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THE PARTICIPATION OF ENERGY CONSUMPTION AND ECONOMIC ACTIVITY IN GLOBAL CO_2 EMISSIONS

TOURIA ABDELKADER-BENMESAUD CONDE*
Spanish University for Distance Education (UNED, Madrid)
Professor Tutor Engineering High School

FERNANDO BARREIRO-PEREIRA
Spanish University for Distance Education (UNED, Madrid)
Faculty of Economics and Business Administration

The pollutants that contribute most to environmental degradation are carbon dioxide emissions and PM10 suspended particles. In 41 years, from 1971 to 2012, greenhouse gas emissions have doubled, with CO_2 accounting for two thirds of greenhouse gas emissions. The aim of this research is to analyse to what extent the excess of CO_2 emissions is directly associated with energy consumption or are due to imperfections in production processes. In order to carry out this analysis, a microeconomic specification has been carried out, which has been applied in the period 1995-2015 on 6 countries of the European Union plus 14 countries, whose total population is equivalent to 61% of the world population. The application has been carried out using econometric techniques that include panel data and the results indicate that imperfections in production processes generally contribute to emissions to a greater degree than energy consumption, suggesting a duty to improve these processes.

Keywords: Emissions, Carbon dioxide, Energy consumption, Greenhouse gases, Production, Energy productivity.

JEL Classification: D21, Q41, Q51.

1. Introduction

Since the last decade of the twentieth century, regions and countries have emphasized the negative effects that, on the environment, require maintaining energy consumption patterns that often cause emissions of gases and other polluting particles also associated with economic activity and to economic growth. Carbon dioxide (CO_2) in natural proportions is not damaging, but as a result of the combustion of fossil fuels, the concentration of this gas in the atmosphere has been increasing to become a greenhouse gas (GHG), that is, it induces a greater absorption of infrared radiation that escapes from the earth and ends up causing an increase in temperature in the atmosphere and on the earth's surface. The increase in production of goods and services generates externalities, many of them

*Corresponding author Email: tabdelkader@madrid.uned.es

negative, which add up to excesses in the use of environmental resources with which energy consumption and production are supplied. Many of the results of research conducted on the relationship between energy consumption and gross domestic product (GDP) indicate that energy consumption patterns have a positive impact on CO_2 emissions. CO_2 emissions are considered to be especially responsible for global warming, since CO_2 is the most abundant greenhouse gas. Several reports from the World Bank maintain that from 1971 to 2012 global greenhouse gas emissions have doubled, being the CO_2 contribution 67% of total GHG gas emissions. Other greenhouse gases, which not only affect health, but also promote environmental degradation are: i) Carbon monoxide (CO), mainly associated with traffic and transportation; ii) Sulphur dioxide (SO_2), associated with the combustion of coal and petroleum products; iii) Nitrogen oxides (NO_x), associated with the combustion of fossil fuels, and iv) Hydrocarbons (CH_x), substances that contain only hydrogen and carbon and influence the formation of photochemical smog. Finally, Plumb (Pb) suspended or diluted in water and suspended particles called aerosols, which are particles of different sizes that influence the formation of sulphurous smog, are also highly polluting. Dust, fibre, soot, fumes, fog, mist and smog, overload the environment so that these particles end up affecting to a greater or lesser extent not only the health of people, but also the environmental degradation. Within the most polluting aerosols, PM10 (Particulate Matter) are small solid or liquid particles of dust, ash, soot, metal particles, cement or pollen dispersed in the atmosphere. The PM10 particle size is less than 10 microns. The daily limit value for the protection of human health is 50 micrograms per m^3 ($\mu g/m^3$) of PM10, which should not be exceeded more than 7 times a year, being the annual limit for the protection of human health 20 $\mu g/m^3$. Exceeding the permissible limit of PM10 is very harmful to health and reveals a poorly developed production technology. The countries with the highest PM10 index are Pakistan, Bangladesh, Nigeria, Egypt, India, China, Saudi Arabia, United Arab Emirates and Kuwait, related in the latter case to the production and distribution of fuels. Table 1 shows the concentrations of PM10 in the 44 agglomerations of the world with more than 9 million inhabitants (Megacities) and the ones that cross the permissible daily limit, which are mostly Asian and African megacities, are shaded. Air pollution is a phenomenon that is exacerbated when the population density is high. The population density is very high in countries such as Bangladesh, South Korea, India, Japan or Bahrain and, in the case of Megacities, in Manila, Lagos, Delhi, Bangalore, Cairo, Dhaka or Tehran. It seems obvious that it is at the local level where pollution control should be most decisive. For these reasons its regulation is very important for the governments of countries and cities, and from the Kyoto protocol (1997) to the climate report (IPCC, 2018) through the Paris[1] agreements (2015) and the Marrakech (2016) Climate Change Conference, they have set as objectives to reduce pollution and greenhouse gases.

[1]. United Nations Conference on Climate Change (Paris, December 2015) whose agreements were ratified and approved by the Parliament of the European Union on October 4, 2016. This European action on climate change has its background in articles 17, 18 and 19 of EU Directive 2009/28 / EC of the European Parliament and Council in April 23, 2009.

