(0) = US$ 27,275.63 and the second turning point is X(0*) = US$ 43,348.30, with an inflection point I(0) = US$ 35,311.97.

reached.[5] From here, CO_2 emissions show a downward trend until reaching an income point of X(2) = US$ 38,534.8, where an increase in GHGpc emissions is identified. To explore technical obsolescence and the re-emerging scale effect between the first and second turning points, we consider that the inflection point[6] between X(1) and X(2) as the income level at which the *scale effect* overcomes the *composition* and *technical effects*, leading to *technical obsolescence*. The inflection point between X(1) and X(2) indicates that when the economy reaches a certain income level, society begins to pay less attention to environmental protection, and the scale effect can become dominant (Antweiler et al., 2001; Song et al., 2013; Lorente and Álvarez-Herránz, 2016). Following Goklany (2012), the inflection point indicating the peak corresponding to the environmental transition is likely to move over time because of technical change and increased problems due to environmental degradation (Figure-3).

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[5] The coefficients β_1, β_2, and β_3 allow us to calculate the turning point for the cubic model. The estimation of the turning points for the cubic model uses theformulation of Diao et al. (2009):

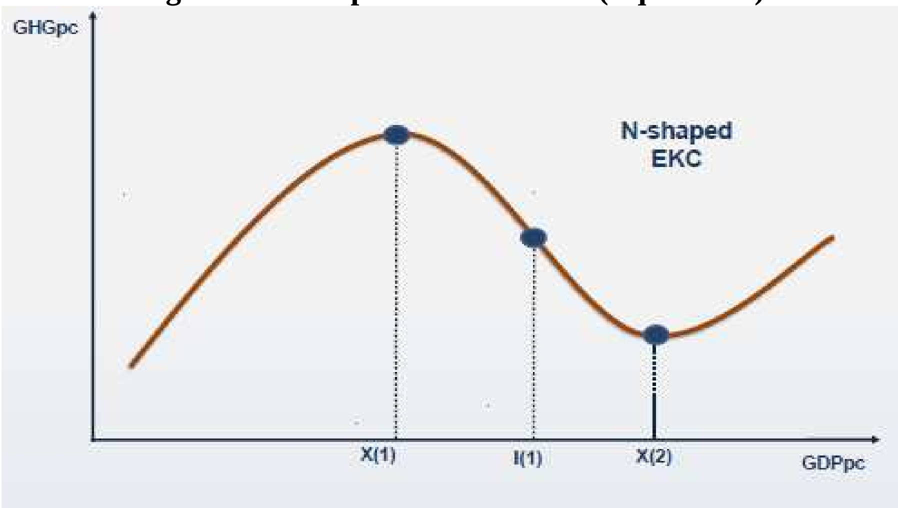
$$Xj = \frac{-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}, \forall j = 1,2. \quad (4)$$

[6] Inflection point I(1): Calculating the derivative of Z, we obtain: We also can calculate inflection point I(1) as

$$Ij = \frac{-\beta_2}{3\beta_3}, \forall j = 1, \quad (5)$$

by setting the quadratic differentials of equation 1 equal to 0.points may not exist, and a corresponding curve can show the trend of continuous decrease (Diao et al. 2009).

Figure-3. N-Shaped EKC Model 2 (Equation 2)

