A multiscale reassessment of the Environmental Kuznets Curve for energy and CO2 emissions

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ABSTRACT

This paper investigates the environmental Kuznets' curve hypothesis for total primary energy supply and CO2 from fuel combustion over the period 1971-2015.

Our analysis has two distinguishing features. Firstly, it adopts a robustness approach by (a) using both parametric and semi-parametric methods, and (b) analysing different geographical scales. Secondly, it strictly adheres to the EKC narrative by (a) not using control variables and (b) taking Energy and CO2 in absolute rather than in per capita terms, which is consistent with the fact that "Nature cares" about absolute pressures.

We show how evidence for EKC changes depending on the model specification, the sample, and the used variables. Hence, this paper contributes to explaining why the literature on the EKC gives mixed results.

The multiscale perspective and some theoretical considerations, however, tell how to perform the analysis appropriately. Thus, we can affirm that, both for CO2 and Energy, the fragile evidence of EKC that was emerging at the end of the last century has vanished with the new wave of globalization. There is only evidence of decreasing elasticities for very-high income countries.

Interestingly, the great recession might have produced structural reductions in TPES and CO2 in the affected countries. Finally, the case of Germany, which shows EKC patterns, indicates that active energy policies can reduce energy and CO2 without harming the economy.

Keywords: Environmental Kuznets Curve, Energy, CO2 emissions, semi-parametric estimates, robustness, Sustainable development

1 Introduction

As is well known, the Environmental Kuznets Curve (EKC) is a hypothesized inverted-U relationship between environmental quality and income. The EKC debate started in the 1990s and is still very much alive. From 2010 to 2017 the number of articles in the SCOPUS database that mention the term "Environmental Kuznets curve" in their abstract and/or title grew at an average yearly rate of 19%, as compared with the articles mentioning "GDP", "prices", and "oligopoly" which grew at rates of about 7.8%, 5.3% and 2.2% respectively.

Empirical research on the EKC gave mixed results (Luzzati, 2015). This is explained by its multifaceted nature. For instance, differences are observed between global and local pressures, the latter being more easily the object of regulation (Roca et al., 2001). However, mixed evidence is also due to the variety of research strategies. Actually, criticism has often been levelled at the scant attention paid to robustness (e.g. Stern, 2004). Several facets of robustness have been investigated, for instance by applying non-parametric methods (e.g. Bertinelli and Strobl, 2005; Azomahou et al., 2006), by comparing alternative datasets and different parametric specifications (Galeotti et al., 2006), and by testing for time series stationarity (Galeotti et al., 2009).

The research presented here is a robustness exercise that involves both comparisons between parametric and non-parametric methods, and the validation of cross-country findings by looking at other levels of analysis (i.e. the world as a single unit and individual countries). This should mitigate the risk of statistical artefacts arising from pooling heterogeneous country patterns. Two other distinctive features of the research are that 1) the dependent variables are taken in absolute rather than per capita terms, and 2) the model does not include control variables. As discussed in greater detail in Luzzati and Orsini (2009), both these features follow from the original EKC narrative, according to which "higher levels of development [… will] result in levelling off and gradual decline of environmental degradation" (Panayotou, 1993, 1). In other words, the research question is "Will continued economic growth bring ever greater harm to the earth's environment? Or do increases in income and wealth sow the seeds for the amelioration of ecological problems?" (Grossman and Krueger, 1995, p. 353). It is self-evident that 'environmental degradation' or 'ecological problems' cannot be proxied by per capita indicators. We need indicators in extensive terms because 'Nature' is affected by total human pressure, and not per capita. The appropriateness of investigating a reduced form in which per capita income is taken as the only explanatory variable (Azomahou et al. 2006, p. 1348) also comes from the EKC original issue. The issue is the relationship between income and environmental degradation and not the anthropogenic drivers of the environmental pressures or states, which would entail modelling the structural linkages explicitly.

In the present work, the above described research strategy is applied respectively to total primary energy supply (TPES) and to carbon dioxide emissions from fuel combustion (CO2). Our analysis covers more than one hundred countries for the time span 1971-2015.