Table 1. Level of PM10 in the megacities of the world (2016)

Agglomerations classified by population	Population 2016 (millions)		Agglomerations classified by population	Population 2016 (millions)	
	PM10			PM10	
TOKYO-YOKOHAMA	35	37.126	BANGKOK	41	14.566
CHONGQUING	77	29.101	BUENOS AIRES	22	14.300
JAKARTA	82	28.019	ISTANBUL	55	13.855
GUANGZHOU	56	25.800	TEHRAN	72	13.500
SHANGHAI	59	25.700	LAGOS	122	13.400
SEOUL	31	25.600	TIANJIN	103	13.266
MEXICO	34	24.178	RIO JANEIRO	35	12.700
DELHI	292	23.500	LAHORE	198	12.500
MUMBAI	104	22.376	PARIS	14	11.950
KARACHI	290	22.100	KOLN-RUHR	22	11.215
NEW YORK	21	22.000	CHENGDU	105	11.001
METRO-MANILA	118	21.951	IZMIR	29	10.046
BEIJING	92	21.900	NAGOYA	30	10.027
SAO PAULO	45	21.100	WUHAN	92	10.020
CAIRO	169	20.384	HARBIN	74	9.874
LOS ANGELES	34	18.100	CHICAGO	25	9.800
OSAKA-KOBE	39	17.550	JOHANNESBURG	85	9.616
MOSKOW	40	17.000	KINSHASA	40	9.518
KOLKATA	136	15.835	LIMA	58	9.400
DHAKA	134	15.414	CHENNAI	80	9.182
SHENZHEN	42	15.250	BANGALURU	96	9.044
LONDON	17	15.211	BOGOTA	40	9.009

Shaded megacities indicate that they exceed the permissible limits of PM10.
Source: own elaboration based on data from the International Energy Agency 2016.

On the other hand, all these polluting elements can also end up being a source of conflicts between neighbouring countries, regions and even between neighbouring cities, due to toxic gas emissions over areas less contaminated. In volume, the most important pollutants are CO_2 emissions and PM10 suspended particles.

In this research, only the CO_2 emissions caused by energy consumption and the processes of production of goods and services are analysed. The relationship between emissions and energy consumption, as well as the relationship between energy consumption and output, or output growth, has been extensively analysed since the work of Kraft and Kraft (1978), from which a great deal of research on this subject is derived, but there is still no precise consensus as to the relationship between energy consumption and economic growth. In this sense, two opposite positions can be identified: the first maintains that changes in energy consumption do not have a clear effect on economic growth and, the second, that there is some relationship between energy consumption and the level of production. Enough studies have tried empirically to prove this relationship in economies such as the United States (Abosedra and Baghestani, 1989), Gardner and Joutz (1996) and Soytas, Sari and Ewing (2007); Canada (Ghali, 2004); Mexico (Caballero and Galindo, 2007) and Gómez (2010); Central America and Caribbean countries (Apergis and Payne, 2009). Studies in Asian countries have been carried out by Razzaqi, et al., (2011); specifically in Bangladesh (Alam, et al., 2012); China (Zhang and Cheng, 2009) in the period 1960-2007; Taiwan (Cheng, 1997) over the period 1980-2007; Pakistan (Siddiqui, 2004); Iran (Zamani, 2007); India (Mallick, 2009); Turkey (Jobert and Karanfil, 2007) and Halicioglu (2009) for the period 1960-2005; and Ang (2007a) examines the relationship between GDP, pollutant emissions and energy consumption in Malaysia between 1971 and 1999. In Africa, Belloumi (2009) examines the causal relationship between energy consumption per capita and GDP per capita capita in Tunisia, for the period 1971-2004. Studies in European countries have been carried out in France (Ang, 2007b), Greece (Tsani, 2010), Russia (Zhang, 2011) and in Spain (Labandeira et al., 2017). Some analysis performed for groups of countries have been carried out by Medlock and Soligo (2001) on 28 countries of different levels of development, Pao and Tsai (2010) that examine the relationships between CO_2 emissions, energy consumption and the GDP in the BRICS countries during the period 1990-2005; Mehrara (2007), which examines the causality between energy consumption per capita and GDP per capita through panel data on eleven oil exporting countries; Luzzati and Orsini (2009), who study the relationship between energy consumption and GDP per capita in 113 countries for the period 1971-2004 and Farhani and Ben Rejeb (2012) who conducted a study for 90 countries. Other research argues that increases in GDP increase pollution until the country reaches a certain per capita income, from which pollution begins to decrease (Hettige, Mani and Wheeler, 2000). In addition to all these authors, Srnivasan and Siddanth (2015) also found relationships between energy consumption and the level of production, which does not happen in the investigations of Yu and Choi (1992) and Altinay and Karagol (2004).

The purpose of this article is to analyse the extent to which CO_2 emissions are directly associated with energy consumption or with imperfections in the production process of goods and services. The analysis is carried out throughout 20 countries during the period 1995-2015 with annual data coming from the International Energy Agency (2016). The countries in which the analysis is carried out represent in 2018 61% of the world population and belong to four continents. By the European Union (EU) Ireland, United Kingdom, France, Germany, Portugal and Spain are listed. Also figure Iceland as a European country. The Asian countries analysed in this research are: India, Indonesia, Saudi Arabia, Iran, Japan and China. Also figure Russia. Some American countries such as United States, Brazil and Mexico are included. And the African countries listed in this analysis are Morocco, South Africa and Nigeria. The five most important emerging countries considered in this analysis are framed in the BRICS block. Certain energy characteristics of some of the countries and blocks that are analysed in this research are exposed below.

The EU countries considered in this analysis have 53.7% of the EU population in 2018. These countries have a high gross domestic product per capita, and a joint GDP that represents 59% of the EU and 10% of world GDP. In Germany, energy production is based on obtaining coal, biofuel and waste treatment, nuclear and renewable energy, highlighting wind, solar and hydraulic. In Spain, energy production is based on obtaining nuclear and renewable energy, highlighting wind, solar, biofuel, waste treatment and hydraulics. In France, energy production is based on obtaining nuclear energy, biofuel, waste treatment, hydraulics and renewable energy, highlighting wind and solar. In Ireland, energy production is based on obtaining natural gas, coal and renewable energy, highlighting wind power. In Portugal, energy production is based on obtaining biofuel, waste treatment and renewable energy, especially wind and water. In the United Kingdom, energy production is based on obtaining oil, natural gas, nuclear energy, biofuel, waste treatment, renewable energy, highlighting wind, solar and hydraulic. As for Iceland, geothermal energy provides 66.3% of primary energy, hydroelectric power 19.1% and fossil fuels 14.6%. Brazil, Russia, India, China and South Africa form the so-called BRICS countries, which form an economic-trade partnership between these five emerging economies. All these nations have in common a large population, estimated in 2019 in more than 40% of the world's population. Brazil in recent decades has excelled in the production of oil, biofuels and waste, natural gas, nuclear energy and coal, in this order. It is the third largest hydroelectric power in the world and the majority energy consumption comes from natural gas, petroleum products and biofuels. Regarding renewable energy, despite its great potential, only wind and solar energy have been developed. Russia produces natural gas, oil, coal, nuclear and hydroelectric power, in this order, with a majority consumption of natural gas and petroleum products. The great extension of Russia allows the development of renewable energies, with geothermal energy being the most developed, followed by solar and wind energy. India is considered the third world energy power, and produces coal, biofuels and waste, oil and natural gas. Most of its energy consumption comes from biofuels, petroleum products, coal and natural gas. China is today the world's first energy power, especially in the development of renewable energy. The production of coal, oil, biofuels, hydroelectric and nuclear remains very important, but it also has wind, solar, photovoltaic and thermal, geothermal and marine energy. Consumption comes from coal, petroleum products, natural gas, biofuels and renewable. South Africa is the last country added to the BRIC group, it is a producer of coal and biofuels, and consumption is mainly based on petroleum products, coal and biofuels.