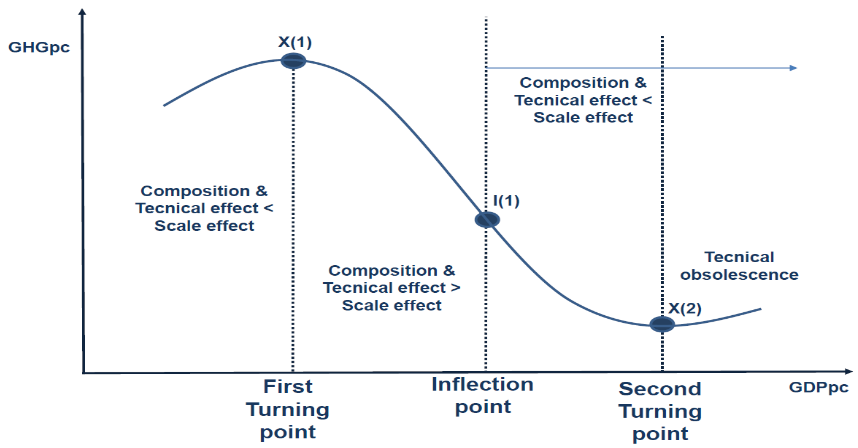


Notes: X(1) US$29,647.48; X(2) US$38,534.87; I(1): US$34,091.17

Coefficients of $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$ determine the N-shaped pattern of the EKC, and the signs of the coefficients of the additional variables that make up the model help explain the evolution of GHGpc-emissions. A negative β_4 coefficient implies that renewable electricity consumption ($RNWELECT_{it}$) is an environmentally friendly source to which policy makers should pay attention to improve environmental quality. For the variable $RNWELECT_{it}$, a more thorough analysis is conducted through the incorporation of an interaction effect, which allows testing for the existence of an interaction between economic growth and renewable electricity consumption. The negative relationship between CO_2 emissions and the share of renewable electricity consumption is significant at the highest level for all models. As expected, the results indicate that a higher percentage of renewable electricity consumption causes a decrease in CO_2 emissions. The positive sign on β_5 ($RNWELECT*GDPPC_{it}$) implies that economic growth reduces the positive effect of $RNWELECT_{it}$ on environmental quality. This implies that growing economies meet increased energy requirements by reducing the share of renewable energies in the energy mix, which deteriorates environmental quality by increasing CO_2 emissions. One possible regulation would be to increase renewable energy share of total energy consumption (Boluk and Mert, 2015; Balsalobre-Lorente and Shahbaz, 2016). Following Vaona (2012) and Balsalobre-Lorente and Shahbaz, (2016), we assume that greater non-renewable energy use promotes economic growth and increases carbon emissions. On the other hand, increases in renewable energy consumption will allow for sustainable economic growth due to greater efficiency in energy use.

The positive sign of coefficient β_6, corresponding to trade openness (TO), indicates that an increase in trade openness increases CO_2 emissions ($GHGpc_{it}$). This result validates the hypothesis that the *scale effect* exerts a strong influence on trade openness and relates to environmental pollution. Ahmed et al. (2016) argue that trade openness contributes to economic growth, implying an increase in environmental pollution. We show that the environmental impact of trade openness will be positive or negative depending upon the magnitudes of the *scale, technical, and composition effects* (Antweiler et al., 2001; Farhani et al., 2014). Figure-3 presents an inflection point I(1) = US$ 34,091.18, an income level that all EU-5 countries had reached by 2013. The econometric results validate our hypothesis that EU-5 countries are in a situation where *scale effects* starts to overcome *technical and composition effects*. In the EU-5 countries, trade openness relates to a productive system that demands dirty inputs. Therefore, in a non-regulated environment for cleaner production processes, CO_2 emissions will again increase in these economies. One potential solution would be to increase the production of high-technology outputs to mitigate the requirements of highly polluting inputs. The negative β_7 coefficient of natural resource abundance shows that more natural resources abundance helps control CO_2 emissions of an economy, as there is little need to import fossil energy sources (e.g., petrol or gas) (Shahabadi and Feyziand, 2016). These results are linked to the employment of own energy sources (e.g., natural gas and renewable sources), which produce fewer emissions than do fossil sources, such as petrol, imported by the EU-5 countries.

