CO_2 emissions, energy consumption, and economic growth: Determining the stability of the 3E relationship[1]

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Abstract

This study analyzed the stability of the relationship between carbon dioxide (CO_2) emissions, energy consumption, and economic growth among a sample of 31 countries. Our results revealed the presence of structural breaks in this relationship, with the Great Recession playing an important role. Once these breaks were considered, we observed that most of the countries decoupled the level of CO_2 emissions from their economic growth, with more striking evidence among advanced economies. Although emerging markets have made progress, their levels of decoupling were lower. Conversely, we found that the relationship between CO_2 emissions and energy consumption intensified, implying that the countries have maintained consumption patterns that remain somewhat carbon-intensive. This also indicates that additional efforts are necessary for finding cleaner methods of energy production and achieving more sustainable economies.

Keywords: decoupling; carbon dioxide emissions; economic growth; energy consumption; structural breaks; Great Recession.

JEL Codes: C22; Q43; Q50.

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1. Introduction

The relationship between the economy, energy, and the environment has become one the most relevant topics not only within so-called energy economics but also for economists and policymakers. However, meeting energy needs to maintain the development of countries in a sustainable manner requires a balanced energy portfolio that is adapted to different economic and social conditions (Flavin and Aeck, 2005). The importance of this issue is reflected in the fact that the seventh objective of the United Nations Sustainable Development Goals (SDGs) is to ensure universal access to safe and clean energy. This is closely related to SDG 13, which focuses on adopting urgent measures to combat climate change by ensuring access to affordable energy for all citizens. Thus, it is not surprising that there is increasing interest on the part of politicians, researchers, and academics in studying the interactions between the three aforementioned variables (i.e., the economy, energy, and the environment).

Economic growth has been closely linked to increased carbon dioxide (CO_2) emissions and energy consumption, leading to the opinion that a more prosperous world implies negative impacts on the natural environment and climate. To date, there have been lively academic debates about the possibility of achieving a complete decoupling of emissions and growth (Balcilar et al., 2019; Bekun, 2022; Bekun and Agboola, 2019; Hubacek et al., 2021), i.e., the extent to which the adoption of clean energy technologies can allow emissions to decline as economic growth continues. As stated by Ozcan et al. (2020), the most developed parts of the world have started to harmonize their economic growth and energy consumption patterns with their environmental policies.

Recent years have seen stagnation in global CO_2 emissions, while the world's gross domestic product (GDP) growth has been sustained. The International Environmental Agency (IEA) stated that this stagnation in the pace of emissions is due to the decrease in CO_2 emissions related to electricity generation in advanced economies (caused by the increased use of renewable energies such as wind and solar), the replacement of coal with natural gas, and the increase in atomic production. As a result, CO_2 emissions from advanced economies have fallen to late-1980s levels. This has even been seen in countries, such as India and China, which have been undergoing rapid economic growth and lowering their level of per capita emissions. However, relative decoupling alone is insufficient, especially in a world where CO_2 emissions must decline in order to have any chance of limiting global warming below 2°C, which is in line with the Paris Agreement.

Overall, this study contributes to the existing literature in two fundamental aspects. First, it considers the triple relationship between energy, the economy, and the environment, commonly referred to as the 3E relationship. Most studies have initially focused on the bivariate relationship of any combination of environmental effects, the economy, and energy. However, recent research has cast some doubt on the suitability of this relationship, concluding that the consideration of the triple relationship between energy, the economy, and the environment reveals the presence of bias in the bivariate estimations.

Second, this study provides insights into the stability of the 3E relationship. If we consider the length of the sample sizes that are commonly employed, then this restriction appears unrealistic, due to the presence of several historical events that have clearly modified economic trends. Under these circumstances, it is necessary to re-estimate the 3E nexus by admitting the presence of multiple breaks. The framework defined by Bai and Perron (1998, 2003a, and 2003b) is a solid option for cases in which the analyzed variables are not integrated. This procedure endogenously estimates the number and duration of the structural breaks. Then, it is possible to understand the evolution of the estimated elasticities, which, in turn, can offer useful information for ascertaining whether the 3E relationship has been altered by the Great Recession or any other economic events.

The remainder of the study is organized as follows. Section 2 contains the literature review, while Section 3 describes the data, methodology, and analysis framework. Section 4 presents the empirical results of the unit root inference and the 3E relationship. Finally, Section 5 presents the conclusions and identifies the economic implications and policy recommendations.

2. Literature Review

Recent studies have indicated that increases in the GDP and CO_2 emissions do not have to occur at the same time, and that we could be at the dawn of the era of decoupling the two indicators. Conversely, some voices have pointed out that many developed countries have reduced their CO_2 emissions because they are importing them in the goods acquired through international trade. In other words, such emissions are attributed to the producing country. In regard to developing countries, this fact is particularly relevant for two reasons. First, is their CO_2 pathways have experienced a marked growth in recent years, as opposed to the decrease observed in developed countries (IEA, 2011). Second, because when understanding climate change as a global phenomenon (Schelling, 1992), the emission reduction targets set in developed countries make no sense if they only generate a shift of polluting activities from those countries to less developed ones. In this respect, Cohen et al. (2018) showed that average trend elasticities for production-and consumption-based emissions for a large group of countries decline with per capita incomes, although this decline is starker in regard to production-based estimates.

The literature in this field has grown rapidly in recent years. The majority of the studies initially focused on the bivariate relationship of any combination of environmental effects, the economy, and energy, with these three variables mostly proxied by CO_2, the GDP, and energy consumption, respectively. In addition, the list of articles on the subject is wide and varied, with many focusing on different countries or groups of countries, time periods (from 1947 to the present), and econometric techniques (co-integration, panel unit roots, threshold co-integration, etc.). In particular, the studies by Payne (2010), Narayan and Popp (2014), Narayan (2016), Mardani et al. (2019), and Waheed et al. (2019), among others, provided a good summary of the advancements in this area.

Despite the indubitable interest in all of these studies, some have cast doubt on the suitability of this bivariate relationship, claiming the need to include new variables in the empirical model to avoid the bias caused by misspecification. In this regard, we cite the studies by Soytas and Sari (2009), Apergis et al. (2010), Acaravci and Ozturk (2010), Farhani et al. (2014), Yang and Zhao (2014), Zhang et al. (2019), and Munir et al. (2020), among others. More recently, Rehman et al. (2021) demonstrated the influence of urbanization, energy utilization, fossil fuel energy consumption, per capita GDP growth, and CO_2 emissions on economic growth in China, applying unit root tests and analyzing the asymmetric impacts on the study variables with short- and long-run dynamics.

The conclusion from these studies is that the consideration of the triple relationship between energy, the economy, and the environment reveals the presence of some bias in the previous bivariate estimations. In particular, Ehigiamusoe et al. (2020) showed how the estimated elasticities vary in comparison to those obtained from bivariate specifications. These results also suggest the suitability of using the 3E nexus as the starting point for this type of analysis.

Most of the literature on this issue assumed that either the bivariate or 3E relationships have remained stable over time. However, this assumption has been challenged by Altinay and Karagol (2004), Narayan et al. (2016), Cai et al. (2018), Balcilar et al. (2019), and Churchill (2020). Specifically, these authors found the presence of breaks in the trend of the variables in the 3E relationship. Under these circumstances, it seems appropriate to re-estimate the 3E nexus by admitting the presence of multiple breaks, and paying close attention to the possible effect caused by the so-called Great Recession. This crisis, which began in 2008, led to a series of financial and economic disturbances that disrupted the main macroeconomic variables of global economies. There is extensive literature devoted to the analysis of the causes and effects of this crisis.[1] Since we consider that the 3E nexus can also be affected, it is important to determine to what extent the Great Recession has modified the 3E relationship.

Thus, it is necessary to determine whether we are facing a cyclical fluctuation or a change in trend. Moreover, a distinction must be made between decoupling and reducing resources in absolute terms. The decoupling of resources means that the growth rate of the corresponding environmental parameter (i.e., the resources used or some measure of the environmental impact) is lower than the growth rate of the corresponding economic indicator (e.g., the GDP). Although such decoupling appears to be quite common, it does not necessarily lead to a reduction in resources in absolute terms. Such a reduction will only occur if the rate of increase in resource productivity is higher than the growth rate of the economy.

In this respect, Ajmi et al. (2015) investigated how the relationship among CO_2 emissions, energy consumption, and output has changed since 1960, especially for G-7

[1] In this regard, we cite Gadea et al. (2020) and Prados de la Escosura and Rodríguez-Caballero (2020), among others.

countries using a time-varying vector autoregressive model. Kristrom and Lundgren (2005) studied CO_2 emissions in Sweden since 1900 and determined how the behavior has changed over time. Several studies have focused on decoupling in European Union (EU) countries. However, their results were inconclusive and included strong and weak decoupling. Some authors even found coupling in different sub-periods (Roinioti and Koroneos, 2017). Cohen et al. (2018) provided evidence of decoupling between greenhouse gas emissions and output in richer countries, while Rehman et al. (2021) demonstrated that industrialization has a constructive influence on CO_2 emissions in Pakistan. Moreover, using Maki co-integration, Bekun and Agboola (2019) found empirical evidence of the long-run equilibrium relationship between electricity consumption, the GDP, and CO_2 emissions in Nigeria, while Samu et al. (2019) found similar results in Zimbabwe.

Finally, we consider the so-called environmental Kuznets curve (EKC), which can be an alternative specification for capturing possible non-linearities. The EKC hypothesis has been extensively explored in the empirical literature on the economic growth and environment nexus (Kasman and Duman, 2015; Kalayci, 2019; Chen et al., 2019; Awan et al., 2020; Le and Ozturk, 2020; Farooq et al., 2022). Therefore, we also compared the EKC results to the ones in Bai and Perron's (1998, 2003a, and 2003b) methodology.

3. Databases and Methodology

3.1. Databases

As mentioned earlier, the purpose of this study was to analyze the 3E relationship. In this regard, we required variables that could help us measure the evolution of the environment, economic growth, and energy use. Following Apergis and Payne (2009) and Ehigiamusoe et al. (2020), the commonly used variables are CO_2 emissions, the GDP, and energy consumption. In our case, the selected international sample (i.e., 31 countries) covered the 1974–2018 period, and all of the variables were expressed in terms of per capita. These countries consisted of the following 27 Organization for Economic Co-operation and Development countries for which there was relevant data: Australia, Austria, Belgium, Canada, Chile, Denmark, Finland, France, Germany, Greece, Ireland, Israel, Italy, Japan, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Portugal, South Korea, Spain, Sweden, Switzerland, Turkey, United Kingdom, and the United States, with the remaining four countries of Brazil, India, China, and South Africa. The comparison of the latter group was particularly interesting because they are four major emerging economies, which together represent a significant volume of global CO_2 emissions.

The data on CO_2 emissions from fossil fuels and cement production by country was taken from the Global Carbon Project.[2] These estimates of global and national fossil CO_2 emissions include the combustion of fossil fuels through a wide range of activities (e.g., transportation, heating and cooling, industries, the fossil fuel industry itself, and natural gas flaring), the production of cement, and other process emissions (e.g., the production of chemicals and fertilizers). Most of the existing literature has used the GDP as a proxy for economic activity in each country, while some studies have employed population components as control variables. Hence, we used the data on the GDP and population from the World Development Indicators database. As for the data on per capita primary energy consumption, it was obtained from the British Petroleum Statistical Review of World Energy.