The structure of this article is as follows: The modelling of the equations that try to explain the causal relationship between energy consumption and production and between CO_2 emissions and energy consumption are carried out in section 2. Section 3 contains the results obtained from the estimates of the equations obtained in the second section for the 20 countries in the sample and finally, section 4 contains the most relevant Conclusions of this research.

2. Energy Consumption, Production and Emissions

Energy is a consumer good for consumers and, at the same time, a factor of production for companies. We can assume an economy in equilibrium where there is a small number F of companies in imperfect competition, under oligopoly, in charge of supplying energy to a population of H consumers and to a large number N of companies that for simplicity we assume in perfect competition, producers of consumer goods. In the absence of political or governmental interventions, calling e to the amount of energy and c and R respectively to consumer goods and production factors other than energy, being p_e, p_c and p_R the respective unit prices, the utility function that we propose for consumers when they are choosing between energy consumption and other consumer goods is by simplicity Cobb-Douglas type and it will have the following expression, being $0 < \alpha < 1$:

$$U(e,c) = e^{\alpha} c^{1-\alpha} \tag{1}$$

Consumer energy demand: Consumers maximize their utility conditional on their budget constraint. Calling m to the disposable monetary income per capita of the consumer, the behavior of the individual agents in each period will then be as follows:

$$Max\left\langle U(e,c) = e^{\alpha} c^{1-\alpha} \right\rangle \text{ subject to: } e\,p_e + c\,p_c = m \tag{2}$$

Solving this maximization we have: $m = \frac{p_e}{\alpha} e$, If we don´t consider taxes, then: $H\,m = Y$ (monetary income of the economy), ie: $Y = \frac{p_e}{\alpha} H \cdot e$. Therefore, the aggregate demand for energy as a consumer good, by consumers, will be:

$$H \cdot e = \frac{\alpha Y}{p_e} \tag{3}$$

Energy demand of companies producing consumer goods c: In the economy there are N companies in a regime of perfect competition, which produce consumer goods *c,* maximizing the profit. We assume by simplicity that goods c are produced from a Cobb-Douglas type production function based on a series of production factors (R), plus energy (e), which in this case functions as a production factor (e_0). That is to say:

$$c = A e_0^{\beta} R^{1-\beta} \tag{4}$$

where $0 < \beta < 1$. A is the total factor productivity coefficient that we assume neutral in the sense of Hicks. The objective of each one of these companies is to maximize profit $B = p_c c - p_e e_0 - p_R R$. The demand for energy as a factor of production is a demand derived from profit maximization. That is to say:

$$MaxB = Max\left\langle p_c A e_0^{\beta} R^{1-\beta} - p_e e_0 - p_R R \right\rangle \tag{5}$$

We assume perfect competition in the consumer goods c and factors R markets, so prices p_e and p_R appear as fixed. With regard to energy prices, in principle we assume that the F companies that supply energy to consumers and companies are in a non-collusive competition in prices in the sense of Bertrand (1883), which implies that their equilibrium is similar to perfect competition, even if they form an oligopoly: For the F companies that produce energy, the following must be fulfilled: $p_e = C'_e$, since the product they offer (energy) is homogeneous. The energy derived demand is obtained by maximizing B with respect to e_0:

$B'_{e0} = 0 = \beta \cdot p_c \cdot A \cdot e_0^{\beta-1} \cdot R^{1-\beta} - p_e$, hence the energy demand of each company is: $e_0 = \frac{\beta \cdot p_c \cdot c}{p_e}$, and for the *N* companies, the aggregate demand will be:

$$e_0 N = \frac{\beta \cdot (p_c \cdot c \cdot N)}{p_e} \tag{6}$$

Energy demand of the companies that supply energy: The *F* companies that supply the energy good also use a part of it as a factor of production (e_0) according to a production function that for simplicity we assume Cobb-Douglas type and whose arguments are the energy (e_0) and the rest of the production factors *R*:

$$e = A e_0^{\beta} R^{1-\beta} \tag{7}$$

where *e* is the energy produced and supplied to companies and consumers. Demand for energy is derived from the profit maximization by each one of the *F* companies: $MaxB = Max\left\langle p_c A e_0^{\beta} R^{1-\beta} - p_e e_0 - p_R R \right\rangle$, whose result, considering that the price p_e is given by Bertrand equilibrium, is: $e_0 = \frac{\beta \cdot p_c \cdot e}{p_e}$, and for the *F* companies the aggregate demand will be:

$$e_0 F = \frac{\beta \cdot (p_c \cdot e \cdot F)}{p_e} \tag{8}$$

Knowing that in an economy in equilibrium the income of sellers is equal to consumer spending and that the total annual nominal income of the economy (*Y*) is the sum of the annual income of all companies: $Y = (p_c\ c)N + (p_e\ e)F$, the total derived energy demand as a factor of production by companies, taking into account (6) and (8) will be: $N \cdot e_0 + F \cdot e_0 = \frac{\beta}{p_e}[(p_c c)N + (p_e e)F] = \frac{\beta}{p_e} Y$. And the total energy aggregate demand (E_D) from companies and consumers, taking into account (3), (6) and (8), will be:

$$E_D = H \cdot e + N \cdot e_0 + F \cdot e_0 = (\alpha + \beta)\frac{Y}{p_e} \tag{9}$$