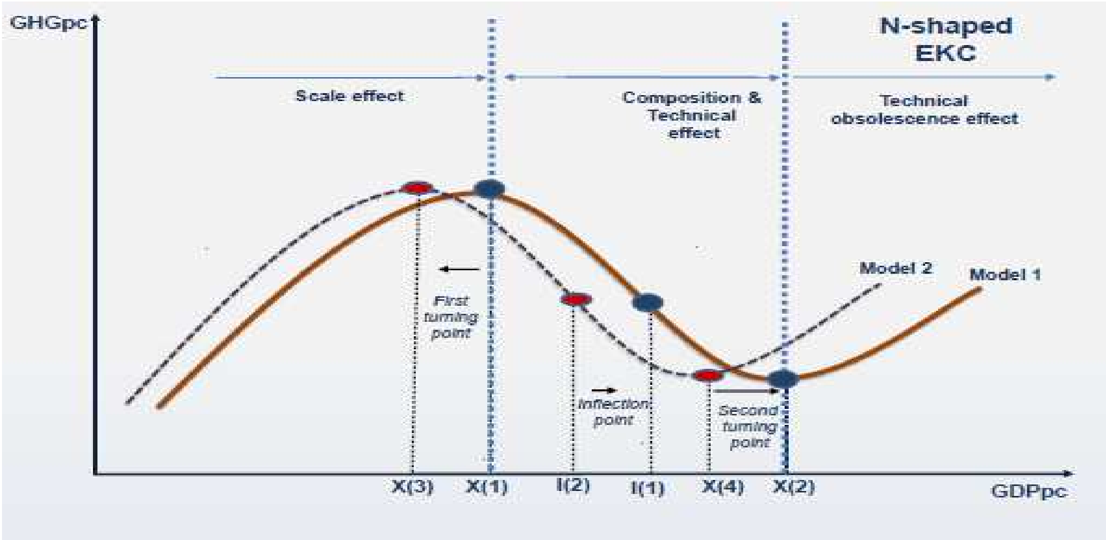
Figure-4. Inflection Point



In Figure-4, the inflection point determines the income level at which scale effects start to overcome *composition* and *technical effects*, although these economies are decreasing CO_2 emissions. This pattern implies that economies are in a scenario where scale effects are stronger than *composition* and *technical effects*, and the effects of trade openness on environmental degradation will be negative (Antweiler et al., 2001; Farhani et al., 2014; Lorente and Álvarez-Herránz, 2016). Finally, the negative sign of β_8 shows that the public budget devoted to energy RD&D reduces CO_2 emissions in Model 3 (equation 3). This result verifies that public energy innovation measures will reduce environmental pollution levels. Within the structure of the EKC, increases in energy innovation measures may be associated with the *scale effect* noted by Torras and Boyce (1998). In an N-shaped scheme, $ENERG\_INNOV_{it}$ provides *technical compensation* for the *scale effect* (Figure-3) in the sense that when there are no technical advances aimed at correcting environmental degradation, decreasing technical returns lead to increases in CO_2 emissions. Therefore, the results provide empirical evidence that energy RD&D contributes positively to environmental quality. The *technical effect* describes the impact of technological improvements, where the incentives for energy innovation measures are linked to developed countries that can afford to invest in energy RD&D (Komen et al., 1997).

We analyse the effects of energy innovation on the *technical effect* and the potential appearance of *technical obsolescence*. In a second step, we compare Model 2 (equation 2) and Model 3 (equation 3) to isolate the *technical effect* by omitting several variables related to energy RD&D. Model 3 omits $ENERG\_INNOV_{it}$ to demonstrate that technical efforts help to reduce *scale effects* (Torras and Boyce, 1998; Balsalobre et al., 2015). High-income countries that invest in energy innovation processes, use high-technology equipment, and operate in a more service-centred economy generate large differences in the trade preconditions of developed and developing countries. Trade theory postulates that economies specialize in products in which they have effective producers to benefit from comparative advantage and trade openness.