Within the group of analyzed countries, the top five countries that emitted the most CO_2 in 2018 were China, the United States, India, Japan, and Germany. However, when

[2] This database, published by the Integrated Carbon Observation System (ICOS) Carbon Portal, is available at https://doi.org/10.18160/gcp-2019.

we accounted for the population of each country, the top per capita emitters were Australia, the United States, Luxembourg, Canada, and South Korea. Based on these findings, developing countries and major emerging economy nations lead in total CO_2 emissions. However, developed nations typically have high CO_2 emissions per capita. These uneven contributions to the climate crisis are one of the core challenges that the global community faces in finding effective and equitable solutions to global warming.

Table A1 in the Appendix presents the average growth rates in CO_2 emissions, the GDP, and energy consumption per capita during two periods: before the Great Recession (1974–2007) and after (2008–2018). In regard to CO_2 emissions, there was a notable decrease after the Great Recession, with most countries showing negative average growth between 2008 and 2018. The only exceptions were Brazil, Chile, China, India, South Korea, and Turkey. However, although the average growth rate in these countries was positive, only India showed a higher growth rate of CO_2 emissions: 3.5% before the crisis, compared to 4.3% afterwards.

As for energy consumption, it has a similar pattern to that of CO_2 emissions. Only India had a higher average growth rate in per capita energy consumption after the Great Recession. Meanwhile, Brazil, Chile, China, India, South Korea, and Turkey showed an increase in the growth rate of per capita energy consumption, with New Zealand and Portugal joining this group. In terms of per capita GDP, the crisis caused a slowdown in the economy for all countries. The exceptions were China, India, and Turkey, which grew at a higher rate during the post-crisis period.

To better understand how CO_2 emissions evolve with respect to the two variables of interest, Table A1 shows the growth rate of emissions intensity per unit of GDP and per energy consumption. Based on the findings, the growth rate of CO_2 intensity per unit of GDP was negative after the Great Recession for all countries, except Brazil, where it grew by 1% (on average) between 2008 and 2018. Although negative, the rate at which CO_2 emissions per unit of income declined was lower after the crisis for South Korea, Luxembourg, the Netherlands, South Africa, Japan, Chile, Germany, France, and Norway. Meanwhile, the rate of decline intensified in the remaining countries.

As for the relationship between CO_2 emissions and energy consumption, the rate of variation after the crisis increased in South Korea, Japan, India, the Netherlands, Brazil, France, Chile, and Belgium. In addition, in the first four countries, the variation was positive. In sum, this initial analysis confirms the close relationship between our three variables of interest and suggests the effect of the Great Recession on this relationship.

3.2. Testing for Unit Roots

The use of time-series data requires an understanding of the time properties of these variables in order to determine the most appropriate econometric techniques. If we cannot reject the presence of unit roots in the variables, then the use of co-integration analysis is the most suitable approach. This was the framework employed by Acaravci and Ozturk (2010), Apergis and Payne (2009), and Baek (2015), among others. However, if we can reject the presence of unit roots, then standard techniques can be used, including those that can detect multiple structural breaks. Note that we employed the variables in terms of per capita, which may be important for determining their time properties.

There has been a significant increase in the number of studies on developing methods for testing the unit root null hypothesis, especially after the seminal research by Dickey and Fuller (1979). Part of this literature considered the presence of breaks in the trend function of the variables, based on the influential work by Perron (1989). Given that the Great Recession and other events may have altered the trend function of the variables, it seems appropriate to consider their presence. We also followed Adedoyin et al (2020), who found solid evidence of structural breaks in CO_2 emissions.

There are also several statistics for testing the unit root null hypothesis in the presence of breaks in the trend function. Thus, we used the statistics in Carrión-i-Silvestre et al. (2009), which are based on quasi-generalized least squares detrending methods (Elliot et al., 1996). Based on these authors, let y_t be a stochastic process generated as follows:

$$y_t = d_t + u_t \tag{1}$$

$$u_t = \alpha\, u_{t-1} + v_t \; t = 0, \dots, T \tag{2}$$

where d_t reflects the deterministic elements in the specification. For instance, Elliot et al. (1996) considered the presence of an intercept and a linear trend (DF-GLS). In order to allow for the presence of changes in the deterministic function, d_t should include these changes. Hence, following the most general case reported in Carrión-i-Silvestre et al. (2009), which allowed for changes in both the slope and the intercept of the trend function, we defined $DU_{j,t} = 1$ and $DT_{j,t} = (t - T_j)$ for $t > T_j$ and 0 elsewhere, with $T_j = [T\,\lambda_j]$ as the *j-th* break date, $[\cdot]$ as the integer part, and $\lambda_j \equiv T_j/T\ \in (0,1)$ as the break fraction parameter. Then, we obtained:

$$d_t = z_t'(\lambda)\,\psi \tag{3}$$

with $z_t(\lambda) = [z_t'(T_0), z_t'(T_1), \dots, z_t'(T_m)]'$ and $\psi = (\psi_0', \psi_1', \dots, \psi_m')'$. In the present case, $z_t(T_j) = \left(DU_{j,t}, DT_{j,t}\right)'$ and $z_t(T_0) = (1, t)'$, while $\psi_j = \left(\mu_j, \beta_j\right)'$ and $\psi_0 = (\mu_0, \beta_0)'$, with $1 \leq j \leq m$ and *m* being the numbers of breaks in the specification. These authors also designed some statistics based on the use of the quasi-difference variables $y_t^{\bar{\propto}}$ and $z_t^{\bar{\propto}}(\lambda)$, defined by:

$$y_t^{\bar{\propto}} = (y_1, (1 - \bar{\alpha}L)y_t),$$

$$z_t^{\bar{\propto}}(\lambda) = (z_1, (1 - \bar{\alpha}L)z_t(\lambda)) \tag{4}$$

for $t = 2, \ldots, T$ with $\bar{\alpha} = 1 + \bar{c}/T$, where $\bar{c}$ is the non-centrality parameter. Once the data was transformed, ψ was estimated by minimizing the following objective function:

$$S^*(\psi, \bar{\alpha}, \lambda) = \sum_{t=1}^{T} (y_t^{\bar{\alpha}} - \psi' z_t^{\bar{\alpha}}(\lambda))^2 \tag{5}$$

Although alternative statistics can be employed for testing the unit root null hypothesis, we used the DF pseudo t-ratio, which can be obtained by estimating the following model:

$$\Delta \tilde{y}_t = b_0\, \tilde{y}_{t-1} + \sum_{j=1}^{k} b_j \Delta \tilde{y}_{t-j} + e_{tk} \tag{6}$$

and subsequently testing for $H_0: b_0 = 0$, with $\tilde{y}_t = y_t - \tilde{\psi}' z_t(\lambda)$ and $\tilde{\psi}$ obtained by the minimization of Equation (5). The value of k was selected by using the MAIC criterion suggested by Ng and Perron (2001), with the modification proposed by Perron and Qu (2007). Given our sample size, we selected a maximum value of $k = 5$, while the critical values were approximated by estimating surface responses. In our case, we considered a maximum of 3 breaks, with the unit root statistics referred to as CKP_1, CKP_2, and CKP_3 for 1, 2, and 3 breaks, respectively.

3.3. The Stability of the 3E Relationship

In order to analyze the 3E relationship, we estimated the following model:

$$\ln(CO_2)_{it} = \alpha_i + \beta_i \ln(GDP_{it}) + \gamma_i \ln(EC_{it}) + e_{it}, \; i = 1, \ldots, 31, \; t = 1974, \ldots, 2018 \tag{7}$$

where CO_2, EC_{it}, and GDP_{it} represent the per capita CO_2 emissions, the per capita energy consumption, and the per capita GDP of the i-th country, respectively, with t controlling the time dimension. In addition, e is the perturbation of the model.

However, the presence of structural breaks has been shown to be pivotal when analyzing the time properties of variables. These breaks may also affect the relationship between the three variables in this study. Thus, it is advisable to allow for the presence of these breaks when estimating the elasticities. To this end, we followed the methodology of Bai and Perron (1998, 2003a, and 2003b), which has the advantage of endogenously determining the number of breaks as well as the period when these breaks occur. This is based on the estimation of the following model:

$$\ln(CO_2)_{jt} = \alpha_{ij} + \beta_{ij} \ln(GDP_{it}) + \gamma_{ij} \ln(EC_{it}) + v_{it}, \; t = TB_{j-1}, \ldots, TB_j, \; j = 1, \ldots, m+1 \quad (8)$$

where TB_j is the period when the breaks appear, with $TB_o = 1974$ and $TB_{m+1} = 2018$, m is the number of breaks, and v is an innovation that follows a wide range of stationary models, including the general autoregressive-moving-average model.

The Bai–Perron procedure involved the estimation in model (8), considering that the break may appear in any period of the sample. A Chow-type test was then defined to determine the existence of the first break. The estimation of the period where this first break occurred coincided with the period in which the Chow-type statistic attained its maximum value. Subsequently, the existence of multiple breaks was tested by applying this statistic sequentially. In addition, the presence of multiple breaks was analyzed by using the UD_{max} and WD_{max} statistics, which test the null hypothesis of no structural breaks vs. the presence of an unknown number of breaks, using a maximum value of 5.

Note that we used the quadratic spectral kernel to consider the presence of autocorrelation and heterogeneity in the perturbation of the model, combined with the automatic bandwidth selection with AR(1) approximation of Andrews (1991). Given that the Bai–Perron procedure only works correctly once regime-wise stationarity is proved, we only applied it to those cases where the unit root null hypothesis was previously rejected. Hence, an appropriate strategy should be based, first, on the application of the unit root tests, and once this hypothesis is rejected, we should apply the Bai–Perron sequential procedure for estimating the number of breaks, combined with the repartition method of Bai (1997), to determine the periods when the breaks appear.

Moreover, we could have alternatively considered the EKC to capture possible non-linearities. For instance, Ehigiamusoe et al. (2020) used the following specification:

$$CO_{2it} = \alpha_i + \beta_i\ GDP_{it} + \gamma_i\ EC_{it} + \delta_i\ GDP^2_{it} + e_{it}, \tag{9}$$

which could be appropriately extended to account for the presence of breaks as follows:

$$CO_{2it} = \alpha_{ij} + \beta_{ij}\ GDP_{it} + \gamma_{ij}\ EC_{it} + \delta_{ij}\ GDP^2_{it} + e_{it},\ t = TB_{j-1}, \ldots, TB_j,\ j = 1, \ldots, m+1 \tag{10}$$

The estimation of model (10) is presented in Table A2 of the Appendix. As we can see, the use of the Bayesian criterion presented by Schwartz (1978), commonly referred to as the Schwartz Bayesian information criterion (SBIC), suggests that the estimation of model (8) clearly outperforms that of model (10). Meanwhile, the estimation of model (10) does not provide evidence of an inverted-U behavior, given that the estimation of the parameter δ is mostly greater than 0. Consequently, we discarded the use of the EKC specification and focused on that of model (8).

Finally, we did not employ a panel data approach, unlike previous literature. Instead, we based our study on the analysis of a sample of countries. The main reasons for doing so are related to the variety in the heterogeneity of the periods in which the different breaks appear, as well as the differences in the estimated elasticities. Both motives allowed us to consider that an individual estimation for each country in the sample is much more appropriate than using panel data techniques. We are aware of the trade-off between the flexibility of the Bai–Perron methodology and the gain in efficiency that a joint analysis can offer. However, this gain is not significant. We also calculated the pair-wise correlation coefficients of the residuals obtained from the estimation of model (8) for the different countries. While the statistic of Pesaran (2015) allowed us to reject the null hypothesis of weak cross-sectional independence, taking the value of 2.046 (p-value = 0.41), it is also true that the largest absolute value of these estimated coefficients was 0.3 and that these correlation coefficients were highly concentrated around 0 (only 5% of these pair-wise correlation coefficients were greater than 0.2 in absolute terms). Then, the possible gain in efficiency of, for instance, a seemingly unrelated regression equation estimation is small. Therefore, we preferred to maintain the individual analysis.