The energy supply: We have assumed that each of the *F* supply companies produce energy according to a Cobb-Douglas production function of the type: $e = A e_0^{\beta} R^{1-\beta}$, with a cost function of type $C = p_e\ e_0 + p_R\ R$, where e_0 is the endowment of energy as a factor of production, *R* other factors of production different from the energy but necessary to produce it, *A* is the technical progress coefficient o tor technology and *e* the amount of energy produced and supplied. To the mentioned Cobb-Douglas production function (7) corresponds a variable cost function dependent on *e*, which is obtained by minimizing the cost function *C* subject to the production function:

$$Min\left\langle C(e_0, R) = p_e e_0 + p_R R \right\rangle \text{ subject to: } e = A e_0^{\beta} R^{1-\beta} \tag{10}$$

Minimizing this by Lagrange once considering as given the factor prices, a relationship between the two factors of production that allows each of them depending on the output *e* is established. Once these results have been substituted in the expression of costs (*C*) we can obtain the expression of variable costs (*Cv*) as a function of *e*, corresponding to the production function (7):

$$Cv = \left(\frac{p_e}{\beta}\right)^{\beta}\left(\frac{p_R}{1-\beta}\right)^{1-\beta}\frac{e}{A} \tag{11}$$

to which corresponds the following function of marginal costs (C') with respect to *e* :

$$C_e^{'} = \frac{1}{A}\left(\frac{p_e}{\beta}\right)^{\beta}\left(\frac{p_R}{1-\beta}\right)^{1-\beta} \tag{12}$$

This function in this case turns out to be constant for the *F* companies, because it does not depend on the amount of energy *e.*

Market equilibrium and energy consumption: When the *F* oligopolistic suppliers of energy maintain a Bertrand-type competition, competing in prices, in the equilibrium they will match the sale price of energy to the marginal cost ($p_e = C'_e$) in a only market. If then the *F* companies end up colluding then the equilibrium price will no longer be competitive but monopolistic, that is, $p_e = \mu\ C$ ', where μ is a *mark -up* over marginal costs such that if $\mu=1$ there is a Bertrand equilibrium and if $\mu>1$ there is collusion among the *F* companies. Therefore, in the most general case, the market equilibrium in prices from (9 and 12) can be expressed as:

$$p_e = (\alpha+\beta)\frac{Y}{e} = \frac{\mu}{A}\left(\frac{p_e}{\beta}\right)^{\beta}\left(\frac{p_R}{1-\beta}\right)^{1-\beta} \tag{13}$$

from where we can obtain the total energy consumption in the market equilibrium:

$$e = (\alpha+\beta)\beta^{\beta}(1-\beta)^{1-\beta}\frac{A\cdot p\cdot y}{\mu\cdot p_e^{\beta}\cdot p_R^{1-\beta}} \tag{14}$$

where the monetary income *Y* has been broken down into its components: $Y = p \cdot y$ that is, real income *y* and the general level of prices *p*, where *y* is now the real income or GDP at constant prices. What expression (14) indicates is that energy consumption depends directly on real income and inversely on the price of energy and on the prices of the other production factors different from energy. By calling $\lambda_0 = \log_e\left[(\alpha+\beta)\beta^{\beta}(1-\beta)^{1-\beta}/\mu\right]$ and taking Neperian logarithms in (14), we can obtain a first linear expression, explanatory of the energy consumption in the economy:

$$\log_e e = \lambda_0 + \log_e A + \log_e y + \log_e p - \beta\log_e p_e - (1-\beta)\log_e p_R$$

When we estimate this equation along a database, most likely the coefficient λ_0 would be highly significant, indicating it the existence of omitted variables. One of them may be related to the population level (*PO*) of the economy since it seems clear that the greater the population may correspond to a higher energy consumption; so a more complete econometric specification of the equation for regressing could be:

$$\log_e e = \lambda_0 + \lambda_1 \log_e A + \lambda \log_e y + \lambda_3 \log_e p + \lambda_4 \log_e p_e + \lambda_5 \log_e p_R + \lambda_1 \log_e PO + \varepsilon \tag{15}$$

where ε is a random disturbance. To this expression should be added the determinants of energy consumption in the very long term: If by simplicity we avoid doing considerations regarding the substitutability of production factors and we assume that the aggregate production function that governs long-term growth of a closed economy without public sector, is of the type $y = (AL)^{1-\eta} K^{\eta}$, with a neutral technical progress coefficient in Harrod sense to ensure the existence of a non-zero stationary state, and denoting by L labour and K the physical capital factor, if we consider the technology A as exogenous and increasing at a constant rate g , then in the very long term at steady-state, it must be fulfil that: $s \cdot y = (n + g + \delta) \cdot K$, , where n and g are respectively the constant growth rates of population and technology respectively while s and δ are, respectively, the saving and capital depreciation constant growth rates. Although energy is a production factor not strictly cumulative, today it is the use of capital that causes energy consumption as a production factor. Therefore, we can assume that $e = \varphi K$. Substituting this expression in the steady state equation we can obtain that the energy consumption at the steady-state will be: $e = \frac{\phi \cdot s \cdot y}{(n + g + \delta)}$, so $\log_e e = \log_e \phi + \log_e s + \log_e y - \log_e (n + g + \delta)$. That is, $\lambda_7 \log_e s + \lambda_8 \log_e (n + g + \delta)$ are the terms related to the long term that we should be added to the second member of the specification (15). The consumption of energy dedicated to transport has not been explicitly considered in this work.