Figure-5. Comparison Model 2 (equation 2) and Model 3 (equation 3)



Model 2 (equation 2)	Model 3 without RD&D (3quation 3)
X(1) = USD 29,647.48 **X(2) =** USD 38,534.87	**X(3)** = USD 29,609.11 **X(4)** = USD 38,410,65
Inflection point between X(1) and X(2)	**Inflection point between X(3) and X(4)**
I(1) = USD 34,091.18	**I(2)** = USD 34,009.89

The predicted positive relationship for CO_2 emissions and the moderation effect between income and renewable electricity consumption are significant. When comparing the coefficients on electricity production, the different units on the variables (percentage and US$) need to be considered. When Model 2 (equation 2) is compared with Model 3 (equation 3), which omits the energy innovation variable ($ENERG_INNOV_{it}$), in Model 2, the income requirements necessary to achieve reductions in CO_2 emissions are higher (X(1) = US$ 29.647,48 > X(3) = US$ 29.609,12). This implies that in the short run, more effort is needed to reduce GHG levels. Another consequence of the application of energy regulations is that the income level required to reach the second turning point, and thus return to increasing pollution, is higher (X(2) = US$ 38.534,87 > X(4) = US$ 38.410,65). In the long-run, energy innovation measures delay scale effects and thus technical obsolescence. Model 2 (equation 2) suggests the appearance of a new effect, which we define as the *technological obsolescence effect* (Lorente and Álvarez-Herránz, 2016), that occurs because of inadequate or poor energy regulation management. Figure-5 shows that without energy innovation, economies may return to a pattern of increasing environmental degradation, a phenomenon that this study defines as the *technological obsolescence effect*. To avoid this increasing pollution, measures must be taken to encourage technological innovation to avoid falling into the trap of decreasing technological returns. When economies reach technical obsolescence, they once again experience an increase in environmental pollution. Therefore, this study demonstrates the relevance of both renewable energy sources and energy innovation measures to keep countries on a path of decreasing CO_2 emissions at higher income levels. This study considers the fact that the selected economies operate in a structure that employs dirty inputs, which implies that trade openness increases carbon emissions. Finally, natural resource abundance has a negative impact on CO_2 emissions, thus helping to reduce carbon emissions as these countries use their own natural resources with lower pollution rates than oil imports.

We have included two sub-samples to distinguish the pre-and-post crisis periods around the 2008 global financial crisis and subsequent economic recession. The results of both sub-samples (Tables A1 and A2 in the Appendix) are similar to those of the full sample, which confirms the robustness of the empirical findings. The empirical results obtained in this study can be applied as energy strategies in both scenarios. Instead of recession-related decreases, the promotion of renewable energy sources and energy innovations measures is needed during recession[7].

[7] These results confirm that the wrong strategy was pursued by some countries (e.g., Spain) during the crisis period, which reduced promotion of renewable energy measures.

5. Conclusions and policy implications

This paper analysed the factors affecting CO_2 emissions in EU-5 countries during the 1985-2016 period. To examine this impact, we have employed an EKC model with additional explanatory variables, renewable electricity consumption, trade openness, natural resource abundance, and energy innovation, to test the relationship between CO_2 emissions and economic growth. To test the EKC hypothesis for the EU-5 countries, we estimate two separate specifications. The first includes all proposed variables, while the second omits energy innovation to determine the existence of a *technical obsolescence effect* (Álvarez-Herránz at al., 2017). This omission follows the argument of Andreoni and Levinson (2001) that pollution reduction processes depend mainly on technical innovation. Regarding the results obtained in our econometric model, we can conclude that energy innovation measures are linked to environmental pollution and to the delay of technical obsolescence for selected countries. Therefore, implementing measures related to energy innovation and the replacement of conventional sources with renewable ones results in a deviation from diminishing technological returns, thus leading to a reversal in the upward trajectory of the EKC (Torras and Boyce, 1998). Reforms and institutional changes are necessary to reach this objective (Unruh and Moomaw, 1998; Stagl, 1999). This implies that in selected developed countries with lower growth rates but high income, where pollution reduction processes depend mainly on innovation in low-carbon technologies, technological changes could offset *scale effect* and delay *technical obsolescence* (Aghion et al., 2014, Álvarez-Herránz et al., 2017).