On the contrary, the recent literature on CO2- and Energy-EKC has mainly focused on groups of countries, pooled either by the level of income and development or by geographic proximity. Zaman et al. (2016), Beck and Joshi (2015), and Kearsley and Riddel (2010) compared OECD and non-OECD countries. Nabaee et al. (2015) distinguished between groups of countries belonging or not to the G7. Some studies were specifically devoted to Middle-East and North-Africa countries (Farhani et al., 2014; Arouri et al., 2012) and the Asian continent (Heidari et al., 2015; Apergis and Ozturk, 2015; Saboori and Sulaiman, 2013). In other works, the research on EKC is developed on a wider number of groups of countries across all the continents (for instance, Zaman et al., 2016 for East Asia and Pacific and European Union; Kais and Sami, 2016 for Europe, Latin America, Caribbean, Middle-East, North Africa and Sub-Saharan Africa). Analyses dedicated to single countries have been performed in some other cases, for instance Sinha and Shahbaz (2018) for India, Shahbaz et al. (2017) for the U.S., Bento and Moutinho (2016) for Italy, Pilatowska et al. (2015) for Poland, Shahbaz et al. (2015) for Portugal, Shahbaz et al. (2014) for Tunisia and Iwata et al. (2010) for France.

“CO2 emissions” was the most used dependent variable in the models estimated for the detection of the EKC (e.g. Zaman et al. (2016), Kais and Sami (2016), Saidi and Hammami (2015), Apergis and Ozturk (2015), Pilatowska et al. (2015), Farhani et al. (2014), Arouri et al. (2012) and Iwata et al. (2010)). In other cases the analysis was enriched with energy as dependent variable. In particular, Bento and Moutinho (2016) adopted non-renewable and renewable electricity production, Beck and Joshi (2015) used primary energy before transformation into other end-use fuels, while Heidari et al. (2015), Nabaee et al. (2015), and Saboori and Sulaiman (2013) used kg of oil equivalents per capita.

The results of the recent EKC literature are still mixed as in previous studies, mainly to differences in the setups. Specifically, an EKC for energy does not emerge according to Arouri et al. (2012), Kearsley and Riddel (2010) and Barra and Zotti (2017). Indeed, in the first two studies, the turning points for different countries lie on very heterogeneous ranges of values, while the latter showed that the evidence of an inverted U-shaped relationship disappears after taking into account the issue of (non-) stationarity of the time series. On the contrary, an EKC shape is supported for CO2 emissions by Sinha and Shahbaz (2018), Shahbaz et al. (2017), Zaman et al. (2016), Kais and Sami (2016), Apergis and Ozturk (2015), Pilatowska et al. (2015), Fahrani et al. (2014), Shahbaz et al. (2014), Saboori and Sulaiman (2013) and Iwata et al. (2010), and both for CO2 emissions and energy by Bento and Moutinho (2016) and Heidari et al. (2015). Finally, some works show differences in the results depending on the analysed units. In particular, according to Beck and Joshi (2015) an EKC is detected for African and Asian countries, while it is not for OECD countries. Differently, Nabaee et al. (2015) found an EKC for G7 countries and not for developing countries.

The number of recent works in which several countries are analysed is relatively low, while the time span usually does not exceed 25 years. Moreover, the main focus remains on CO2, while the importance of energy use in the overall relationship between humans and ecosystems remains neglected. On the contrary, the massive use of fossil fuel started with the Industrial Revolution is the primary cause of most human impacts, to the point that many scholars argue that it started a new geological phase, the Anthropocene (Crutzen, 2002; Steffen et al., 2011). The availability of energy has made possible huge increases in the material size of our economy and society (e.g. Smil, 2000; Krausman et al., 2009). Moreover, there is consolidated clear-cut evidence that chemical processes linked to fossil fuel use are at the basis of most forms of pollution[1].

In the present paper, the time span is significantly longer, from 1971 to 2015, covering the process of globalization starting with the WTO, the economic growth of emerging countries like China, the impressive technological change occurringin recent years, and the Great Recession (2007-2012). Finally, the analysis of the CO2-income relationship allows us also to assess re-carbonization due to the increasing consumption of carbon-rich fuels in emerging countries.

The paper is organized as follows. Section 2 discusses the dataset; section 3 presents the analyses of the world as a single unit; section 4 presents the panel data analysis; section 5 focuses on country patterns, while section 6 concludes.

