Article

Carbon dioxide emissions, energy consumption and economic growth: A comparative empirical study of selected developed and developing countries. The role of exergy.

Raúl Arango-Miranda[1]*, Robert Hausler[1, †], Rabindranarth Romero-Lopez[2, †], Mathias Glaus[1, †], Sara P. Ibarra-Zavaleta[3, †].

[1] Affiliation 1; Station Expérimentale des Procédés Pilotes en Environnement, École de Technologie Supérieure, Université du Québec, 1100, rue Notre-Dame Ouest Local A-1500, Montréal, QC.; H3C 1K3, Canada ; e-Mails: robert.hausler@etsmtl.ca (R.H.) ; mathias.glaus@etsmtl.ca (M.G.);
[2] Affiliation 2; Unidad de Investigación Especializada en Hidroinformática y Tecnología Ambiental, Facultad de Ingeniería Civil, Universidad Veracruzana, Lomas del Estadio s/n, Zona Universitaria,
[3] Affiliation 3; Instituto de Biotecnología y Ecología Aplicada, Universidad Veracruzana. Av. de las Culturas Núm.101, col. Emiliano Zapata. Xalapa 91090., Veracruz, México. e-Mail: rabromero@uv.mx. (R.R.L.) Xalapa, 91000 Veracruz, México; e-Mail: saibarra@uv.mx (S.P.I.Z.).
† These authors contributed equally to this work.

* Correspondence: raul.arango-miranda.1@ens.etsmtl.ca; Tel.: +1-514-396-8800 (ext. 7686)

Abstract: Diverse factors may have an impact in Carbon dioxide (CO_2) emissions; thus, three main contributors, energy consumption, exergy indicator and gross domestic product (GDP) are examined in this work. This study explores the relationship between economic growth and energy consumption by means of the hypothesis postulated for the Environmental Kuznets Curve (EKC). Panel data for 10 countries, from 1971 to 2014 have been studied. Despite all this wide gamma of research, the role of an exergy variable has not been tested to find the EKC; then exergy analysis is proposed. Exergy analyses were developed to propose an exergetic indicator as a control variable and a comparative empirical study is developed to study a multivariable framework with the aim to detect correlations between them. High correlation between CO_2, GDP, energy consumption, energy intensity and trade openness are observed, conversely not statistically significant values for trade openness and energy intensity. The results do not support the EKC hypothesis, however exergy intensity opens the door for future research once it proves to be a useful control variable. Exergy provides opportunities to analyze and implement energy and environmental policies in these countries, with the possibility to link exergy efficiencies and the use of renewables.

Keywords: climate change, energy policy, exergy analysis, exergetic intensity, greenhouse gases

1. Introduction

Growing consumption trends of modern societies increase the pressure on manufacturing to satisfy such demands [1,2]. The growing request of fossil fuels as the main source of energy is triggering environmental degradation, that is without a doubt, one of the

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most pressing global atmospheric challenges experienced by developed and developing countries in 21st century in the form of greenhouse gases (GHG), global warming (GW) and climate change (CC) [3]. Once natural resources are not infinite as a source for economic activities, then uncontrolled economic development entails actual risks for the global environment [4] The rates of worldwide economic development indicate that increased energy demand at all sectoral levels may represent a threat to the achievement of global reduction objectives for 2050 [5]. Rapid global economic growth between 2005 and 2013, influenced global GHG emissions increased by 18.3% reaching more than 35 billion tons by 2013 [6]. Virtually 90% of the CO_2 emissions has a fossil-fuel source and therefore are determined by the energy demand or the level of energy-intensive activity. After several periods of economic growth without considering environmental damage, academics, practitioners and policy makers, mostly representing developed countries perceiving the risk related with industrialization and deforestation processes among other anthropogenic activities and react, a heated debate between the importance of economy without compromising our natural resources then started [7]. How to tackle the problem of climate change is a great challenge. Sustainability offers an approach to combat GHG and CC. In late 80's efforts from governmental and non-governmental organizations mainly in industrialized countries, were the first steps in the route of sustainable development [8]. In 1992, Munasinghe introduced three major poles to the definition of sustainability: economic, social, and environmental [9]. However, due its complexity, only a limited number of studies had tested the three axes of sustainability and the interrelationship of its variables in the same framework [10,11]. The idea of causal relationship between energy consumption and economic growth was first introduced in the influential paper of Kraft [12], once the causality relationship between them has important policy implications. The debate about what becomes first, economics or environment, no matter at local or global level was settled and the functional relationships between economic growth and environmental degradation were masterfully expressed by the environmental Kuznets curve (EKC), an inverted U-shape curve [13].