4. Results

4.1. Unit Root Inference

As mentioned earlier, we determined the time properties of the variables before proceeding to the estimation of the 3E relationship. The results for the unit root inference are presented in Tables 1–3. First, the evidence against the null hypothesis of a unit root is scarce when no trend breaks are included. However, if we include the presence of breaks in the trend, then the unit root null hypothesis is mostly rejected. In other words, the greater the number of breaks, the greater the number of rejections of the unit root null hypothesis.

Second, we did not find evidence against the null hypothesis when using a 5% significance level for the per capita CO_2 emissions in China. The importance of this country, in economic terms and in terms of the global volume of its CO_2 emissions, led us to retain it in the analysis in order to compare its evolution with other countries. However, the result for this country should be treated with caution, due to the lack of evidence against the unit root in the per capita CO_2 emissions. For the remaining countries, the evidence against the unit root null hypothesis was robust.

Finally, after examining the years around which most of the breaks were concentrated, four clearly differentiated periods can be distinguished: 1) the second oil crisis, from 1979 to 1982; 2) the financial crisis of the early 1990s; 3) the dot-com bubble, along with the Asian financial crisis of the late 1990s and early 2000s; and 4) the Great Recession, which was the period with the highest concentration of estimated breaks. This confirms our initial suspicion that the Great Recession affected the evolution of the three variables under analysis. Therefore, it is possible that the relationship between them has also changed, an issue considered in the following section.

4.2. The Relationship between CO_2 Emissions, Economic Growth, and Energy Consumption

Since we confirmed the absence of unit roots in our set of variables, we analyzed the relationship between them by using standard methods, given that co-integration analysis was not required. Table 4 presents the results based on the application of the Bai–Perron methodology. If we consider the results of the UD_{max} and WD_{max} statistics, the null hypothesis of no structural breaks in Equation (2) is clearly rejected. Again, the use of the sequential procedure developed by Bai–Perron helped us determine the number of breaks and the periods when they occurred. We found that the number of breaks differed for each country, which confirms that it is more appropriate to individually analyze each country, rather than use panel data.

The times at which these breaks occurred also differed, although they were clearly concentrated around four different periods, as in the univariate analysis. The first was related to the escalation of oil prices after the war between Iran and Iraq, which led to the second oil crisis (1979–1982). The second was related to the crisis in the early 1990s following the global stock market crash in 1987, also known as Black Monday. Most of the ruptures during this period were concentrated at the end of the 1980s and the beginning of the 1990s. The third was related to the crisis in Southeast Asia in 1997, combined with the dot-com financial bubble at the beginning of the 21st century.

Numerous ruptures occurred during this period, except for most European countries, Canada, Japan, and the United States, all of which experienced no breaks. Finally, the fourth period is related to the Great Recession, the global economic crisis that occurred between 2008 and 2012. If this period is extended back to 2005, then almost one-third of the breakdowns were concentrated during these years. This was the case for Australia (2006), Greece (2005), Ireland (2006), Spain (2005), and Turkey (2006), where the estimations of the break periods were slightly earlier. Conversely, Austria, India, Israel, Luxembourg, and South Korea were the only countries that did not exhibit any breaks related with the Great Recession. Based on these findings, we can conclude that the Great Recession did, in fact, affect the 3E relationship.

Table 2 presents the estimated elasticities. According to the results, there is a clear change over time with respect to CO_2 emissions. In this regard, the changes that occurred in the relationship between CO_2 emissions and the GDP indicated a gradual decrease in elasticity. Specifically, at the beginning of the research period, 14 of the 31 countries had CO_2/GDP elasticity values of greater than zero, while Portugal, Turkey, Greece, and Switzerland had income elasticity values of greater than one. In addition, Spain and Norway had values close to one. However, it was from 2005 onwards that the relationship between CO_2 emissions and the GDP became mostly negative, indicating that most of the countries decoupled their economic growth from CO_2 emissions. However, there were some exceptions. On the one hand, although Israel, Brazil, and Spain had positive elasticities, they were lower than unity. On the other hand, France and Portugal had elasticities higher than unity.

Figure 1 shows both the elasticity in the fourth period, i.e., after the Great Recession, and that of the immediately preceding one. Based on the findings, there was a general reduction in the elasticities. Undoubtedly, the Great Recession modified the CO_2/GDP elasticity in the direction required to minimize the environmental impact of economic growth. It should be noted that the larger emitters of CO_2 in volume (i.e., China, the United States, India, Japan, and Germany) went from having positive elasticities to negative CO_2/GDP elasticities after the Great Recession. Additionally, the United States and Japan, which did not commit to the Kyoto Protocol, implemented numerous environmental protection measures that, in light of the results in this study, appear to have been effective. Conversely, the cases of France and Portugal are somewhat striking: both countries had negative values of elasticity before the Great Recession, but positives ones after this crisis.

Interestingly, when we focused on the elasticity of CO_2 emissions with respect to energy consumption, we obtained a somewhat different view. While the aforementioned results indicated that increases in the GDP go along with reductions in emissions (in most cases), it is not accompanied by decreases in emissions related to energy consumption. Thus, there is still a long way to go to achieve effective environmental protection. Specifically, at the beginning of the period, the estimated elasticities of emissions to energy consumption were mostly positive. We even found that 25 countries had estimated elasticities higher than 0.5, with 17 greater than 1. This figure could be even larger if we add countries, such as South Africa, Japan, and Belgium, whose confidence intervals include a value of 1. However, upon comparing the value of the initial and final elasticity, we observed a remarkable reduction in Portugal, the United Kingdom, Chile, Italy, and Australia. There was also a decrease in the case of Norway, the Netherlands, Germany, and Belgium, although it was somewhat more moderate. For the remaining countries, the value of elasticity increased.

Similar conclusions can be drawn when comparing the estimated elasticities for the periods before and after the Great Recession, as shown in Figure 1. Among the 31 countries analyzed, 28 showed a positive effect of energy consumption on CO_2 emissions (with 17 having elasticity values of greater than one). The exceptions were Norway, New Zealand, and Portugal. Meanwhile, Switzerland and the United Kingdom, although with positive values, had elasticities close to zero. The conclusion derived from this figure is that, in general, CO_2/energy consumption elasticity increased since the Great Recession.

In general, the literature confirms our conclusion. As Waheed et al. (2019) pointed out, energy consumption is the main source of CO_2 emissions, due to the higher dependence on non-renewable energy in the total energy mix, the use of oil for transportation, and the high consumption of energy for industrialization, urbanization, and farming. This indicates that current energy consumption patterns are still harmful, resulting in environmental degradation. Note that some previous studies showed that non-renewable energy consumption tends to increase CO_2 emissions, while the effect of such consumption remains unclear. In this regard, Bolük and Mert (2014) found that renewable energy consumption contributes approximately 50% less per unit of energy consumed than fossil energy consumption to greenhouse gas emissions in EU countries, while Bekun (2022) focused on the Indian economy and indicated that renewable energy significantly decreases emissions. Similar results were found in the Chinese context by Sunday Riti et al. (2018). If we also consider the results of Apergis et al. (2010), then the abandonment of nuclear energy production may have helped increase the value of CO_2/energy consumption elasticities, given that such energy is cleaner in terms of greenhouse gas emissions.

In the light of our results, it seems that policies aimed at promoting the efficient use and conservation of energy are failing to reduce CO_2 emissions. Even worse, this effect has intensified since the Great Recession. Therefore, it is essential to pay special attention to both consumption patterns and energy sources. In particular, the development of technologies that do not consume natural resources and simultaneously emit lower amounts of polluting gases is necessary for achieving the SDGs adopted by the United Nations member states.

5. Conclusions and Policy Recommendations

This study analyzed the relationship between CO_2 emissions and two fundamental variables: the GDP and energy consumption. This analysis allowed us to verify whether decoupling between emissions and the GDP has occurred, and if countries have been opting for cleaner energy sources in order to reduce CO_2 emissions. Thus, our study adds new empirical evidence to the ongoing debate on the 3E relationship.

The literature describing the relationship between these three variables is extensive, although mostly based on the assumption of stability. We relaxed this assumption by using econometric techniques that allow the elasticities to vary over time. Our results confirm our initial hypothesis and provide evidence that the 3E relationship is not stable. In this regard, the Great Recession played a very important role.

Once the structural breaks were accounted for, we observed how the estimated elasticities changed in each country. Moreover, we found that most countries managed to decouple the level of CO_2 emissions from their economic growth in such a way that the elasticity was negative. However, in some cases, this already occurred before 2008, but intensified after the Great Recession. Although the reduction was more striking for advanced economies, emerging markets also made some progress. Only Portugal and France presented weak negative coupling with positive elasticities, which was probably due to the decline in the GDP related to the European debt crisis. Some developing countries presented a relative decoupling level with positive elasticities, but with an estimated value of less than one. Even so, more than 80% of the countries in the sample had negative elasticities. These findings reflect the success of adopting appropriate measures to mitigate CO_2 emissions without harming economic development.

Furthermore, we found that the positive relationship between CO_2 emissions and energy consumption intensified, especially after the Great Recession, which implies that energy consumption patterns have a positive impact on CO_2 emissions. For most of the advanced economies, they exported goods and services that were less pollution-intensive than their imports. Meanwhile, the consumption elasticities revealed that they maintained consumption patterns that were carbon-intensive, despite reducing their CO_2 emissions. For emerging markets, the differences were smaller. The results consistently showed that energy consumption increased its influence on CO_2 emissions. In this regard, there is a need for a gradual transition from conventional energy sources (fossil-fuel based) to clean energy sources, as suggested by Adebola et al. (2020) and Solarin et al. (2021). Overall, significant steps are still required for improving the combination of energy consumption. The development of new and more efficient technologies, which can generate cleaner energy without consuming natural resources, is crucial.

This being said, our analysis showed that it is possible to have economic growth at the same time as a decline in CO_2 emissions. However, it is important to note that the behavior of countries is far from homogeneous and that there are still nations where increases in the GDP lead to increases in CO_2 emissions. These countries must consider the adoption of measures to change their energy supply and consumption patterns and reduce environmental degradation.

With the rapid cost reduction of clean energy and the expected peak in the level of CO_2 emissions by developing countries in the near future, it is a matter of time before absolute decoupling becomes the norm. The question remains of whether this will occur rapidly enough to avoid dangerous levels of global warming, which mainly depends on the degree of technological progress and the willingness of governments to invest in mitigating climate change. Overall, there is still substantial room for improvement, and countries should continue to follow appropriate policies, such as carbon taxation, carbon pricing, and promoting the use of less carbon-intensive technologies, in order to mitigate the levels of CO_2 emissions. Otherwise, all of the efforts made so far would be wasted, with negative consequences for the environment.

Finally, we cannot end without mentioning two facts that may have affected the stability of the 3E relationship in recent years: the COVID-19 pandemic and the war in Ukraine. Moreover, these changes may have been extremely abrupt, especially those caused by the pandemic. As a consequence, the econometric tools used may have differed from the standard ones. This will probably pose a number of challenges to future theoretical and applied research, once the corresponding data becomes available.