Additionally, within an N-shaped EKC relationship, this study explores the role of renewable electricity outputs in CO_2 emissions. The results confirm the negative effect of renewable electricity consumption on CO_2 emissions. This suggests that more attention should be paid to using renewable energy sources for domestic production to improve environmental quality. EU Member States have already agreed on a new renewable energy target of at least 27% by 2030. For instance, **Germany** has made significant progress towards its GHG emission reduction target, achieving a 27% decrease between 1990 and 2014. Germany spends €1.5 billion per annum on energy research in an effort to solve the technical and social issues of the transition. The share of renewable electricity consumption increased to 30.7% in 2015 (Eurostat, 2017). In July 2015, the **French** parliament passed a comprehensive energy and climate law that includes a *mandatory renewable energy target* requiring 40% of national electricity production to come from renewable sources by 2030. In **Italy**, the renewable energy sector has developed rapidly over the past decade and has provided the country with a means of escaping its historical dependency on imported fuels. In 2015, 33.5% of national electric consumption came from renewable sources, representing 16% of total energy consumption in the country (Eurostat, 2017). The Italian National Renewable Energy Action Plan (NREAP) set a target of 17% for the total share of renewable energy of final total energy consumption. To achieve this target, renewable electricity goals were set to 26% in the electricity sector, 17% in the heating/cooling sector and 10% in the transport sector by 2020.

Similarly, **Spain** has long been a leader in renewable energy and has recently become the first country in the world to rely on wind as its top energy source for an entire year. Most of renewable electricity generated in Spain comes from wind, which provided 22.5% of the country's electricity (REE, 2016). In 2015, the share of renewable electricity was 36.9% (19% in 2004). In 2007, the **United Kingdom** agreed to an overall EU target of generating 20% of the EU's energy supply from renewable sources by 2020. Successive UK governments have outlined numerous commitments to reduce CO_2 emissions. One such announcement was the *Low Carbon Transition Plan* launched by the Brown administration in July 2009, which aimed to generate 30% electricity from renewable sources and 40% from low-carbon-content fuels by 2020.

Although previous studies have extensively examined the causal relationships among renewable energy, CO_2 emissions, and economic growth, they have not incorporated the effect of an interaction between renewable electricity and economic growth. Our study includes an interaction between economic growth and renewable electricity consumption, finding that the positive effect of renewable electricity output is reduced by economic growth. This effect is consistent with the *growth hypothesis*, which suggests that economic growth implies an increase in energy requirements, both renewable and fossil based. When economies experience an increase their energy requirements, the share of renewable sources decreases, implying an increase in environmental pollution from fossil sources. One policy implication is that the use of renewable sources should be promoted to reduce the share of fossil and other highly polluting sources in the energy mix. Otherwise, for the selected sample, the econometric results show that trade openness exerts a negative effect on environmental quality. This negative effect is related to a *scale effect*; that is, in selected countries, employment and trade in pollutant inputs increase CO_2 emissions. The *scale effect* suggests that when economic systems achieve a given technological level, increases in the inputs employed to obtain outputs entail an increase in environmental pollution. One reasonable solution would be the promotion of high-tech industries with lower requirements of dirty inputs to reduce the scale effects of trade openness. In keeping with this argument, Heerink et al. (2001) hold that the extent to which the technical effect dominates the total effect depends on incentives for policy makers.