A literature review on the EKC starts with the seminal research from Grossman and Krueger [14] in their attempt to explore the path of sustainable development theory to describe the environmental degradation-economic growth relationship. Then, many scholars have been developed empirical studies of the EKC hypothesis in single or multiple countries, even regions, applying different econometric methodologies [13,15-18]. Other researches have focused their attention for different environmental dimensions (i.e., CO_2, SO_2, particulate matter, waste water, protected areas) or time contexts. Mixed findings still reported. Scholars found that the relationship presented multiple shaped EKC such as U, inverted-U, N, etc. Additionally, there were also evidences that the testing results depended on the specific econometric models [19]. The results of [20,21] deliver two comprehensive and detailed reviews of the relevant past empirical studies.

Despite all this wide gamma of research, the role of an exergy variable has not been tested to find the EKC, then exergy analysis is proposed with the goal to enrich sustainability and exergy as elements of environmental studies once exergy links thermodynamic principles and system under study with the environment [22]. Loiseau [23] compared environmental assessment tools and methods and quotes that among others, exergy analysis are part of the "energy family of methodologies" applying thermodynamics to sustainability able to study cities or industries [24-26].

Exergy has been evolved by years, as showed by Sciubba [27] in his essential brief commented history on exergy in 2007. From the theoretical concepts from Carnot and Gibbs, the research by Reistad [28], as a notion to resource accounting approaches by Wall [29,30], the

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efficiency improvements in industrial equipment or power cycles and its components [31], complex systems analysis [32], sectors and extended exergy analysis in societies or countries [33-36].

To the more recently link to the environment studied by Dincer & Rosen [37] in their comprehensive Exergy: energy, environment and sustainable development. The conducted studies on exergy analysis of the industrial sector are classified into three main subsections: of exergy analysis of the industrial sector of different countries; exergy analysis of different industries and exergy analysis of industrial devices [38]. Romero in his review of the state of the art indicators for sustainability, claims the suitability of using exergy as an indicator for energy sustainability studies, also exergy can serve as a link to fill gaps in the generation of economic and environmental indicators [39]. Gong established that "to improve energy and material conversion processes, the exergy concept should be applied. Therefore, exergy analysis is a tool to create and maintain a sustainable or rather a vital society" [40]. Researchers also claim that exergy brings opportunities in decision-making to increase energy efficiency and energy conservation [41]. In parallel, exergy analysis was also studied regarding the environment and sustainability [42,43].

It may be reported that to the best of authors' knowledge, there is no work on the review of exergy analysis and the CO_2 emissions involving the EKC theory regarding the industrial sector. This research is expected to contribute to fill this gap. The aim of this work is to examine correlations between economic growth, energy consumption and CO_2 emissions. Additionally, an exergy variable is suggested as a control variable, to test its influence for the EKC on the selected countries.

2. Data sources

In this study, yearly data of GDP (in constant 2005 US dollars) and energy consumption (million tons oil equivalent) is revised for a set of 10 countries (a mix of 5 developed and 5 developing countries, includes: Brazil, Canada, China, Italy, Mexico, Norway, South Africa, Turkey, UK and USA) to investigate the relationship between CO_2 emissions, energy consumption and economic growth. Data from the IEA database [44] and the report "CO_2 Emissions from Fuel Combustion, IEA 2017" [45], was achieved and analyzed chronologically from 1971 to 2014. The temporal dimension was restricted due to data availability.