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Table 1. Testing for unit roots in per capita CO_2 emissions

	DF-GLS	CKP_1	TB_1	CKP_2	TB_1	TB_2	CKP_3	TB_1	TB_2	TB_3	CKP_4	TB_1	TB_2	TB_3	TB_4	CKP_5	TB_1	TB_2	TB_3	TB_4	TB_5
Australia	−0.56	*−3.10*	2007	**−4.17**	1982	2007	**−4.11**	1978	1982	2007	**−4.96**	1981	1986	2007	2012	**−4.65**	1978	1982	1986	2007	2012
Austria	−1.81	**−3.84**	2000	**−4.73**	1979	2005	**−5.38**	1979	1989	2002	**−6.00**	1979	1989	2000	2005	**−5.72**	1979	1983	1989	2002	2009
Belgium	−1.64	−1.89	1988	−3.41	1980	2001	**−4.90**	1980	1988	2004	−4.10	1977	1982	1989	2004	**−6.84**	1977	1982	1989	2004	2009
Brazil	−1.88	−2.18	2009	−2.78	1980	2009	−2.92	1980	2008	2013	−4.13	1980	1994	2008	2013	**−5.36**	1980	1994	2001	2008	2013
Canada	−1.51	−2.79	1996	**−4.07**	1981	1999	**−4.42**	1980	1995	2007	**−4.97**	1980	1990	2000	2007	**−6.01**	1980	1985	1989	1998	2007
Chile	−1.94	−2.73	1993	*−3.73*	1985	1999	−3.83	1985	1999	2013	**−4.79**	1981	1995	1999	2013	**−5.58**	1981	1987	1991	1999	2013
China	−1.81	−1.10	2002	−2.83	2001	2011	−3.57	1993	2001	2011	−4.01	1979	1997	2001	2011	−4.38	1979	1989	1996	2001	2010
Denmark	−1.01	**−4.00**	1990	**−4.67**	1989	1996	**−4.57**	1990	1995	2000	*−4.47*	1984	1989	1995	2005	**−5.01**	1980	1987	1991	1995	2005
Finland	−1.34	**−4.24**	2007	**−5.40**	1980	2003	**−4.49**	1980	2004	2009	**−4.62**	1980	1987	2004	2009	**−5.13**	1980	1987	2001	2005	2009
France	−2.26	−2.14	1980	−2.84	1980	1995	**−6.48**	1979	1988	2005	**−7.31**	1979	1985	1991	2005	**−7.98**	1979	1986	1991	2005	2013
Germany	−1.76	**−4.02**	1977	**−4.56**	1979	2009	**−6.18**	1980	1990	2008	**−8.03**	1979	1983	1991	2008	**−9.71**	1979	1983	1991	2008	2013
Greece	−0.92	−2.63	2007	−3.96	1988	2007	**−4.54**	1979	1988	2007	−3.51	1979	1988	2007	2013	*−4.69*	1979	1985	1989	2007	2013
India	−0.40	−2.50	2000	−2.27	2005	2009	−2.20	2000	2004	2009	**−6.25**	1984	1995	2004	2009	**−6.26**	1984	1995	2003	2007	2012
Ireland	−0.90	−2.46	2005	−3.31	1998	2008	−3.29	1978	1998	2008	**−5.26**	1977	1981	1999	2008	*−4.70*	1978	1984	1991	2001	2008
Israel	−0.66	−2.89	1991	*−3.53*	1991	2012	**−4.94**	1980	1997	2005	**−5.57**	1981	1997	2005	2009	**−5.68**	1981	1991	2001	2005	2011
Italy	−0.81	−2.88	2006	**−4.33**	1988	2005	**−4.12**	1988	2003	2009	**−5.09**	1980	1988	2005	2009	**−6.36**	1980	1988	2002	2008	2012
Japan	−1.64	−2.11	1988	*−3.57*	1981	1989	−3.72	1987	2001	2009	**−5.29**	1983	1989	2007	2011	**−5.91**	1978	1983	1989	2007	2011
Luxembourg	−2.14	−2.22	1983	−3.07	1987	2001	−3.96	1983	1994	2003	**−4.56**	1983	1989	1994	2003	**−5.59**	1983	1988	1993	1998	2003
Mexico	−1.81	−2.13	1982	−2.34	1982	1996	−3.06	1982	1986	2008	**−5.96**	1982	1988	1994	2008	**−6.28**	1982	1988	1994	2008	2012
Netherlands	*−2.71*	−2.14	1980	**−4.06**	1979	1988	**−5.11**	1977	1981	1988	**−5.78**	1977	1981	1988	2009	**−6.75**	1977	1981	1985	1996	2009
New Zealand	−1.21	−2.39	2000	**−4.11**	1983	2000	−3.44	1977	1984	2000	−3.77	1977	1983	1988	2008	**−6.40**	1977	1984	1998	2003	2008
Norway	−0.84	−2.50	2007	−1.93	1979	1995	−3.45	1979	1993	2007	**−4.89**	1979	1983	1995	2007	**−7.59**	1979	1985	1990	1995	2007
Portugal	−0.83	−2.19	2005	−2.94	1988	2002	**−4.28**	1988	1998	2008	**−5.00**	1988	1998	2002	2013	**−5.59**	1988	1992	1997	2002	2013
South Korea	*−2.63*	−2.23	1997	−3.58	1987	1997	−3.57	1987	1997	2009	*−4.33*	1987	1997	2004	2011	**−5.46**	1987	1997	2001	2007	2011
South Africa	−1.86	−2.80	1988	−2.70	1988	2002	−3.53	1988	2000	2004	−4.26	1980	1989	2000	2004	**−5.41**	1980	1989	2000	2004	2008
Spain	−0.91	−2.04	2007	−2.14	1988	2007	−2.21	1988	1998	2007	−2.57	1988	1998	2007	2012	**−6.41**	1979	1988	1998	2007	2012
Sweden	−2.20	*−3.21*	1984	**−4.25**	1979	1993	**−4.34**	1979	1993	2009	−4.11	1978	1983	1993	2009	*−4.65*	1978	1983	1993	2001	2009
Switzerland	−1.69	−2.07	1989	**−5.25**	1989	2010	**−5.50**	1978	1989	2010	**−5.51**	1978	1982	1989	2010	**−5.83**	1978	1982	1986	1990	2010
Turkey	**−2.82**	−2.97	2000	**−3.86**	1988	2004	**−4.41**	1977	1988	2004	*−4.43*	1977	1995	2000	2007	**−4.70**	1977	1995	1999	2004	2012
U. K.	−1.06	**−3.60**	2002	−3.11	1979	2004	**−5.17**	1979	1991	2006	**−7.58**	1978	1982	1991	2007	**−8.05**	1978	1982	1991	2002	2007
U.S.A.	−1.16	−2.25	2007	−3.03	1980	2005	−3.36	1980	2000	2007	**−5.94**	1977	1982	2000	2007	**−5.83**	1977	1982	1987	2004	2009

This table presents the results of the unit root inference, when testing $H_0: b_0 = 0$ in (6) by way of the pseudo t-ratio. DF-GLS means the statistic proposed in Elliot et al. (1996) for the specification that does not include breaks in the trend. By contrast, CKP_i (i = 1,…,5) reflects the Carrión-i-Silvestre et al. (2009) statistic for 1–5 breaks in the trend function, respectively. Bold and italic values mean rejection at the 5% and 10% significance levels, respectively.

Table 2. Testing for unit roots in per capita GDP

	DF-GLS	CKP$_1$	TB$_1$	CKP$_2$	TB$_1$	TB$_2$	CKP$_3$	TB$_1$	TB$_2$	TB$_3$	CKP$_4$	TB$_1$	TB$_2$	TB$_3$	TB$_4$	CKP$_5$	TB$_1$	TB$_2$	TB$_3$	TB$_4$	TB$_5$
Australia	−1.52	−2.34	1996	*−3.78*	1992	2008	**−4.76**	1982	1990	2008	**−4.94**	1982	1990	2000	2008	**−5.18**	1982	1990	2000	2008	2012
Austria	−1.50	−2.27	2008	−3.46	1994	2008	−3.72	1980	1992	2008	**−4.52**	1980	1997	2002	2008	**−5.01**	1977	1987	1992	2002	2008
Belgium	−1.37	−2.52	2008	**−3.82**	1987	2008	**−4.87**	1987	1992	2008	**−5.65**	1987	1992	1998	2008	**−6.39**	1982	1992	1998	2007	2013
Brazil	−1.77	−2.27	2004	*−3.58*	2000	2011	−2.98	1998	2002	2011	**−5.39**	1993	1998	2002	2011	**−5.95**	1988	1994	1998	2002	2011
Canada	−1.95	−2.53	1997	−3.33	1989	2007	−3.49	1981	1989	2007	**−4.71**	1981	1989	1997	2008	**−5.73**	1981	1985	1990	1998	2008
Chile	−1.45	−2.52	1981	−2.52	1981	1998	−2.98	1981	2003	2007	−3.10	1981	2003	2008	2012	*−4.67*	1981	1985	1998	2008	2012
China	−0.68	−2.11	2001	−2.55	1993	2002	**−4.15**	1993	2003	2010	*−4.24*	1993	1997	2003	2010	**−5.72**	1993	1997	2001	2005	2013
Denmark	−1.42	−2.94	2007	−3.21	1981	2007	−3.75	1979	1987	2008	*−4.32*	1980	1986	1993	2008	**−5.24**	1980	1986	1992	2000	2008
Finland	−1.58	−2.00	2008	−2.93	1990	2008	−3.08	1990	2008	2012	*−4.05*	1990	1994	2008	2012	**−4.78**	1990	1994	2001	2008	2012
France	−1.29	−2.88	1998	*−3.54*	1997	2007	−3.81	1987	1997	2008	**−4.73**	1977	1987	1997	2008	**−5.53**	1979	1987	1997	2001	2008
Germany	**−3.64**	−2.71	2008	−3.05	2001	2008	−3.32	2001	2008	2012	−4.19	1981	1992	2002	2008	**−5.14**	1981	1992	2002	2008	2012
Greece	*−2.86*	−1.69	2001	−2.42	1992	2008	−3.01	1992	2006	2010	**−4.71**	1980	1995	2006	2010	**−5.18**	1980	1992	1998	2006	2010
India	−0.55	**−4.23**	2002	**−4.89**	2002	2011	**−4.45**	2001	2006	2011	**−5.21**	1990	2002	2006	2011	**−6.75**	1990	2000	2005	2009	2013
Ireland	−1.12	−1.53	2013	−2.39	1998	2013	−3.21	1989	2007	2013	**−5.40**	1985	1996	2007	2013	**−7.40**	1987	1994	2000	2007	2013
Israel	−1.53	−1.96	2006	−2.31	2006	2011	−2.01	2000	2006	2013	**−7.35**	1985	1994	2001	2006	**−5.85**	1985	2000	2004	2008	2013
Italy	−1.24	−2.47	2007	−3.16	1999	2008	**−4.34**	1987	2007	2013	**−4.84**	1981	1987	2007	2012	**−6.39**	1981	1992	2001	2007	2012
Japan	−0.89	*−3.23*	1989	−3.25	1987	2008	*−4.12*	1987	1997	2008	**−5.38**	1986	1991	1997	2008	**−5.73**	1983	1991	1997	2005	2009
Luxembourg	−1.14	−2.20	1998	*−3.64*	1982	2007	*−4.09*	1985	1998	2007	*−4.27*	1985	1998	2007	2012	**−5.62**	1982	1991	1998	2007	2012
Mexico	−2.45	−2.91	1981	*−3.68*	1981	1985	−3.13	1982	1994	2008	−3.47	1981	1985	1994	2008	−4.42	1981	1985	1994	2000	2008
Netherlands	−1.95	−2.11	1996	−2.25	1981	2008	−3.03	1980	1996	2008	−3.40	1980	1992	2001	2008	**−5.40**	1980	1992	2001	2006	2013
New Zealand	−1.84	−2.05	1992	−3.01	1990	2007	−3.63	1980	1990	2007	−3.78	1980	1990	1998	2007	**−5.69**	1977	1986	1990	1996	2007
Norway	−1.67	−2.03	2007	−2.97	1995	2007	−3.56	1987	1995	2007	**−4.88**	1980	1987	1995	2008	**−5.57**	1980	1987	1992	1997	2008
Portugal	−1.45	−2.28	1996	−2.52	1996	2008	−3.07	1986	2001	2008	**−4.87**	1983	1992	2000	2011	−3.93	1983	1992	2001	2006	2011
South Korea	−1.50	−1.80	1997	−1.41	1982	1997	**−4.39**	1983	1997	2007	**−4.98**	1979	1985	1997	2007	*−4.69*	1979	1985	1997	2005	2009
South Africa	−1.96	−2.30	2002	−3.29	1997	2009	−3.38	1997	2009	2013	*−3.99*	1994	2002	2009	2013	**−5.30**	1983	1995	2002	2009	2013
Spain	*−2.76*	−1.74	1998	−2.05	1985	2008	−2.31	1984	2007	2013	−3.62	1986	1998	2007	2013	**−5.21**	1984	1991	1998	2007	2013
Sweden	−1.83	−2.57	1997	**−3.96**	1992	2007	−3.58	1992	2005	2009	**−4.55**	1978	1991	2005	2009	**−4.89**	1978	1991	2005	2009	2013
Switzerland	*−2.71*	−2.76	1977	*−3.51*	1992	2008	−3.86	1977	1992	2008	**−4.58**	1977	1991	2002	2008	**−5.91**	1977	1988	1996	2001	2008
Turkey	−0.52	−3.06	2000	−3.24	2000	2007	**−5.42**	1978	2000	2007	**−4.84**	1979	1993	2000	2008	**−5.25**	1979	1993	2000	2008	2012
U.K.	−2.39	−1.91	2008	−2.85	1993	2007	−3.59	1979	1990	2007	−4.11	1979	1986	1990	2007	**−4.88**	1979	1986	1990	1996	2008
U.S.A.	−1.83	−2.46	2007	−3.25	1990	2007	−3.94	1979	1990	2007	*−4.39*	1977	1982	1990	2007	**−5.66**	1977	1982	1990	1997	2008