Emissions: Energy production and consumption processes involve emissions of gases and particles. We assume that a certain percentage of pollutant emissions (Em) are a by-product of the energy consumption process, so that in principle we can express:

$$Em = \rho e \theta \tag{16}$$

where ρ and θ are parameters. In logarithms, we have: $\log_e Em = \log_e \rho + \theta \log_e e$. When we try to estimate this equation through a database is likely that the intercept parameter ($log_e \rho$) turns out to be too significant, which may imply the existence of omitted variables. Some of these omitted variables that explain the emissions could be related to environmental conditions, and in particular with variations in the ambient temperature that affect the consumption of heating, sanitary hot or cooling water, as well as wind or rainfall can affect the dispersion of gas and particle emissions associated with energy production and consumption.

From Joule (1850) it is known that the amount of heat necessary to raise or lower the temperature of a body of mass M is: $Q = s \cdot M \cdot \Delta T$, where Q is heat, s is a constant called specific heat, and T the temperature in $°C$; at the same time it is established that the energy accumulated (E) by heat is: $E = J \cdot Q$, where J is a universal constant called mechanical equivalent of the kilocalorie. Under these conditions, the extra energy consumption caused by variations in the ambient temperature can be established as:

$$E = J \cdot s \cdot M \cdot \Delta T \tag{17}$$

Emissions caused by energy consumption are amplified or reduced by the effect of environmental conditions. Hence, the relationship (16) can be expressed more properly as: $Em=\rho e^{\theta}E^{\varphi}$. E is given by (17). In logarithms: $\log_e Em = \log_e \rho + \theta \log_e e + \phi \log_e E$. Gathering the constant terms and being ε a random disturbance, emissions equation is:

$$\log_e Em = \gamma_0 + \gamma \log_e e + \gamma_1 \log_e (M \cdot \Delta T) + \varepsilon \tag{18}$$

3. Data and Empirical Results

As mentioned above, the objective of this research is to determine whether emissions of CO_2 to the atmosphere are mainly due to energy consumption or to imperfections in the production process of the countries, or both problems and in what proportion. To find out, equations (15) and (18) have been regressed throughout 20 countries during the period 1995-2015 with annual data. The 20 selected countries belong to consolidated economic blocs: Ireland, the United Kingdom, France, Germany, Spain and Portugal are part of the European Union. A non-EU European country is Iceland. BRICS countries include India, China, Russia, Brazil and South Africa; Other Asian countries listed are Indonesia, Japan, Saudi Arabia and Iran; Other American countries are the United States and Mexico; and finally in the sample there are other African countries such as Nigeria and Morocco. The application has been carried out with data from the *International Energy Agency* and equations (15) and (18) have been adapted to be able to perform the regressions according to the data. In order to have sufficient degrees of freedom, the prices of goods and factors, together with technology, have been included in the intercept parameter. In this way, the equation (15) that explains the energy consumption (e) has been simplified like this:

$$\log_e e = \lambda_0 + \lambda \log_e y + \lambda_1 \log_e PO + \varepsilon \tag{19}$$

where ε is a random disturbance and e is the annual energy consumption[2] measured in thousands of equivalent tons of oil (*ktoe*[3]). *PO* is the population of the country measured in millions of inhabitants, and y is the real output of the economy measured at power parity purchasing in constant billions of US \$ of the year 2010. Equation (18), which explains the emissions of CO_2, is to estimate considering that the following considerations will be made on the term $M \cdot \Delta T$: we take as ΔT the difference between the maximum and minimum average temperatures annual measures ºC with respect to an ideal temperature, which in our case has been taken as 19ºC. M is the mass of the bodies to be heated or cooled. In this research, M has been taken, by simplicity, as the total population (*PO*) of the country[4] measured in millions of inhabitants. And calling $PO \cdot \Delta T$ as *TPO*, the equation (18) that will finally be estimated will be:

$$\log_e Em = \gamma_0 + \gamma \log_e e + \gamma_1 \log_e (TPO) + \varepsilon \tag{20}$$

2. Total final consumption: residential, transportation, industrial, commercial and primary sector energy consumption, according to the International Energy Agency database.

3. 1 ktoe = 11630000 kWh.

4. Strictly speaking, each inhabitant should have been multiplied by their weight or by the average weight of the inhabitants but, assuming that on average the inhabitants of the countries have a similar weight, it has been preferred for simplicity to standardize the weight of each inhabitant to one.

where ε is a random disturbance, *e* is the annual energy consumption and *Em* is the annual emissions of CO_2 discharged by each economy.

Table 2. Estimates of energy consumption and CO_2 emissions by country.

	UK	France	Spain	Portugal	Russia	India	Iran	Indonesia	China	Morocco	Global
I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
Met.	**AR1**	**MCO**	**MCO**	**AR1**	**AR1**	**MCO**	**AR1**	**MCO**	**MCO**	**AR1**	**Panel Random Effects**
Ln **e**											
Const	19.27 (23.6)	15.35 (11.5)	10.02 (2.87)	2.89 (1.00)	-26.1 (-1.0)	16.6 (2.53)	-1.22 (-1.3)	8.32 (3.67)	53.9 (1.37)	4.50 (1.55)	5.25 (3.48)
Ln *y* [λ]	0.43 (3.64)	0.96 (3.56)	1.55 (1.71)	0.95 (1.88)	0.40 (1.69)	0.88 (3.09)	0.38 (2.23)	0.56 (2.18)	1.03 (2.48)	0.82 (2.06)	0.53 (3.06)
Ln PO	-2.62 (-6.7)	-2.61 (-3.5)	-2.60 (-1.1)	0.67 (0.76)	6.52 (1.31)	-1.57 (-1.2)	2.41 (4.9)	-0.12 (-0.18)	-6.86 (-1.1)	0.16 (0.11)	0.35 (2.10)
DW	3.04	2.51	1.81	1.29	2.44	3.27	2.94	2.06	2.98	2.01	
R^2-adj	0.81	0.73	0.70	0.61	0.48	0.98	0.99	0.76	0.94	0.97	0.56
Lagr. Mult.											21.5 pv: 0.004
Haus											7.77 pv: 0.1
XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV
Met.	MCO	MCO	AR1	MCO	AR1	MCO	MCO	AR1	AR1	MCO	Panel Between
Ln **Em**											
Const	-15.4 (-5.3)	-14.4 (-1.4)	-5.60 (-1.9)	-3.08 (-0.54)	1.73 (0.47)	-10.1 (-7.1)	-5.50 (-3.4)	-13.7 (-14.06)	-11.3 (-6.8)	-6.10 (-7.7)	-6.62 (-5.8)
Ln e [γ]	1.73 (8.04)	1.81 (2.03)	0.77 (2.67)	0.85 (1.93)	0.36 (1.51)	1.70 (10.2)	0.91 (2.64)	1.59 (8.23)	1.20 (23.0)	0.82 (5.52)	1.03 (6.40)
Ln TPO	0.14 (1.14)	-0.21 (-0.5)	0.36 (1.23)	-0.31 (-0.24)	0.09 (0.77)	-0.49 (-1.4)	0.11 (0.13)	0.08 (0.35)	0.31 (1.67)	0.36 (1.06)	0.71 (0.47)
DW	3.16	1.21	1.51	2.34	2.35	3.01	1.46	2.38	1.76	2.78	
R^2-adj	0.94	0.67	0.65	0.66	0.50	0.99	0.98	0.97	0.99	0.99	0.90