2.1. Countries selection criteria.

2.1.1. Socioeconomic criteria.

According to the World Bank to pay attention about the economical–social–environmental challenges of the future, the upper-middle income countries, whose industrialization process increased strongly, need to be assessed deeply [46]. The idea to contrast two sets of countries is based on the socio economic and environmental changes through last four decades. The selected sample consists of a mixture of developed and developing countries. Between them, there are similarities: economic growth, geographical, population and the production of manufacturing goods to exports. Another interesting factor is that usually, some developing countries evolved from an economic base of agriculture towards manufacturing [47]. Agreeing their economic and social development, a key factor in terms of data availability was that most of them share an association with two international institutions: The Organization for Development and Economic Cooperation (OECD); and the

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International Energy Agency (IEA). Additionally, 9 out of 10 countries are part of the G20 countries.

2.1.2. Environmental criteria.

Four of them were listed as the world's major GHG emitters [48,49]. The Climate Change Performance Index (CCPI) 2014 report [50] assesses and compare the climate protection performance of 58 countries, that are, jointly, responsible for more than 90 percent of global energy-related CO_2 emissions , the results for the selected countries were the following: Canada and Turkey received a "very poor rank", the 58th and 54th; China, United States, South Africa, Brazil received a "poor" rank, the 46th, 43rd, 39th and 36th; Norway, Mexico and Italy received a "moderate" rank, the 24th, 20th and 18th; while the United Kingdom received a "good" rank, the 5th.

3. Methods

A theoretical-descriptive approach was applied in this study with a comparative empirical test based on a statistical generalized linear model (GLM); this section involves three main steps.

3.1 Exergy analyses to compute exergy consumption and exergy intensity

3.2 A descriptive statistical analysis to detect linear correlations (R) between the variables

3.3 An econometric analysis, including an ordinary least squares analysis (OLS).

A data set of 440 observations is considered in this research. The carbon dioxide emissions per capita (CO_2/ Capita) measured in metric tons per person was considered as the environmental decline variable. The growth variable is estimated by the per capita GDP, measured in United States dollars at 2005 prices. Since exergy can serve as a link to fill gaps in the generation of economic and environmental indicators, to serve as control variables, two exergetic variables were computed: exergetic consumption and exergetic intensity. In a global economy, the selected ten countries have been increasing their economic or commercial trade; accordingly, the specific impact of trade was analyzed through the trade openness variable.

3.1 Exergy analysis theoretical Background.

An energy and exergy analysis of the selected countries, from 1971 to 2014 is developed; in parallel detect energy intensities to compute exergy ones, with the goal to propose those exergy indicators as an innovative control variable in search of the EKC hypothesis. Scholars have been studying exergy analysis on a large-scale base, such as a country, its society or their own economic sectors [35,51]. In 1997, Dincer [52] assessed the energy consumption of the industrial sector in Canada to increase its efficiency based on exergetic analyses. To formulate an exergy balance of a non-constant flow system (like mass or energy balances), a common scenario requires establishing a control volume as well as a reference environment; it is usually established through a temperature T_0 = 25 °C and a P_0=1 atm. [44]. The flow of exergy entering in a system can be best described as the sum of the totality of their exergies (physical, chemical, potential, kinetic and nuclear exergies) [53]:

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$$Exergy_{sys} = Exergy^{Ph} + Exergy^{Kn} + Exergy^{Pt} + Exergy^{Ch} + \cdots (1)$$