Finally, the econometric results support the idea that natural resource abundance reduces per capita CO_2 emissions in the EU-5 countries. Societies with abundant natural resources can reduce their imports of fossil sources and thus help control carbon emissions. This effect justifies the implementation of energy strategies that reduce both dependence on fossil sources and energy intensity, as non-renewable energy sources still exert a high impact on the energy mix. This may explain the substitutability of renewable and non-renewable energy sources that may occur in the long-run. Indeed, we expect that in the long-run, the proportion of renewable energy consumed with respect to total energy consumed will increase. There are additional policy implications to our findings. First, renewable electricity improves environmental well-being. Second, economic growth implies additional energy requirements and, in the EU-5, fossil sources are still consumed a high rate. Third, technological innovation, as in endogenous growth theory, is effective in reducing carbon pollution. Moreover, the EU-5 should establish a strategy for maximizing their benefits from renewable energy technology transfers when importing capital goods, such as machines and equipment, to promote renewable energy consumption. Fourth, trade openness increases carbon emissions, making it necessary to implement cleaner production processes to reduce supplies of polluting inputs. Finally, natural resource abundance has a positive effect on CO_2 emissions, which implies that countries with natural sources reduce their imports of dirty energy sources. The EU energy policy strategy has set medium-term targets of 20% for renewable energy, GHG reduction, and energy efficiency for 2020. This study validates the positive role of innovation and renewable energy sources in carbon emissions. In addition, our results reveal that it is necessary to increase the share of renewable energy sources to reduce the negative impact of non-renewable energy sources in terms of carbon emissions. In the long term, the EU's energy strategy establishes targets for renewables, energy efficiency, and GHG reductions and outlines a transition to a competitive, secure and sustainable energy system by 2050 to reduce GHG emissions by at least 80%. These objectives are compatible with the results obtained in this study.

Appendix

Table 1A: 1985-2007

PLS with correction for heteroscedasticity

Dependent variable: GHG_PC		
Variable	*Coefficient*	*Coefficient*
C	-86.6518	-108.327
	[-3.3056]*	[-3.5303]*
GDPPC	0.00820913	0.0102108
	[3.1323]*	[3.2850]*
GDPPC^2	-2.14143e-07	-2.73237e-07
	[-2.4911]**	[-2.6400]*
GDPPC^3	1.6849e-012	2.20362e-012
	[1.8060]***	[1.9321]***
RNWELECT	-0.000276431	-0.000273124
	[-6.2488]*	[-6.2337]*
RNWELECT*GDPPC	6.05719e-09	6.69592e-09
	[4.6165]*	[5.0679]*
TO	2.86117e-012	3.53153e-012
	[9.6005]*	[7.6858]*
NRA	0.20925	0.928882
	[0.4697]*	[2.0233]**
ENERGY_INNOV	0.00124963	
	[4.6316]*	
Effects specification: cross-section fixed (dummy variables)		
R-squared	0.928383	0.928383
Adjusted R-squared	0.837757	0.922927
F-statistic	102.9809	170.1428
p-value	5.45e-57	1.68e-56
S.E. of regression	1.511305	1.303827

*Notes: t-statistics and p-values are given in [ ]; *, **, and *** show significance at the 1%, 5%, and 10% levels, respectively.*

Table 2A: 2008-2016

PLS with correction for heteroscedasticity

Dependent variable: GHG_PC		
Variable	*Coefficient*	*Coefficient*
C	-121.972	-440.232
	[-1.4642]	[-3.2760]*
GDPPC	0.0121065	0.038864
	[1.7410]***	[3.4638]*
GDPPC^2	-3.63466e-07	-1.1235e-06
	[-1.8671]***	[-3.5816]*
GDPPC^3	3.57649e-012	1.08876e-011
	[1.9537]***	[3.7034]*
RNWELECT	-7.35019e-05	8.21218e-05
	[-2.0978]**	[1.5144]
RNWELECT*GDPPC	9.44316e-010	-3.33871e-09
	[0.9248]	[-2.0864]**
TO	1.94589e-012	2.88791e-013
	[4.2621]*	[0.5628]
NRA	-1.18167	-0.482112
	[-3.0289]*	[-1.1792]
ENERGY_INNOV	-0.000926732	-
	[-5.0878]*	-
Effects specification: cross-section fixed (dummy variables)		
R-squared	0.992708	0.975090
Adjusted R-squared	0.991088	0.970377
F-statistic	612.6150	206.9045
p-value	4.43e-36	1.12e-27
S.E. of regression	0.534584	0.725783

*Notes: t-statistics and p-values are given in [ ]; *, **, and *** show significance at the 1%, 5%, and 10% levels, respectively.*

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