This table presents the results of the unit root inference, when testing H_0: $b_0 = 0$ in (6) by way of the pseudo t-ratio. DF-GLS means the statistic proposed in Elliot et al. (1996) for the specification that does not include breaks in the trend. By contrast, CKP$_i$ (i = 1,…,5) reflects the Carrión-i-Silvestre et al. (2009) statistic for 1–5 breaks in the trend function, respectively. Bold and italic values mean rejection at the 5% and 10% significance levels, respectively.

Table 3. Testing for unit roots in energy consumption

	DF-GLS	CKP_1	TB_1	CKP_2	TB_1	TB_2	CKP_3	TB_1	TB_2	TB_3	CKP_4	TB_1	TB_2	TB_3	TB_4	CKP_5	TB_1	TB_2	TB_3	TB_4	TB_5
Australia	−0.75	−2.98	2005	**−4.44**	1981	2006	**−4.66**	1981	1997	2005	**−4.82**	1980	1993	1998	2005	**−6.84**	1979	1983	1990	1998	2008
Austria	−1.51	−3.03	2005	*−3.56*	1980	2005	−3.52	1980	2005	2011	**−4.12**	1980	2000	2004	2013	−4.25	1980	1994	2004	2009	2013
Belgium	−1.39	−2.29	1993	**−4.38**	1981	2000	**−4.74**	1980	1995	2008	**−5.49**	1980	1995	2008	2012	**−6.57**	1977	1983	1995	2008	2012
Brazil	−1.97	−2.48	2006	−2.85	2000	2009	−3.36	1988	2000	2009	−3.85	1979	1989	2000	2009	**−5.29**	1980	1989	2000	2008	2012
Canada	−1.78	**−4.11**	2000	**−4.46**	1980	2000	**−4.66**	1977	1983	2008	**−6.35**	1980	1989	1996	2008	**−6.06**	1978	1983	1989	2000	2008
Chile	−1.56	−2.12	1990	**−4.20**	1984	1996	**−5.10**	1985	1996	2007	**−5.50**	1985	1996	2005	2010	**−6.27**	1981	1987	1996	2005	2010
China	−1.40	−1.35	2002	−2.02	2001	2005	−3.41	2000	2007	2011	−4.01	1980	1999	2003	2010	**−4.87**	1980	1996	2001	2005	2010
Denmark	−2.24	**−3.89**	1993	**−5.14**	1980	1993	**−5.10**	1980	1995	2001	*−4.21*	1984	1990	1995	2002	**−6.33**	1977	1984	1990	1995	2002
Finland	−0.83	**−4.41**	2004	**−3.68**	2004	2009	**−4.43**	1979	2004	2009	**−5.14**	1980	1994	2004	2009	**−5.90**	1980	1994	2001	2005	2009
France	−0.63	**−3.90**	2004	**−4.50**	1983	2000	**−6.57**	1980	1990	2004	**−6.43**	1980	1990	2001	2008	**−7.03**	1977	1982	1990	2001	2008
Germany	−1.67	**−3.40**	1979	**−4.80**	1979	1990	**−5.21**	1979	1990	2008	**−6.07**	1978	1982	1990	2008	**−6.11**	1978	1982	1990	2008	2012
Greece	−1.66	−1.88	2007	−2.56	1978	2007	−2.98	1978	2007	2013	*−4.28*	1978	1986	2007	2013	**−5.41**	1978	1982	1990	2007	2013
India	−1.28	−2.14	2000	−3.30	1981	2000	−3.20	1981	2000	2013	**−4.43**	1981	2000	2006	2013	**−5.42**	1980	1987	2000	2006	2013
Ireland	−1.60	−2.03	1996	−2.63	1995	2008	−3.40	1984	1997	2008	−3.88	1981	1995	2001	2008	**−5.61**	1981	1995	2001	2008	2012
Israel	−0.69	−3.08	1996	*−3.77*	1984	1994	*−4.02*	1984	1996	2012	−4.10	1984	1996	2008	2012	**−5.07**	1984	1989	1996	2008	2012
Italy	−1.23	−2.33	2006	*−3.74*	1981	2005	**−4.43**	1981	2002	2012	**−5.04**	1981	1997	2004	2012	**−5.82**	1981	1992	1998	2004	2013
Japan	−0.80	−2.56	2005	*−3.73*	1983	1997	**−4.91**	1983	1997	2008	**−4.57**	1983	1997	2005	2009	**−5.60**	1979	1983	1997	2005	2009
Luxembourg	−1.87	−2.56	2001	−3.00	1983	2001	*−4.10*	1983	1994	2003	**−4.65**	1983	1988	1994	2003	**−5.19**	1983	1987	1991	1995	2003
Mexico	−1.39	−2.58	1982	**−4.14**	1982	2003	*−4.09*	1981	1985	2003	**−4.78**	1981	1985	2003	2011	**−5.34**	1980	1985	1994	2003	2011
Netherlands	−1.67	−2.23	2009	−3.22	1979	2009	−3.40	1978	1982	2009	−3.82	1978	1982	2005	2009	**−4.23**	1978	1982	2005	2009	2013
New Zealand	−1.32	−2.42	2002	−3.16	1993	2004	**−4.45**	1981	1993	2004	**−6.27**	1981	1996	2002	2009	**−5.98**	1981	1989	2000	2004	2013
Norway	−0.93	**−5.26**	2000	**−6.15**	1990	2000	−2.64	2000	2005	2011	**−6.13**	1990	1995	1999	2011	**−6.15**	1990	1995	2000	2005	2011
Portugal	−1.17	−2.66	1994	*−3.52*	1997	2010	**−4.35**	1985	1997	2012	**−5.14**	1987	1997	2008	2012	**−5.42**	1987	1991	1997	2008	2012
South Korea	−1.49	−2.46	1991	−3.02	1985	1997	−3.49	1985	1997	2011	*−4.36*	1981	1987	1997	2012	**−5.15**	1981	1987	1997	2007	2011
South Africa	−1.60	−2.95	1988	−3.13	1980	2007	−2.95	1980	2002	2007	**−6.46**	1980	1988	2002	2007	**−6.25**	1980	1988	2000	2004	2008
Spain	−1.08	−1.75	2007	−2.37	1984	2007	−3.76	1993	2003	2008	**−4.56**	1993	2003	2007	2012	**−5.62**	1984	1992	2001	2007	2011
Sweden	−0.90	**−3.97**	1977	**−4.78**	1977	1983	**−5.54**	1977	1983	1996	**−5.32**	1977	1983	1996	2000	**−6.56**	1977	1984	1996	2000	2008
Switzerland	−0.94	**−3.90**	2001	**−5.17**	1988	1996	**−5.94**	1988	1996	2013	**−6.26**	1988	2001	2005	2013	**−8.32**	1981	1988	1994	2001	2013
Turkey	−1.76	*−3.18*	2000	**−4.26**	1978	2000	**−4.59**	1978	2000	2007	*−4.37*	1978	1993	2000	2007	*−4.66*	1978	1993	2000	2007	2012
U.K.	−1.08	**−3.40**	2005	**−4.14**	1979	2005	**−5.71**	1977	1984	2005	**−6.47**	1977	1984	2004	2009	**−7.23**	1977	1984	1995	2004	2009
U.S.A.	−1.59	−2.00	1986	−3.46	1979	2000	−3.86	1979	2000	2007	**−6.29**	1979	1983	1995	2007	**−6.86**	1979	1983	1987	2000	2007

This table presents the results of the unit root inference, when testing $H_0: b_0 = 0$ in (6) by way of the pseudo t-ratio. DF-GLS means the statistic proposed in Elliot et al. (1996) for the specification that does not include breaks in the trend. By contrast, CKP_i (i = 1,…,5) reflects the Carrión-i-Silvestre et al. (2009) statistic for 1–5 breaks in the trend function, respectively. Bold and italic values mean rejection at the 5% and 10% significance levels, respectively.