3.1.1. Exergy of a flowing stream of matter

In principle, the exergy of matter can be determined by letting it be brought to the dead state by means of reversible processes. The basic formulas used in exergy analysis modeling are given below. The total exergy can be divided into two-parts: physical exergy (thermo-mechanical exergy) and chemical exergy. The specific total exergy of the flowing stream of matter can be expressed as:

$$Exergy = Exergy^{Ph} + Exergy^{Ch} \quad (2)$$

The first part of Eq. (1) represents the physical exergy, while the second represents the chemical exergy. The physical exergy is the maximum work obtainable by taking the matter through reversible processes from its initial state (temperature T and pressure P) to the state determined by the environment conditions (temperature T_o and pressure P_o). The chemical exergy is the maximum work that can be obtained by taking a substance having the parameters (To, Po, mjo) to the state determined by the dead state (T_o, P_o, mjo_o).

3.1.2. Exergy of fuels

One of the most common mass flows is hydrocarbon fuels at near-environment condition, for which the first term in the Eq. (2) is zero, and the specific exergy reduces to chemical exergy, which can be written as ([36,54-56]:

$$Exergy_f = \gamma_f HHV_f \quad (3)$$

Were γf denotes the fuel exergy grade function, defined as the ratio of fuel chemical exergy to the fuel higher heating value (*HHVf*). With the use of the quality factor, conversions of energy data to exergy values of energy carriers are given by a proportionality constant, also called exergy factor [56,57]. Due to the complexity of the chemical composition of these fuels, the following simple approach, which is since the higher heating value (*HHVf*) is close to the chemical exergy, was applied.

In this paper, the average exergy grade functions for different energy carriers are considered, extracted of several sources [35,36,41,58,59]. There are also other fuels that are obtained as by products from the different processes in the manufacturing sector.

3.2. Linear correlations coefficients(R) detection

First, in a set of 44 observations, the annual averages are calculated by country for each variable, proceeding to estimate the correlations based on the variable $pcCO_2$. Secondly, the complete data were analyzed, by year and by country (440 observations) in function of $pcCO_2$.

Subsequently, a descriptive statistical analysis is developed, based on empirical tests, with the aim of detecting the strength and direction of a linear relationship and proportionality between two study variables, by means of linear correlation (*R*) among the proposed variables. Table 1 describes the total set of variables applied in this study in search of the existence of the EKC.

Table 1. Multivariable framework summary.

No.	Abbreviation	Description	Units
1	$pcCO_2$	CO_2 Emissions	Mt of CO_2/year/Capita
2	$ffCO_2$	CO_2 Emissions from Fossil Fuels	Mton/year
3	pcTPES	Total Primary Energy Supply	toe/Capita
4	pcGDP	GDP per capita; USD 2005	Billion USD, 2005
5	Tr opn	Trade openness	%
6	ffEn con	Energy consumption from Fossil Fuels	PJ/year
7	En int	Energy Intensity	TPES/GDP
8	C int	Carbon intensity	Mton/year
9	Ex con	Exergy Consumption	PJ/year
10	Ex int	Exergy Intensity	TPES/GDP

Source: [60].

Prior to the econometric analysis, the data sets were are analyzed and the moderate correlation coefficients (-0.5 <*R*) and (*R*> 0.5) were identified [61].

3.3. Econometric analysis

To test the existence of the EKC hypothesis, a model using panel data estimation techniques was developed. The approach on this research adjusts to the simplest specification of EKC hypothesis, a linear equation, with the aim to test the viability of exergy indicators and its possible effects. Additionally, to test the significance of the model, an ordinary least squares analysis (OLS) was developed

The EKC literature refers there are four main hypotheses to explain the direction of the relationship between energy consumption and economic growth: growth, conservation, feedback and neutrality[16,62]. The growth hypothesis validates a unidirectional causality flowing from energy consumption to economic growth. The conservation hypothesis argues that there is a one-way causality flowing from economic growth to energy consumption. The feedback hypothesis validates that energy consumption and economic growth cause each other. The neutrality hypothesis contents that there is no causality flowing between economic growth and energy consumption. According to Grossman and Krueger, Panayotou, De Bruyn, Dinda, among others, the generalized functional form of the equation to test the EKC is presented as follow [14,15,63,64]:

$$ED = f\,(EG_{it}, EnC_{it}, ExC_{it}, TrO_{it}, \mu_{it})$$

Were:

ED=Environmental degradation = $ffCO_2$

EG=Economic Growth= pcGDP

EnC=Energy consumption= En con

ExC=Exergy consumption= Ex con

TrO=Trade openness= Tr opn

$\mu_{i,t}$ = error term

The Environmental Kuznets Curve for lineal model can be written as follows:

$$CO_{2t} = \beta_{0it} + \beta_{1it} * GDP + \mu_{it} \quad (4)$$

In this research, an extended form of the model, used to investigate the influence of an exergetic variable on the environment, can be described as follows:

$$ffCO_2 = \beta_1 * GDP + \beta_2 * ffEn\,con + \beta_3 * Ex\,con + \beta_4 * Ex\,int + \beta_5 * pcTPES + \beta_6 * Tr\,opn \quad (5)$$

4. Results and discussion.

4.1. Energy and exergy analysis

This section discusses the measurement concept of exergy indicators, presents the new data set, and clarifies the relationship between energy losses and exergy indicators. Energy and exergy analysis were developed to calculate exergetic variables from a selected panel of ten countries, from 1971 to 2014.

Starting with the compute of the energy and exergy inputs by selected countries, Table 2 shows the results of exergy input consumption (PJ) as an example for the year 2014; energy carriers were considered, with fossil fuels largely highlighting as the main source for most of the countries and along the 44 years span.

Table 2. Exergy consumption rates of countries, year 2014.

	Energy carriers (ktoe)					
Country	**Hydrocarbons**	**Renewables**	**Nuclear**	**Electricity**	**Heat**	**Total exergy consumptions (PJ)**
Mexico	173,077	16,989	2,446	45	0	8,060
Canada	208,128	51,229	27,119	3,923	0	12,597
USA	1,878,318	167,673	209,961	4,576	0	99,790
Italy	116,650	29,163	0	3,760	0	6,829
Norway	15,508	13,489	0	1,340	59	1,771
U. Kingdom	151,000	14,433	16,115	1,765	0	7,974
Turkey	112,122	12,390	0	452	0	5,213
China	2,819,883	259,014	33,504	202	0	131,083
S. Africa	132,893	18,187	3,487	229	0	6,471
Brazil	183,308	129,313	3,888	2,905	44	13,375

Table 2 depicts interesting information; first the use of fossil fuels still has a strong tendency to increase along the 44 years observed in the 10 countries; highlights that hydrocarbons are the main energy carrier with rates from 47% to 90%, despite remarkable consumption rates of natural gas near 30%. Renewable fuels are employed with higher rates than 10% in six of ten countries, highlighting Norway with a highest 48%, followed by Brazil with 39%. According to the IEA, China, USA, Canada, UK, Brazil, Turkey, Italy and Mexico are listed among the worldwide major producers of iron, steel and cement [65]. The most important topic in exergy analysis is the second law efficiency. Due to a continuous increase in the energy price in the last forty years, engineers tend to utilize thermal systems or

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components that have maximum second law efficiencies, in industrial processes or devices. In this way, they can be confident is the best way to use the energy source thus, minimizing the expenditures.

In parallel, energy security is an essential ingredient to development. Therefore, increasing energy consumption may be one of the fundamental aspirations of developing regions such as Latin American, Asian and African countries [61,66]. Paired with energy increasing to satisfy societal demands, another key factor to boost energy security is minimizing energy lost or degradations in the form of inefficiencies. Hereafter, it is important to create datasets of exergy indicators to improve energy efficiencies, consequently to strong energy security.