Source: Own elaboration. Note: t-ratios in brackets

Table 2 shows the results of the estimates of the relationship (19) - regressions I to XII - and of the relationship (20) - regressions XIII to XIV - for half of the countries in the sample, plus the global regression on the 20 countries with panel data (models XII and XIV). From these regressions we estimate the coefficients of $\log_e y$ and $\log_e e$, respectively λ and γ coefficients of equations (19) and (20). According to estimates, these coefficients are significant at 99% in general, except for regressions IV, V, VI and XVII where the significance of the estimates is somewhat lower. The regressions for the countries have been carried out by the method of ordinary least squares (OLSQ), correcting as far as possible the autocorrelation by assuming that residuals follow a first-order autoregressive process (AR1), although in some of the estimates autocorrelation still persists. All the regressions have a coefficient of determination R^2-adjusted high or acceptable. Table 2 does not include the regressions for the entire sample of countries, only for ten of them, but the rest of the coefficients λ and γ that are not listed in Table 2 are collected later in columns IV and V of the Table 4. Regression XII in Table 2 shows the panel data estimation for all the 20 countries of the sample during the period 1995-2015 of the logarithmic relation between energy consumption and real production (equation 19), being the best estimate the random effects model, since the p-value of the Lagrange multiplier test (Breuch and Pagan, 1980) is less than 0.05, which makes rejecting the estimate by OLSQ- plains, while the p-value test Hausman (1978) is greater than 0.05, which rejects the fixed effects model. As for the panel estimation of the logarithmic relation between CO_2 emissions and energy consumption (equation 20), the results indicate that the best panel estimate is the between groups model (XIV regression). The economic interpretation of the estimator λ is relevant, since: $\lambda = \frac{\partial \log_e e}{\partial \log_e y} = \frac{\Delta e}{\Delta y} \cdot \frac{y}{e}$, that is, they are energy-income elasticities, from which we can know what the energy consumption varies when the production of the country varies:

$$\frac{\Delta e}{\Delta y} = \lambda \cdot \frac{e}{y} \tag{21}$$

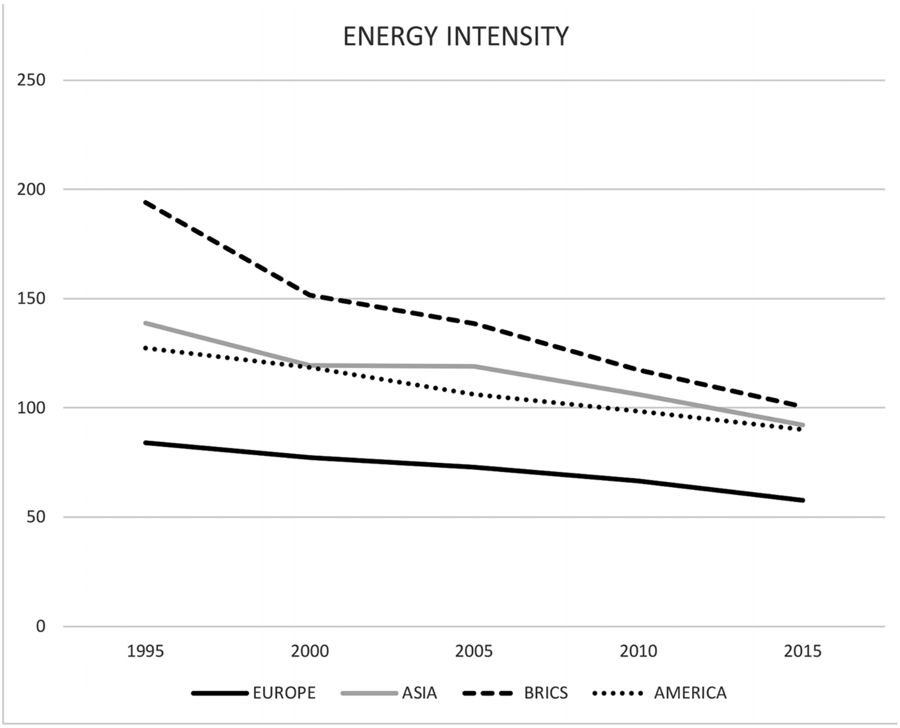
The term (*e/y*) is so-called energy intensity and it is an indicator of the efficiency of each country. The evolution of the energy intensity by blocks of countries in the sample from 1995 to 2015 can be seen in Figure 1. In the Figure 1 it can be seen that the lower energy intensity is given in the European countries and the largest in the BRICS countries. It can also be seen how the energy intensity decreases over time in the four blocks of countries probably due to the increased efficiency in energy consumption, due to the progressive replacement of fossil energy with renewable. From equation (20) it can be deduced that $\gamma = \frac{\partial \log_e (Em)}{\partial \log_e e} = \frac{\Delta (Em)}{\Delta e} \cdot \frac{e}{Em}$, where we can infer what emissions increase when energy consumption increases:

$$\frac{\Delta Em}{\Delta e} = \gamma \cdot \frac{Em}{e} \tag{22}$$

It is desired to know, to what extent, if the increase suffered by CO_2 emissions when increases energy consumption, is greater or less than the increase suffered by CO_2 emissions when GDP increases.