Table 4. Stability of the 3E relationship

	UD_{max}	WD_{max}	α_o	β_o	γ_o	TB_1	α_1	β_1	γ_1	TB_2	α_2	β_2	γ_2	TB_3	α_3	β_3	γ_3	TB_4	α_4	β_4	γ_4	SBIC
Australia	145	145	20.26	−3.43	3.31	1979	−2.56	0.29	0.44	2006	10.00	−1.00	0.69									−7.84
			(7.26)	(0.99)	(0.59)		(0.17)	(0.07)	(0.16)		(3.23)	(0.20)	(0.27)									
Austria	120	120	3.33	−0.51	0.79	1989	−2.17	−0.41	1.69													−6.35
			(0.54)	(0.16)	(0.38)		(0.75)	(0.08)	(0.20)													
Belgium	613	715	−2.84	−0.12	1.25	1982	0.90	0.25	−0.22	1989	4.14	−0.59	0.84	2008	18.68	−1.99	0.89					−7.17
			(1.09)	(0.10)	(0.06)		(2.69)	(0.40)	(0.33)		(0.43)	(0.10)	(0.14)		(4.19)	(0.34)	(0.20)					
Brazil	511	511	−1.41	−0.52	1.67	1982	−3.65	−0.04	1.21	2002	−4.01	−0.13	1.47	2011	−11.16	0.05	2.82					−6.77
			(0.21)	(0.08)	(0.18)		(0.18)	(0.02)	(0.08)		(0.50)	(0.04)	(0.22)		(0.99)	(0.04)	(0.30)					
Canada	188	353	1.33	−0.41	0.99	1984	−4.74	0.15	1.00	2007	5.58	−1.03	1.39									−7.03
			(2.21)	(0.25)	(0.38)		(0.99)	(0.10)	(0.31)		(0.82)	(0.11)	(0.28)									
Chile	143	143	0.72	−1.15	2.82	1982	7.60	−2.09	3.08	1990	−4.37	−0.02	1.39	2000	−6.02	0.55	0.51	2010	0.84	−0.19	0.56	−5.74
			(0.94)	(0.16)	(0.39)		(2.24)	(0.40)	(0.34)		(4.47)	(0.81)	(0.72)		(0.52)	(0.12)	(0.32)		(1.41)	(0.15)	(0.40)	
China	285	440	−2.76	0.01	1.09	1988	−2.44	0.02	0.97	1998	−2.66	0.11	0.83	2010	−1.17	−0.36	1.42					−7.46
			(0.10)	(0.04)	(0.04)		(0.31)	(0.07)	(0.21)		(0.07)	(0.02)	(0.05)		(2.73)	(0.29)	(1.19)					
Denmark	234	272	−2.54	0.02	0.94	1984	−3.68	−0.12	1.48	1992	1.37	−0.49	1.24	2009	10.15	−1.45	1.60					−7.02
			(1.00)	(0.08)	(0.05)		(2.82)	(0.26)	(0.14)		(0.86)	(0.06)	(0.06)		(6.34)	(0.51)	(0.18)					
Finland	98	118	−5.13	0.51	0.47	1980	−0.69	−1.84	4.11	1987	−8.63	0.38	1.31	1997	−7.26	−0.08	1.91	2010	−13.69	−0.14	3.22	−6.03
			(2.26)	(0.32)	(0.22)		(2.95)	(0.61)	(0.67)		(1.62)	(0.13)	(0.13)		(1.25)	(0.09)	(0.18)		(4.16)	(0.33)	(0.19)	
France	425	571	3.95	−1.43	2.56	1981	5.30	0.67	−2.05	1990	0.32	−0.55	1.43	2009	−34.57	2.22	2.50					−7.02
			(2.05)	(0.41)	(0.47)		(1.98)	(0.28)	(0.27)		(0.93)	(0.07)	(0.08)		(5.82)	(0.42)	(0.27)					
Germany	564	759	1.07	−0.44	1.15	1989	0.82	−0.55	1.42	2005	−7.04	0.38	1.04	2011	10.96	−1.17	0.76					−8.56
			(0.38)	(0.04)	(0.10)		(0.99)	(0.05)	(0.12)		(0.92)	(0.08)	(0.09)		(0.34)	(0.02)	(0.06)					
Greece	352	402	−12.40	1.41	0.04	1981	−4.60	0.25	0.90	1989	−2.92	0.13	0.80	2005	−3.67	−0.17	1.59					−6.63
			(0.70)	(0.08)	(0.09)		(3.96)	(0.45)	(0.13)		(0.48)	(0.11)	(0.13)		(1.04)	(0.22)	(0.29)					
India	169	261	−2.42	−0.01	0.91	1981	−2.74	−0.01	1.09	1993	−4.11	0.60	0.17	2001	−2.79	−0.13	1.39					−7.71
			(0.08)	(0.07)	(0.18)		(0.23)	(0.04)	(0.02)		(0.36)	(0.13)	(0.17)		(0.04)	(0.02)	(0.06)					
Ireland	311	583	−3.37	0.13)	0.90	1986	−1.57	−0.09	0.97	2006	−1.56	−0.24	1.29									−7.84
			(0.30)	(0.04)	(0.07)		(0.12)	(0.05)	(0.11)		(0.36)	(0.03)	(0.03)									
Israel	223	345	2.77	−0.06	−0.13	1981	−2.44	0.46	0.03	2003	−6.63	0.05	1.69									−6.22
			(0.38)	(0.16)	(0.29)		(0.23)	(0.07)	(0.11)		(1.77)	(0.09)	(0.22)									
Italy	165	192	−0.51	−1.17	3.02	1979	−2.34	−0.03	0.96	1989	−0.23	−0.28	1.08	2008	1.55	−0.95	2.16					−7.71
			(0.60)	(0.24)	(0.46)		(0.45)	(0.05)	(0.14)		(0.54)	(0.12)	(0.17)		(8.20)	(0.98)	(0.47)					
Japan	301	425	−0.92	−0.10	0.82	1983	−0.86	−0.70	2.09	1989	−1.51	0.22	0.27	2005	−17.65	1.99	−0.26	2011	7.69	−0.93	0.92	−7.32
			(1.41)	(0.06)	(0.18)		(0.23)	(0.11)	(0.20)		(1.29)	(0.19)	(0.16)		(3.70)	(0.46)	(0.31)		(6.03)	(0.40)	(0.45)	
Luxembourg	510	956	−2.77	0.05	0.94	1989	0.82	−0.63	1.64	2000	−0.53	−0.26	1.12									−7.35

			(0.79)	(0.06)	(0.03)		(0.83)	(0.05)	(0.06)		(0.45)	(0.05)	(0.04)									
Mexico	230	268	−5.89	0.55	0.60	1989	−4.47	0.40	0.54	2009	−3.57	−0.05	1.32									−6.33
			(1.59)	(0.25)	(0.20)		(0.81)	(0.14)	(0.12)		(1.53)	(0.07)	(0.22)									
Netherlands	150	280	−8.65	0.68	0.76	1981	−0.15	−0.02	0.50	1988	−0.33	−0.26	1.02	2004	−3.62	0.02	1.05	2010	−1.55	0.14	0.43	−6.92
			(3.52)	(0.28)	(0.21)		(7.17)	(1.15)	(0.91)		(0.78)	(0.04)	(0.19)		(2.45)	(0.17)	(0.18)		(2.36)	(0.18)	(0.10)	
New Zealand	74	139	5.74	−0.15	−0.50	1980	−13.29	0.78	1.43	1993	−7.49	0.61	0.62	2008	9.03	−0.60	−0.14					−5.62
			(19.29)	(1.04)	(2.26)		(2.69)	(0.29)	(0.14)		(1.03)	(0.05)	(0.19)		(2.03)	(0.31)	(0.57)					
Norway	340	381	−7.31	0.97	−0.17	1979	−1.47	0.31	0.03	1995	1.89	0.09	−0.11	2008	31.41	−2.53	−0.06					−6.63
			(2.65)	(0.34)	(0.24)		(0.61)	(0.11)	(0.16)		(0.39)	(0.03)	(0.03)		(2.40)	(0.16)	(0.17)					
Portugal	276	371	−9.36	1.04	0.15	1989	−3.20	0.26	0.53	1998	11.91	−1.00	−0.02	2007	−19.92	2.50	−0.77					−5.63
			(2.30)	(0.31)	(0.19)		(4.68)	(0.68)	(0.46)		(4.15)	(0.42)	(0.85)		(2.74)	(0.35)	(0.35)					
Korea, Rep.	218	250	−1.94	−0.03	0.91	1985	−4.67	0.58	0.27	1996	−0.70	−0.70	1.87									−6.87
			(0.22)	(0.05)	(0.05)		(1.40)	(0.25)	(0.20)		(0.31)	(0.17)	(0.27)									
South Africa	139	238	−3.41	0.21	0.90	1979	−1.45	−0.05	0.90	1987	7.75	−0.76	0.12	1993	−3.87	0.06	1.21	2009	−2.23	−0.01	0.98	−7.20
			(0.74)	(0.02)	(0.16)		(0.53)	(0.04)	(0.06)		(1.09)	(0.07)	(0.13)		(0.51)	(0.03)	(0.15)		(0.43)	(0.05)	(0.18)	
Spain	418	646	−8.87	0.88	0.45	1982	5.61	−1.08	1.50	1988	−9.11	0.79	0.66	1995	−9.89	1.25	−0.19	2005	−10.02	0.22	1.96	−6.63
			(5.31)	(0.60)	(0.19)		(1.41)	(0.69)	(1.33)		(0.42)	(0.05)	(0.05)		(1.30)	(0.24)	(0.25)		(1.55)	(0.19)	(0.16)	
Sweden	1,780	2,395	−13.32	1.64	−0.23	1979	19.20	−2.52	1.62	1986	5.27	−0.33	0.02	2005	0.34	−0.59	1.43	2011	14.39	−1.47	0.58	−6.22
			(16.82)	(1.79)	(0.32)		(0.18)	(0.02)	(0.02)		(1.44)	(0.06)	(0.19)		(3.86)	(0.44)	(0.29)		(2.92)	(0.20)	(0.20)	
Switzerland	43	60	3.33	−0.22	0.19	2010	43.67	−3.87	0.29													−6.24
			(0.76)	(0.07)	(0.11)		(14.28)	(1.15)	(0.29)													
Turkey	31	49	−10.34	1.21	0.19	1988	−3.54	0.26	0.63	2006	−0.39	−0.14	0.76									−6.87
			(1.90)	(0.28)	(0.16)		(0.66)	(0.12)	(0.12)		(0.58)	(0.13)	(0.18)									
U.K.	136	136	−1.71	−0.19	1.17	1995	−3.77	−0.05	1.29	2011	41.88	−3.77	0.03									−7.54
			(0.60)	(0.03)	(0.09)		(0.79)	(0.06)	(0.05)		(3.82)	(0.29)	(0.19)									
U.S.A.	115	216	−3.12	−0.02	1.09	2008	0.87	−0.55	1.39													−9.08
			(0.20)	(0.01)	(0.04)		(1.36)	(0.06)	(0.17)													

This table presents the results of the estimation of model (8), with TB_i, and i = 1,.5 being the estimated periods. The number of breaks was selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} test the no structural break null hypothesis, which was rejected in all of the reported cases when using the appropriate critical values. The values in parentheses are the corresponding robust estimated standard errors of the estimators. The last column includes the value of the SBIC criterion for each one of the estimated models.

The case of Germany presents the results when the breaks are selected by way of the minimization of the SBIC criterion, given that the sequential procedure of Bai and Perron (1998) cannot find any break. This is also in spite of the fact that the UD_{max} and WD_{max} statistics clearly reject the null hypothesis of non-structural breaks.