Degradation of energy matters because it might be a consequence of process inefficiency or environmental impact producing materials, i.e. GHG's [40,41,67]. According with Hepbasli [68], exergy is concerned with the quality of energy to cause change, degradation of energy during a process, entropy generation and the lost opportunities to do work. Then exergy is a fitted tool to improve efficiencies in manufacturing. Higher amounts of degradation of energy inside the economic and environmental development performance of countries might cause larger environmental impacts affecting societies at local, regional or global levels [22].

4. 2. Linear correlations, empirical evidence

Many factors may have an impact in CO_2 emissions; in this study were examined four major contributors: energy consumption, exergy consumption, exergy intensity and GDP. Prior to the econometric analysis, the prearrangement of the database was based on two criteria: by year, by country and vice versa. In addition, the averages of the values per year for each variable were computed. Last, an analysis of the data applying the linear regression method to obtain the determination coefficients was applied. Table 3 shows the results of the correlation factors (R) between the different variables. As a result, $ffCO_2$ ($R \geq 0.95$) emissions correlations get bigger coefficients compared to those of $pcCO_2$ emissions ($R \geq 0.7$) in terms of the control variables.

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Table 3. Correlation coefficients matrix

	pcGDP (USD 2005)	$pcCO_2$ ($MtonCO_2$)	$ffCO_2$	ffEn cons (PJ)	En int (TPES/GDP)	Ex int (TPES/GDP)	pcTPES (TPES/GDP)	Tr opn (%)
pcGDP	1							
$pcCO_2$	0.654	1						
$ffCO_2$	0.938	0.633	1					
ffEx con	0.956	0.624	0.998	1.000	1			
Ex int	-0.988	-0.537	-0.919	-0.940	-0.940	1		
pcTPES	0.958	0.725	0.845	0.871	0.871	-0.927	1	
Tr opn	0.949	0.624	0.989	0.990	0.990	-0.934	0.861	1

After the first test with a set of 44 observations per variable, yearly averages per country for each was computed, proceeding to estimate the correlations based on the $pcCO_2$ as environmental deterioration; as a result, only three of them presented values of $R \geq 0.95$ (pcTPES, ffEx cons, Tr opn). It is remarkable that Ex int shows negative but high values of $R \geq 0.90$, explaining a linear but inverse or decreasing curve.

In economics, energy intensity is viewed as an indicator of the energy efficiency of an economy. It is calculated as the ratio between the energy consumption (En cons) and the gross domestic product (GDP) of a country, meaning the units of energy needed to produce a unit of economic growth [69]. The dataset of the panel shows that energy intensity countries with high values are the 5 developed ones; contrarily the 5 developing countries shows lower values, except by China with the higher of all of them but with a drastically decreasing trend. A deeper analysis in the datasets reveals that both energy and exergy intensities increased for developed countries plus China and regrettably decrease in developing countries, pointing out opportunities to increase future efficiencies, and exergy efficiency is a fitted tool regarding the industrial sector [36,55,70].

In fact, Energy efficiency is one of the main variables that induce a reduction in fossil-based energy consumption. In a study conducted by the International Energy Agency [71] shows that without the improvements made on energy efficiency during the period from 1973 to 2005 at global scale, the use of energy would have been 58% higher than the level recorded in 2005, highlighting the relevance of energy efficiency to reduce the energy request. However, since 1990, the energy efficiency rate has stagnated due to the lower economic interest affected by the relatively low price of fuels inducing an increase in the demand for oil [72,73]. Considering the energy efficiency as a control variable (reciprocal of energy intensity), the results showed that his trend could be negative but statistically significant (R=0.95).

4.3. Econometric analysis of empirical results.

It is important to understand the relation between renewable and non-renewable energy consumption, CO_2 emissions and economic growth in terms of revealing the dependence of the economy on energy and designing the energy policies [74]. Table 4 shows results of the

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variables used in the analyses of the EKC; it is observed that there is a large dispersion between cross-section units (countries), mainly in the levels of per capita income.