The product $\lambda \cdot \gamma = \left(\frac{\partial \log_e e}{\partial \log_e y} \right) \left(\frac{\partial \log_e Em}{\partial \log_e e} \right) = \frac{\Delta Em}{\Delta y} \cdot \frac{y}{Em}$, so that, what emissions increase when real income increases (real GDP) is:

$$\frac{\Delta Em}{\Delta y} = \lambda \cdot \gamma \cdot \frac{Em}{y} \tag{23}$$



Source: Own elaboration based on data from the International Energy Agency 2016

Figure 1. Evolution of the energy intensity by block of countries (1995- 2015)

In Table 3, the columns III and IV show the countries in the sample from lowest to highest energy intensity for 2015 data. As lower energy intensity generally corresponds to higher energy efficiency. Columns I and II of the same table show the countries sorted by amounts of CO_2 emitted by each *ktoe* of energy consumed, from lowest to highest emission. There seems to be some correlation between the two parts of the Table 3 and also between the massive utilization of fossil energies (column V), in the last countries of column III, and the greater proportion of the use of renewable, in the first countries of this column.

Table 3. CO_2 emissions, Energy Intensities and fossil energies (2015)

Emissions (Mt of CO_2) for each ktoe consumed (2015)		**Energy Intensity: Tn of CO_2 per 10000 US $ produced (2015)**		**Fossil energy consumption (% of total)**
I	**II**	**III**	**IV**	**V**
Nigeria	655	Nigeria	0.82	18.91
Iceland	718	Ireland	1.24	89.95
Brazil	1988	France	1.39	63.33
France	2266	Iceland	1.46	14.60
Indonesia	2734	Brazil	1.52	57.48
Portugal	2889	United Kingdom	1.57	86.34
Iran	3061	Spain	1.67	77.45

Emissions (Mt of CO_2) for each ktoe consumed (2015)		Energy Intensity: Tn of CO_2 per 10000 US $ produced (2015)		Fossil energy consumption (% of total)
I	II	III	IV	V
Spain	3099	Portugal	1.69	73.85
United Kingdom	3119	Indonesia	1.74	66.15
Russia	3210	Germany	2.09	81.60
U.S.A.	3263	Morocco	2.18	87.75
Germany	3315	Mexico	2.19	90.17
Ireland	3332	Japan	2.44	92.24
Morocco	3644	India	2.75	68.51
India	3668	U.S.A.	2.95	86.70
Saudi Arabia	3688	Saudi Arabia	3.41	99.99
Mexico	3689	Iran	4.31	98.94
Japan	3878	Russia	4.65	90.97
China	4650	China	5.00	87.50
South Africa	5835	South Africa	6.14	85.60

Source: Own elaboration based on data from the International Energy Agency 2016

From equations (22) and (23) we can see what emits more, if the process of production of goods and services (*y*) or the process of energy consumption (*e*), that is, how much is the difference: $\frac{\Delta Em}{\Delta y} - \frac{\Delta Em}{\Delta e}$. When this difference is positive, the increase in production emits more CO_2 than the increase in energy consumption; when the difference is negative, the increase in energy consumption emits more CO_2 than the increase in the production of goods and services. The results, for 2015, are shown in column VII of Table 4.

Table 4. Energy productivity and contribution to CO2 emissions (2015)

Countries	Average Energy Productivity (y/e) 2015. Billions US$ ctes (2010) / ktoe	Marginal Energy Productivity (Δy/Δe) 2015	λ · γ	γ	CO_2 Emissions Tn of CO_2 per capita (2015)	Contribution to CO_2 emissions $\frac{\Delta Em}{\Delta y} - \frac{\Delta Em}{\Delta e}$
I	II	III	IV	V	VI	VII
Ireland	0.026	0.096	0.26	0.96	7.29 > 6.19	0.028 < 0.165
UK	0.019	0.045	0.74	1.73	5.93	0.110
Spain	0.018	0.012	1.19	0.77	5.28	0.195
Portugal	0.017	0.017	0.80	0.85	4.53	0.132
Mexico	0.0168	121.6	0.0002	1.27	3.54	-0.004
Morocco	0.0167	0.020	0.67	0.82	1.54	0.142
France	0.0163	0.016	1.73	1.81	4.34	0.200
Japan	0.01586	-0.015	-0.47	0.47	9.10 > 6.19	-0.115 < 0.165
Germany	0.01583	-0.076	-0.57	2.78	8.72 > 6.19	-0.128 < 0.165

Countries	Average Energy Productivity (y/e) 2015. Billions US$ ctes (2010) / ktoe	Marginal Energy Productivity (Δy/Δe) 2015	λ · γ	γ	CO_2 Emissions Tn of CO_2 per capita (2015)	Contribution to CO_2 emissions $\frac{\Delta Em}{\Delta y} - \frac{\Delta Em}{\Delta e}$
I	II	III	IV	V	VI	VII
Indonesia	0.0157	0.028	0.87	1.59	1.72	0.145
India	0.014	0.014	1.49	1.70	1.48	0.401
Brazil	0.012	5.0	0.0028	1.14	2.15	-0.001
U.S.	0.011	0.011	1.02	1.02	15.04 > 6.19	0.297 > 0.165
Saudi Arabia	0.010	0.009	1.20	1.03	16.36 > 6.19	0.402 > 0.165
South Africa	0.0095	-0.00008	2.21	-0.02	7.25 > 6.19	1.350 > 0.165
China	0.0093	0.009	1.23	1.20	6.54 > 6.19	0.607 > 0.165
Nigeria	0.0079	0.074	0.28	2.83	0.40	0.021
Iran	0.0071	0.018	0.34	0.91	6.79 > 6.19	0.143 < 0.165
Russia	0.0070	0.016	0.15	0.36	9.97 > 6.19	0.067 < 0.165
Iceland	0.005	0.005	0.03	0.03	5.85	0.003
	Efficiency of e: (y/e) ≥ (Δy/Δe) > 0		Averages:		6.19	0.165 (panel)

Shaded cells exceed threshold. Source: own elaboration.