Figure 1: Estimated CO_2/GDP elasticities before and after the Great Recession

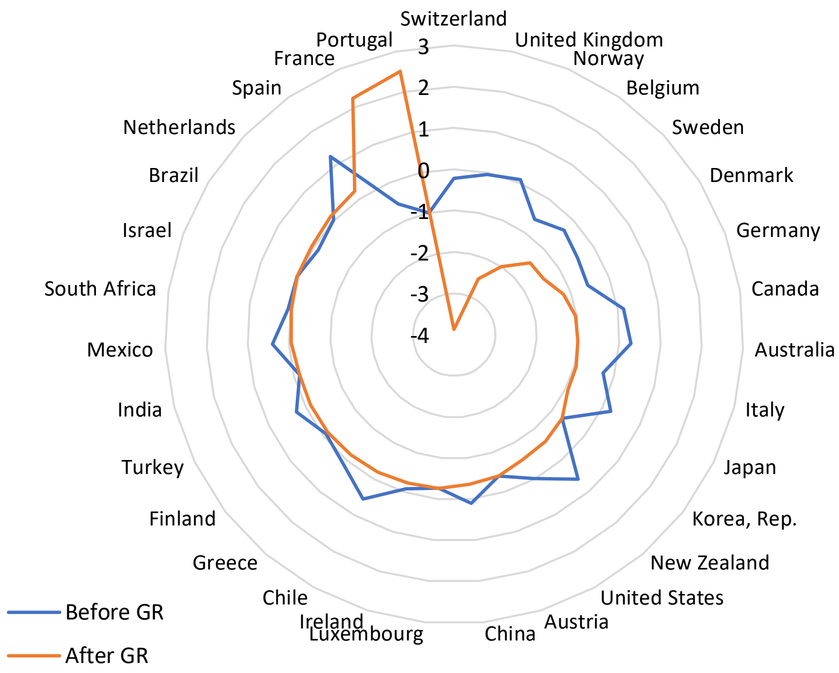
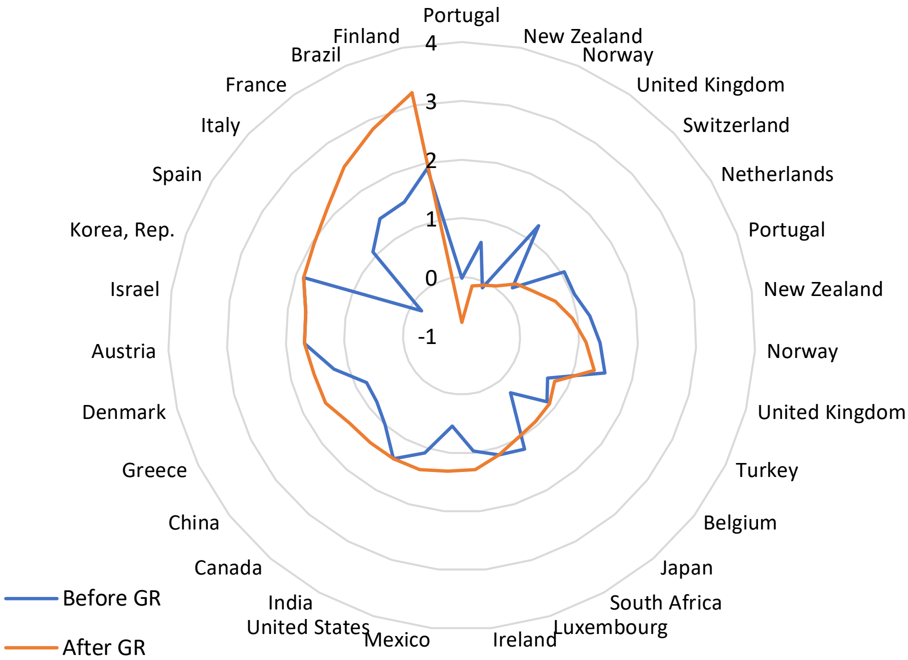


Figure 2: Estimated CO_2/energy consumption elasticities before and after the Great Recession



Appendix A

Table A1. Average growth rates

	CO_2pc		GDPpc		ECpc		CO_2/GDP		CO_2/EC	
	BGR	AGR	BGR	AGR	BGR	AGR	BGR	AGR	BGR	AGR
Australia	1.3%	−1.2%	1.9%	0.9%	1.0%	−0.6%	−0.6%	−2.2%	0.3%	−0.6%
Austria	0.5%	−1.3%	2.2%	0.4%	0.9%	−0.6%	−1.6%	−1.7%	−0.4%	−0.7%
Belgium	−0.6%	−2.5%	1.9%	0.4%	0.8%	−1.5%	−2.5%	−2.9%	−1.3%	−1.0%
Brazil	1.0%	1.0%	6.2%	0.1%	2.2%	1.3%	−4.9%	0.9%	−1.2%	−0.3%
Canada	0.2%	−1.2%	1.7%	0.6%	0.5%	−0.3%	−1.5%	−1.8%	−0.3%	−0.9%
Chile	1.7%	0.8%	3.1%	1.9%	2.8%	1.3%	−1.4%	−1.1%	−1.1%	−0.5%
China	4.8%	2.6%	8.9%	10.9%	5.1%	3.4%	−3.8%	−7.5%	−0.2%	−0.7%
Denmark	−0.3%	−4.3%	1.9%	0.4%	0.1%	−2.0%	−2.1%	−4.7%	−0.4%	−2.3%
Finland	0.7%	−2.6%	2.5%	−0.2%	1.5%	−1.1%	−1.7%	−2.4%	−0.8%	−1.5%
France	−1.2%	−2.0%	1.7%	0.5%	0.6%	−1.2%	−2.8%	−2.6%	−1.7%	−0.8%
Germany	−0.8%	−1.3%	2.0%	1.2%	−0.1%	−0.5%	−2.7%	−2.4%	−0.7%	−0.8%
Greece	2.9%	−3.7%	2.0%	−2.3%	2.0%	−1.9%	0.9%	−1.4%	0.9%	−1.8%
India	3.5%	4.3%	5.7%	7.2%	3.4%	4.1%	−2.1%	−2.8%	0.1%	0.2%
Ireland	1.2%	−2.7%	4.1%	4.1%	1.4%	−1.1%	−2.8%	−6.6%	−0.2%	−1.6%
Israel	1.3%	−2.5%	5.1%	3.5%	2.9%	−0.8%	−3.6%	−5.8%	−1.6%	−1.7%
Italy	0.7%	−3.5%	1.9%	−0.6%	0.6%	−1.5%	−1.2%	−2.9%	0.1%	−1.9%
Japan	0.6%	−0.5%	2.3%	0.8%	0.8%	−1.2%	−1.7%	−1.3%	−0.2%	0.7%
Luxembourg	−1.6%	−3.7%	3.0%	−0.1%	−1.0%	−2.6%	−4.5%	−3.6%	−0.7%	−1.1%
Mexico	1.5%	−1.6%	1.3%	0.8%	1.9%	−0.5%	0.2%	−2.4%	−0.4%	−1.1%
Netherlands	−0.3%	−1.3%	1.9%	0.4%	0.3%	−1.3%	−2.2%	−1.7%	−0.7%	0.0%
New Zealand	1.0%	−2.1%	1.2%	1.1%	0.9%	0.1%	−0.2%	−3.2%	0.1%	−2.3%
Norway	1.1%	−1.3%	2.7%	0.1%	1.1%	−0.9%	−1.6%	−1.4%	−0.1%	−0.4%
Portugal	2.8%	−1.4%	2.2%	0.4%	2.7%	1.0%	0.6%	−1.7%	0.1%	−2.3%
South Korea	4.8%	2.2%	6.6%	2.6%	6.5%	1.8%	−1.7%	−0.4%	−1.7%	0.3%
South Africa	0.8%	−2.0%	4.3%	1.0%	0.9%	−1.6%	−3.4%	−3.0%	−0.1%	−0.4%
Spain	1.6%	−2.4%	2.0%	0.3%	2.2%	−1.0%	−0.5%	−2.6%	−0.6%	−1.4%
Sweden	−1.6%	−3.1%	1.9%	0.8%	0.5%	−0.7%	−3.4%	−3.8%	−2.0%	−2.4%
Switzerland	−0.4%	−3.0%	1.0%	0.4%	0.3%	−1.8%	−1.4%	−3.3%	−0.7%	−1.2%
Turkey	3.2%	1.7%	2.5%	3.5%	3.5%	2.7%	0.7%	−1.8%	−0.3%	−1.0%
U.K.	−0.6%	−4.3%	2.2%	0.5%	−0.2%	−2.0%	−2.7%	−4.8%	−0.4%	−2.3%
U.S.A.	−0.2%	−1.6%	2.1%	1.0%	−0.1%	−0.6%	−2.2%	−2.6%	−0.1%	−1.1%

The table presents the average growth rates of the variables per capita CO_2 emissions (CO_2), per capita gross domestic product (GDP), energy consumption (EC), the ratio CO_2/GDP, and the ratio CO_2/EC.

BGR = Before Great Recession (1974–2007), AGR = After Great Recession (2008–2018).