Table 4. Summary of empiric results of the multivariable framework

	Variables						
	pcGDP (USD 2005)	$pcCO_2$ (MtonCO2/Cap)	ffEn cons (PJ)	ffEx con (PJ)	Ex int (TPES/GDP)	pcTPES (toe/Cap)	Tr opn (%)
Media	23,309.5	7.5	17,814.3	21,199.1	117.8	3.4	64.7
Median	14,843.8	6.6	6,748.0	8,030.1	117.7	2.6	48.6
Stdr Dev	21,027.3	5.7	28,038.4	33,365.7	28.0	2.5	70.5
Max	91,597.2	22.1	128,356.8	152,744.6	230.5	8.5	442.6
Min	262.9	0.9	557.9	664.0	44.3	0.5	9.1

The linear correlation result shows a positive trend between $ffCO_2$ vs pcGDP, $ffCO_2$ vs Ex con and $ffCO_2$ vs Tr opn; as well as an inverted correlation of $ffCO_2$ vs Ex int. This relation depicts the existence of the EKC for the panel, with a feedback hypothesis. Afterwards, regarding the test of the hypothesis cited by Apergis et al [75,76], in the present research work was detected that the pcGDP – exergy consumption relation confirms the growth hypothesis, similar to those results from Lee [77] by developing countries. These findings are on line with Magazzino et al [78,79] once energy consumption tends to be more responsive to economic growth in less developed than in advanced countries; however it is important to state that according to them, the relationship between energy and economic growth activity could be affected by a variety of other factors. In addition to this, an ordinary least squares analysis (OLS) was developed to test the significance of the model; the results are showed in Table 5.

Table 5 Regression of $ffCO_2$ emissions and pcGDP

Variable	Coefficient
Correlation coefficient R^2-	0.98260592
Determination coefficient R^2-	0.96551439
Adjusted R^2-	0.95992213
Standard error	0.0637957
Observations	44
Countries	10

The independent variables pcGDP, Ex con, Ex int, pcTPES and Tr opn explain 96.55% of the variation of $ffCO_2$. Besides, an analysis to test the global significance of the proposed model was developed, confirming its own validity. The overall effects of the model are significant since the null hypothesis is rejected due a low p-value ≤ 0.001. Table 6 shows the long run tests results.

 doi:10.20944/preprints201809.0085.v1

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Table 6. Regression of ffCO2 emissions and pcGDP

	Coefficient	Stdr. Error	t-Statistic	Probability	Inferior 95%	Superior 95%
Interception	-7.843	0.787	-9.968	0.000	-9.440	-6.250
pcGDP	0.000	0.000	3.168	0.003	0.000	0.000
Ex con	0.000	0.000	-1.688	0.100	0.000	0.000
Ex int	0.037	0.010	3.813	0.001	0.020	0.060
pcTPES	0.961	0.257	3.735	0.001	0.440	1.480
Tr opn	0.005	0.005	1.008	0.320	-0.010	0.020

Thus, it was observed that the forecaster variables pcGDP, Ex int and pcTPES are statistically significant because their p-values are low (<0.05). However, the p-value for Tr opn (0.320) and Ex int (0.001) is greater than the common alpha level of 0.050, and an indication of non-statistically significant variables.

The growth of ffCO_2 emissions and pcGDP in the first part of the curve is validated, since the increase in economic growth goes simultaneously with the degradation of the environment. Once it is observed that the sign of the quadratic term is positive, this implies that in a second stage, when the pcGDP remains increasing, it also grows the carbon dioxide emissions, non-validating the second part of the environmental curve. This result could be expected due the comparison of the mixed sample of developed and developing economies. Usually in developed countries, growth or feedback hypothesis is reported, and the curve changes its slope to negative for the reduction of emissions, considering that the country reached a level of economic stability where the degradation of the environment tends to decrease, making intensive use of green technologies [80]. On the contrary, developing economies, particularly China, the CO_2 curve trend tend to remain increasing along the chosen timeline, as a consequence a growth hypothesis is suggested [81,82].