From the estimates for the 20 countries in the sample, of which for 10 of them are shown in Table 2, the corresponding estimators of λ and γ for each country are obtained, which are collected in columns IV and V from Table 4. Using the expressions (22) and (23) with 2015 data we obtain the results of column VII. Considering the coefficients λ and γ obtained in estimates XII and XIV with panel data from Table 2, we obtain that the average difference $\frac{\Delta Em}{\Delta y} - \frac{\Delta Em}{\Delta e}$ is 0.165 which shows that generally: $\frac{\Delta Em}{\Delta y} > \frac{\Delta Em}{\Delta e}$. That is, as seen in column VII, what emissions increase when real GDP increases in general is more than emissions increase when energy consumption increases. This implies that in the economies where this happens there are emitting production processes, regardless of energy consumption, which suggests that an improvement in these production processes could cause a decrease in emissions to the level of emissions associated with energy consumption. There are only four countries in the sample, Mexico, Brazil, Japan and Germany, where the increased emissions of CO_2 related to energy consumption are greater than those associated with economic activity, which means that the marginal productivity of energy is greater than one[5] (Brazil and Mexico) or that emissions decrease when production increases due to the Kuznets effect[6] (Germany and Japan). Countries whose difference is greater than the average provided by the estimation of panel data (0.165) should improve their production

[5].If (ΔEm/Δe) > (ΔEm/Δy) then (1/Δe) > (1/Δy), hence: (Δy/Δe) > 1. See Table 4, column III.

[6] The Kuznets effect indicates that from a high level of per capita income, emissions decrease when production increases. This is specified in the so-called Kuznets curve.

processes. These countries are shaded in column VII of Table 4. In column VI are shaded countries whose CO_2 emissions per capita are above the average of the sample (6.19 Tn. of CO_2 per capita), from the which, Ireland, Japan, Germany, Iran and Russia should reduce energy consumption while the United States, Saudi Arabia, South Africa and China should incorporate less polluting production processes, comparing the results of columns VI and VII. Columns II and III of Table 4 are related to the efficiency in the use of the production factors, including energy, in relation to 2015. Assuming that the production functions of companies in the economy are homogeneous of grade one, as corresponds to the production functions (4), whose arguments are energy as a production factor (e_0) plus a series of production factors (R), some of which we assume fixed during 2015, then if we consider energy as a variable factor all production factors are used efficiently by the company when the output level is between the technical optimum[7] and the technical maximum of the productivity function where energy acts as a variable factor. In that section, the average energy productivity function is above the marginal energy productivity function. Adding the productivity functions of the companies in the economy, it can be deduced that the efficient use of all production factors, including energy, is obtained when, on the aggregate productivity function, the average energy productivity (Table 4, column II) is equal to or greater than the marginal productivity of energy (Table 4, column III), this being non-negative: $(y/e) \geq (\Delta y/\Delta e) \geq 0$. Therefore, the shaded results of columns II and III belong to countries that probably did not use energy efficiently as a production factor in 2015. According to the results collected in Table 4, it can be ensured, under the assumption of aggregate production functions of grade one, that of the 20 countries in the sample only Spain, Portugal, France, India, the United States, Saudi Arabia, China and Iceland used production factors efficiently in 2015 since, in relation to energy, their average productivity is higher than marginal.

4. Conclusions

This research has proposed a microeconomic model that explains the supply and demand of energy, energy consumption and emissions produced by energy consumption and economic activity in the economic equilibrium. The objective of this model is to find from the economic theory causal relationships between energy consumption and economic activity and between emissions and energy consumption. The emissions covered by this research are exclusively those of carbon dioxide, which was selected as the most abundant greenhouse gas and supposedly the most responsible for global warming and therefore of the possible long-term environmental degradation. The most important purpose of this research is to analyse what part of the total carbon dioxide emissions is associated with energy consumption and which part is associated with economic activity, regardless of energy consumption. The model has been applied econometrically on a sample of 20 countries in the period 1995-2015 with data from the International Energy Agency. Six of

[7] The technical optimum is the maximum of the average productivity function. The technical maximum is the maximum of the productivity function.

these countries belong to the European Union and the rest of the countries in the sample belong to Europe, Asia, America and Africa. The total population of these countries accounts for 61% of the world's population. The results of the application indicate that, in general, the process of carrying out economic activity, measured by gross domestic product in real terms, emits more carbon dioxide than the process of energy consumption. This seems to indicate the existence of certain imperfections in the productive processes of most of the countries in the sample. The results also indicate that Ireland, Japan, Germany, Iran and Russia should be able to reduce their energy consumption while the United States, Saudi Arabia, South Africa and China should incorporate less polluting production processes. The carbon dioxide emissions per capita of these nine countries are above the average of the sample. In relation to the productivity of energy in the production processes, only Spain, Portugal, France, India, the United States, Saudi Arabia, China and Iceland used energy efficiently in 2015, while only Portugal and Iceland, in addition to appearing efficient, did not exceed the average energy emissions per capita and the emissions from their production processes did not exceed their energy consumption emissions. Regarding the relationship between energy efficiency and the inverse of energy intensity, it can be ensured that during the period 1995-2015 together the European countries in the sample are those that show less energy intensity, and therefore probably more energy efficiency, followed of the American countries; then there are the Asian countries and finally the BRICS. The analysis and the results contained in this research could be useful for the correction of trends in some environmental degradation processes.

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