Table A2. Estimation of the EKC model under the presence of structural breaks

	α_o	β_o	γ_o	δ_o	TB1	α_1	β_1	γ_1	δ_1	TB2	α_2	β_2	γ_2	δ_2	TB3	α_3	β_3	γ_3	δ_3	TB4	α_4	β_4	γ_4	δ_4	SBIC
Australia	409.9	−0.030	0.000	0.303	1979	−253.3	0.017	0.000	0.040	1986	26.7	−0.001	0.000	0.077	1993	−9.6	0.001	−0.000	0.011	2008	344.23	−0.01	0.00	0.01	−2.40
	(2.4)	(−2.5)	(2.33)	(4.74)		(−3.3)	(3.5)	(−3.5)	(1.3)		(0.3)	(−0.3)	(0.3)	(1.6)		(−2.0)	(3.8)	(−3.5)	(0.5)		(3.7)	(−3.5)	(3.4)	(0.4)	
Austria	6.4	0.000	0.000	0.042	1989	12.6	−0.001	0.000	0.114	2007	−256.5	0.011	−0.000	0.062											−1.95
	(6.5)	(−0.4)	(0.2)	(2.6)		(1.8)	(−2.4)	(2.2)	(4.8)		(−1.1)	(1.1)	(−1.1)	(3.9)											
Belgium	87.6	−0.007	0.000	0.099	1982	41.6	−0.002	0.000	0.004	1989	−91.7	0.006	0.000	0.038	1997	−21.5	0.001	−0.000	0.041	2008	−160.12	0.01	0.00	0.04	−2.13
	(2.1)	(−2.2)	(2.2)	(8.8)		(0.3)	(−0.2)	(0.2))	(0.0)		(−1.4)	(1.5)	(−1.6)	(1.7)		(−1.1)	(1.3)	(−1.5)	(1.7)		(−0.7)	(0.7)	(0.8)	(6.1)	
Brazil	−0.1	−0.000	−0.000	0.069	1982	−1.1	0.002	0.000	−0.001	1988	0.8	0.000	0.000	0.025	1997	1.7	0.000	0.000	0.004	2011	−2.93	−0.00	0.00	0.11	−5.71
	(−0.5)	(−0.3)	(−0.7)	(4.8)		(−1.1)	(1.7)	(1.6)	(−0.0)		(1.4)	(−1.2)	(1.4)	(2.7)		(3.5)	(−1.7)	(4.1)	(0.3)		(−1.7)	(−1.0)	(1.0)	(8.2)	
Canada	220.9	−0.015	0.000	0.088	1983	−16.6	0.001	0.000	0.023	2008	−96.2	0.004	0.000	0.034											−1.34
	(3.3)	(−3.2)	(3.2)	(4.4)		(−2.3)	(2.2)	(−2.2)	(1.5)		(−0.5)	(0.5)	(0.6)	(1.1)											
Chile	2.7	−0.002	0.000	0.194	1982	6.8	−0.003	0.000	0.090	1990	5.3	−0.002	0.000	0.067	1999	11.8	−0.002	0.000	0.032	2006	−24.65	0.00	0.00	0.05	−3.54
	(1.0)	(−1.9)	(1.5)	(5.1)		(0.9)	(−1.2)	(0.9)	(0.9)		(1.8)	(−2.4)	(2.2)	(2.3)		(0.7)	(−0.7)	(0.7)	(0.4)		(−2.5)	(2.5)	(−2.5)	(3.0)	
China	0.0	−0.002	0.000	0.095	1988	0.4	0.003	0.000	0.045	1997	0.5	−0.001	0.000	0.098	2008	−5.3	0.000	−0.000	0.152						−5.88
	(0.1)	(−0.6)	(0.7)	(14.9)		(1.5)	(2.0)	(−1.7)	(2.3)		(7.1)	(−3.9)	(4.3)	(13.6)		(−4.0)	(0.8)	(−3.7)	(4.9)						
Denmark	99.8	−0.006	0.000	0.098	1981	−40.0	0.002	0.000	0.108	1989	20.7	−0.001	0.000	0.084	2008	244.0	−0.008	0.000	0.078						−2.75
	(2.3)	(−2.3)	(2.3)	(11.4)		(−1.6)	(1.5)	(−1.6)	(12.7)		(4.6)	(−4.2)	(3.5)	(23.0)		(2.6)	(−2.6)	(2.5)	(6.6)						
Finland	130.1	−0.011	0.000	0.050	1980	102.0	−0.008	0.000	0.152	1987	−58.2	0.003	−0.000	0.071	1997	−25.9	0.001	0.000	0.099						−1.30
	(1.23)	(−1.2)	(1.3)	(2.0))		(1.2)	(−1.4)	(1.3)	(3.0)		(−1.2)	(1.1)	(−1.1)	(5.6)		(−2.3)	(1.2)	(−1.3)	(21.9)						
France	2.9	−0.001	0.000	0.128	1980	147.1	−0.009	0.000	−0.002	1991	−8.9	0.001	−0.000	0.052	1997	36.4	−0.002	0.000	0.055	2007	191.69	−0.01	0.00	0.06	−3.25
	(0.1)	(−0.3)	(0.2)	(7.1)		(12.9)	(−12.1)	(11.9)	(−0.2)		(−0.1)	(1.0)	(−1.0)	(2.5)		(1.0)	(−0.8)	(0.8)	(1.4)		(2.6)	(−2.6)	(2.6)	(8.1)	
Germany	−63.2	0.005	−0.000	0.115	1979	34.6	−0.002	0.000	0.087	1989	−45.1	0.002	−0.000	0.125	1995	−62.8	0.003	−0.000	0.120	2009	−86.20	0.00	−0.00	0.04	−4.01
	(−4.6)	(4.7)	(−4.9)	(9.2)		(3.7)	(−3.5)	(3.2)	(11.6)		(−0.8)	(0.6)	(−0.6)	(9.8)		(−2.7)	(2.7)	(−2.9)	(6.0)		(−7.9)	(8.3)	(−8.4)	(6.1)	
Greece	−18.1	0.002	−0.000	−0.006	1980	67.9	−0.007	0.000	0.073	1989	−2.2	0.000	−0.000	0.051	2005	8.9	−0.001	0.000	0.087	2011	−1477.7	0.13	−0.00	0.15	−2.74
	(−0.6)	(0.6)	(−0.5)	(−0.3)		(0.8)	(−0.8)	(0.8)	(7.5)		(−0.5)	(0.7)	(−0.6)	(1.8)		(0.5)	(−0.6)	(0.7)	(3.0)		(−3.1)	(3.1)	(−3.1)	(8.4)	
India	0.12	−0.001	0.000	0.063	1981	−0.7	0.004	0.000	0.080	1993	0.2	0.000	0.000	0.072	2007	−0.1	−0.001	0.000	0.113						−7.37
	(0.5)	(−0.3)	(0.3)	(2.0)		(−1.2)	(1.1)	(−1.1)	(18.3)		(1.9)	(−1.0)	(1.0)	(5.3)		(−1.1)	(−3.1)	(2.0)	(14.6)						
Ireland	−29.1	0.003	−0.000	0.099	1979	−6.9	0.001	0.000	0.073	1992	1.1	0.000	−0.000	0.036	1999	5.6	−0.000	−0.000	0.053	2006	−5.46	0.00	−0.00	0.08	−3.11
	(−0.8)	(0.8)	(−0.8)	(4.4))		(−2.1)	(2.1)	(−1.8)	(6.9)		(0.2)	(1.5)	(−1.0)	(0.9)		(0.4)	(−0.1)	(−0.0)	(3.9)		(−1.7)	(1.2)	(−1.5)	(23.7)	
Israel	3.3	0.001	−0.000	−0.007	1981	5.5	0.000	0.000	0.007	1992	7.0	0.000	0.000	−0.017	2003	−9.1	0.001	−0.000	0.075						−1.96
	(0.5)	(0.5)	(−0.5)	(−0.1)		(4.4)	(−0.6)	(1.5)	(0.9)		(1.1)	(0.3)	(0.0)	(−0.7)		(−3.4)	(5.2)	(−5.2)	(4.1)						
Italy	−0.5	0.000	−0.000	0.052	1989	199.4	−0.013	0.000	0.075	1995	39.0	−0.002	0.000	0.045	2003	49.8	−0.003	0.000	0.113						−3.73
	(−0.2)	(0.7)	(−0.6)	(6.8)		(1.8)	(−1.8)	(1.8)	(2.1)		(0.7)	(−0.6)	(0.7)	(1.4)		(2.5)	(−2.8)	(2.8)	(13.9)						
Japan	5.7	−0.000	0.000	0.043	1981	21.3	−0.001	0.000	0.075	1989	37.8	−0.002	0.000	0.047	2010	−339.5	0.014	−0.000	0.124						−2.94
	(0.5)	(−0.2)	(0.2)	(2.4)		(3.1)	(−3.2)	(3.0)	(2.9)		(2.6)	(−2.3)	(2.2)	(6.6)		(−3.7)	(3.8)	(−3.8)	(3.2)						
Luxembourg	−19.8	0.001	−0.000	0.078	1989	26.9	−0.001	0.000	0.124	2000	33.5	−0.001	0.000	0.065	2010	−137.2	0.003	−0.000	0.079						−1.11
	(−3.1)	(3.3)	(−3.2)	(39.4)		(1.9)	(−2.8)	(2.2)	(26.1)		(0.7)	(−0.6)	(0.6)	(13.5)		(−0.2)	(0.2)	(−0.2)	(9.0)						
Mexico	−6.8	0.002	−0.000	0.096	1982	−466.8	0.122	0.000	0.141	1989	−3.4	0.001	−0.000	0.044	2009	−4.1	0.001	−0.000	0.084						−4.29
	(−1.8)	(1.7)	(−1.9)	(3.2)			(−5.1)	(5.1)	(4.1)		(−0.7)	(0.9)	(−0.7)	(3.8)		(−0.1)	(0.1)	(−0.1)	(2.3)						
Netherlands	249.5	−0.017	0.000	0.050	1981	−119.3	0.008	0.000	0.001	1988	−4.9	0.000	−0.000	0.045	2004	60.9	−0.002	0.000	0.033						−2.40
	(2.7)	(−2.8)	(2.8)	(6.2)		(−2.4)	(2.5)	(−2.5)	(0.0)		(−0.8)	(1.1)	(−1.4)	(3.5)		(1.1)	(−1.1)	(1.1)	(7.6)						
New Zealand	251.1	−0.022	0.000	0.014	1979	122.8	−0.010	0.000	0.036	1987	67.3	−0.005	0.000	−0.012	1997	−50.6	0.004	−0.000	−0.026	2008	−80.89	0.00	−0.00	0.02	−1.74
	(1.8)	(−1.8)	(1.8)	(0.2)		(1.8)	(−1.9)	(1.9)	(0.8)		(1.5)	(−1.3)	(1.4)	(−0.7)		(−2.5)	(2.5)	(−2.4)	(−0.9)		(−1.1)	(1.2)	(−1.2)	(0.5)	

Norway	−54.3	0.003	−0.000	0.007	1981	−9.8	0.001	0.000	0.001	1990	−12.3	0.001	−0.000	−0.004	2008	124.4	−0.002	0.000	−0.001						−2.58
	(−5.6)	(6.2)	(−6.2)	(1.3)		(−0.6)	(0.9)	(−0.8)	(0.3)		(−3.8)	(6.7)	(−6.0)	(−1.7)		(0.3)	(−0.3)	(0.2)	(−0.1)						
Portugal	0.2	0.000	0.000	0.007	1987	−41.8	0.005	−0.000	0.021	1997	−206.7	0.020	−0.000	−0.037	2008	−46.8	0.004	−0.000	−0.030						−2.63
	(0.0)	(0.1)	(0.1)	(0.3)		(−4.6)	(4.6)	(−4.1)	(1.0)		(−3.1)	(3.1)	(−3.1)	(−0.7)		(−0.7)	(0.7)	(−0.6)	(−1.8)						
Korea, Rep.	−0.3	0.001	−0.000	0.055	1992	4.1	−0.001	0.000	0.065																−3.10
	(−0.6)	(2.9)	(−3.4)	(2.6)		(5.6)	(−3.5)	(3.6)	(6.1)																
South Africa	−2.0	0.003	−0.000	0.080	1982	4.0	0.005	−0.000	0.010	1993	−4.2	0.000	−0.000	0.125											−2.89
	(−1.3)	(2.5)	(−2.2)	(6.7)		(2.2)	(4.4)	(−5.5)	(0.6)		(−4.5)	(3.0)	(−3.2)	(12.2)											
Spain	−8.8	0.001	−0.000	0.040	1980	70.7	−0.006	0.000	−0.073	1988	31.0	−0.003	0.000	0.032	1995	−13.4	0.001	−0.000	0.029	2007	−21.78	0.00	−0.00	0.08	−2.74
	(−0.0)	(0.0)	(−0.0)	(1.5)		(2.5)	(−2.5)	(2.4)	(−0.7)		(0.3)	(−0.3)	(0.4)	(0.8)		(−1.9)	(1.9)	(−2.0)	(1.2)		(−0.6)	(0.4)	(−0.4)	(8.6)	
Sweden	−778.0	0.053	−0.000	−0.001	1982	11.3	−0.000	0.000	0.008	2004	−192.0	0.007	−0.000	0.022	2011	6.3	−0.000	−0.000	0.012						−1.57
	(−3.8)	(3.9)	(−4.0)	(−0.2)		(2.2)	(−1.1)	(0.9)	(1.7)		(−0.9)	(0.9)	(−0.9)	(2.5)		(0.0)	(−0.0)	(−0.0)	(0.5)						
Switzerland	−62.6	0.003	−0.000	0.001	1980	−5.5	0.000	−0.000	0.009	2010	376.0	−0.010	0.000	0.015											−2.49
	(−0.7)	(0.89)	(−0.8)	(0.1)		(−1.3)	(2.2)	(−2.2)	(0.4)		(0.4)	(−0.4)	(0.4)	(0.7)											
Turkey	−2.1	0.001	−0.000	0.029	2006	4.3	−0.000	0.000	0.045																−4.71
	(−3.2)	(3.5)	(−3.3)	(2.3)		(2.1)	(−1.5)	(1.3)	(3.1)																
U.K.	82.3	−0.008	0.000	0.042	1979	16.8	−0.001	0.000	0.079	1992	10.15	−0.000	0.000	0.053	2008	−186.6	0.009	−0.000	0.072						−3.86
	(3.4)	(−3.3)	(3.3)	(3.3)		(4.3)	(−5.0)	(4.8)	(7.4)		(4.7)	(−2.9)	(2.6)	(6.3)		(−3.8)	(4.0)	(−4.2)	(4.6)						
U.S.A.	56.7	−0.004	0.000	0.072	1983	−84.1	0.005	−0.000	0.088	1989	19.51	−0.001	0.000	0.052	2001	−72.4	0.003	−0.000	0.093						−3.17
	(2.5)	(−2.5)	(2.6)	(25.6)		(−1.5)	(1.5)	(−1.5)	(3.7)		(2.1)	(−1.3)	(1.4)	(3.8)		(−5.4)	(4.9)	(−5.0)	(32.8)						

This table presents the results of the estimation of model (10), with TB_i, and i = 1,.5 being the estimated periods. The number of breaks was selected by using the sequential procedure described in Bai and Perron (1998). UD_{max} and WD_{max} tests are not included to save space, but they allow the rejection of the null hypothesis of non-structural breaks in all of the reported cases when using the appropriate critical values. The values in parentheses are the corresponding t-ratios for testing the single significance of the parameters of the model. The last column includes the value of the SBIC criterion for each one of the estimated models.