These results are in accordance with previous authors, due the influence of several external factors producing ups and downs trends in the curves [16,83]. Also interesting is the correlation between pcCO_2 and exergy consumption, it shows a negative trend, describing possibly an inverted *N* shape. This result opens the door to future research with the use of exergetic indicators, with the possibility to link exergy efficiencies and the use of renewables in countries [40,84]. Hence, detection of degradation of energy through exergy indicators is becoming a prominent topic in energy and environmental literature [39,42,43]. Energy analysis has been widely used by the academics and government agencies. Among others, Hammond [70,85] has argued that it is important for practitioners and policy makers to employ exergy analysis as a complement to the existing methods to develop datasets, official reports and environmental and energetic strategies. It is necessary to increase the contribution of exergy to the environment. Although this is a small sample of panel model of countries, the results of our study extend the debate of previous research in the use of the timeline, set of chosen countries, control variables or other external factors i.e. technology, socio political issues.

5. Conclusions

The results confirm the existence of strong correlations between the multivariable frameworks, excepted by the carbon intensity. Additionally, a long-term feedback hypothesis among CO_2 emissions from fossil fuels, GDP per capita and exergy consumption was

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confirmed; highlights and inverted, but a strong correlation was between CO_2 emissions from fossil fuels and exergy intensity are detected, offering and insight for future efficiency improvements.

Results from developed countries have been increased their effectiveness to manage environmental problems, especially, CO_2 emissions. The use of renewables or natural gas seems to be the right way to combat global warming and reduce CO_2 emissions, enabling the reduction of energy dependency and promoting energy security. The whole period of 44 years, neutrality hypothesis was confirmed by OECD countries such as Canada, Mexico, Norway, Turkey, the UK and the USA. It means that there is no causality amid economic growth and energy consumption.

Comparing the long run correlations between CO_2 emissions from fossil fuels, GDP per capita and exergy consumption, a positive correlation trend was observed, denotes that by improving energy efficiency policies and regulatory instruments, the efficiency of the system under study tends to improve, accordingly decrease emissions and environmental impacts. The EKC was not confirmed, therefore, the efforts to reduce the GHGs emissions like Kyoto Protocol proves insufficient, as permanent patterns for reducing CO_2 emission is not observed for the afore mentioned countries.

The results highlight that restrictions on the use of energy can negatively affect economic growth, while increases in energy can contribute to economic growth. Consequently, it is concluded that energy is a limiting factor for economic growth and, therefore, the impacts on energy supply will have a negative impact on economic growth.

Although our work differs from previous findings regarding the validity of the EKC by the selected countries, however, its importance is based on the proposed exergetic variables since it foresees the possibility of its inclusion in future research. Accordingly, an initial test of an exergetic control variable is on line with a simplistic model. Definitively, future research should be focus on expanding the model and digging into its complexity, thus the inclusion of exergetic variables. Also, could be focused to develop a deeper analysis regarding the correlations of environmental and economic indicators, to increase the contribution of exergy to the environment.

Author Contributions: Conceptualization and methodology design: Raul Arango, Robert Hausler and Rabindranarth Romero. Experiments: Raul Arango and Sara Ibarra. Data analysis and validation: Raul Arango, Rabindranarth Romero and Sara Ibarra. Writing-Original Draft Preparation: Raul Arango, Robert Hausler and Rabindranarth Romero. Writing-Review & Editing: Robert Hausler, Rabindranarth Romero and Mathias Glaus. Supervision: Robert Hausler, Rabindranarth Romero and Mathias Glaus.

Acknowledgments: The authors thanks to the great support provided by the Consejo Nacional de Ciencia y Tecnología (CONACYT) and from the Consejo Veracruzano de Investigación Científica y Desarrollo Tecnológico (COVEICYDET) through Ph.D. scholarship (No. 218934) to Raul Arango-Miranda.

Conflicts of Interest: The authors declare no conflict of interest.

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