2 Dataset

The International Energy Agency publishes online the dataset associated with the yearly report "CO2 Highlights" (IEA, 2017). Also BP makes a wide set of statistics on energy available[2]. BP and IEA use different protocol methods of accounting that are discussed in detail by Giampietro and Sorman (2012). They also show that energy accounting is subject to a series of epistemological problems because of the qualitative differences of the different energy forms. Those problems are not too relevant to the purposes of the present paper, mainly because our focus is on primary energy supply. This is empirically confirmed by the similarity of the two datasets (see the Appendix, 9.3). We chose to work with the IEA Series because the same IEA dataset contains also data on emissions and to make our results closely comparable with a previous paper of ours (Luzzati and Orsini, 2009). IEA (2017) contains the series for total energy supply (TPES), CO2 and other variables derived from other statistical sources, including GDP and population. The time-span is 1971-2015. Data cover 145 countries and several regional aggregates; however, the entire time span

[1] This is acknowledged also by national agencies and international institutions on the environment. See, e.g., https://www.epa.gov/environmental-topics/chemicals-and-toxics-topics
[2] https://www.bp.com/en/global/corporate/energy-economics.html

is covered only for 113 countries. By adding two aggregates, the countries belonging to former USSR and Yugoslavia respectively, we ended up with 115 units[3].

GDP is taken in purchasing power parity[4] due to the cross-country nature of the analysis. GDP is expressed in thousand dollars, TPES in PJoules and CO_2 emissions in million tons. Figure 1 gives a snapshot of the dataset. Per capita income is on the x-axis, while total TPES and CO_2 are reported on the y-axis. Values are in logarithm for a better visualization of the data. All figures and tables in the paper refer to the period 1971-2015 unless otherwise stated.

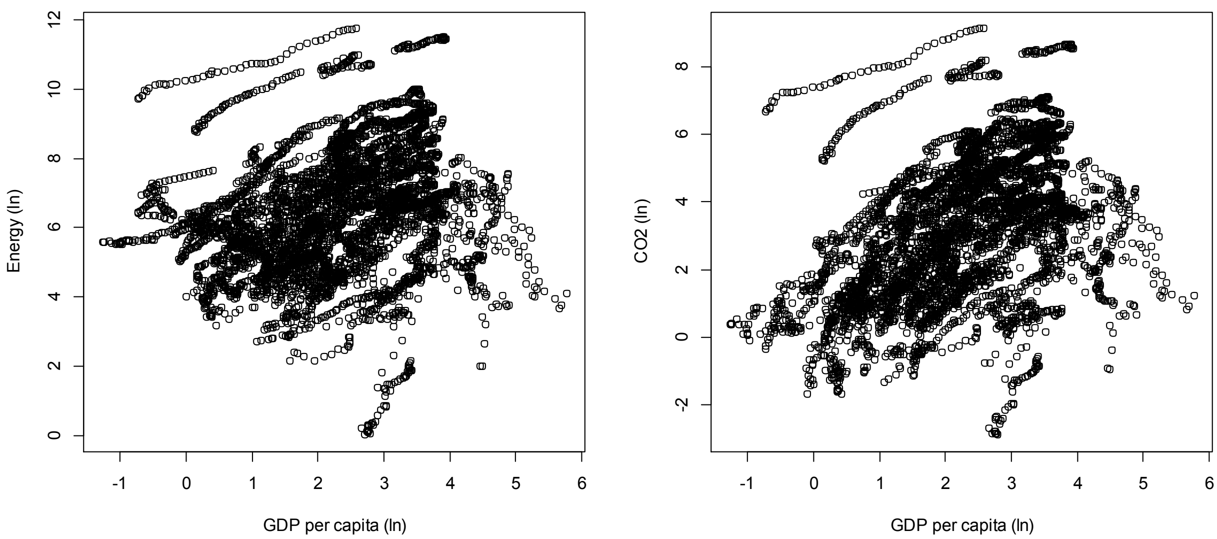

Figure 1. A snapshot of the dataset: Energy and CO2 vs. GDP p.c.

A first look at the series suggested the presence of potential outliers, that is, observations that differ markedly from others and for which regression residuals are large for any possible specification. In some instances, they are influential, that is, their inclusion in the dataset distorts the slope of the regression line, implying in some instances a different model specification (Draper and John, 1981, 21). The theoretical reason for excluding them is that they are so special that other countries cannot be thought to imitate their patterns. The issue of outliers is tricky since, as most

[3] 22 of the 30 countries for which the series are incomplete, refer to countries from the former Soviet Union (15) and the former Yugoslavia (7). Since disaggregated data are not available, we had to group them and prolong the time series of the former Soviet Union and former Yugoslavia.

[4] GDP in PPP terms is gross domestic product converted to international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as a U.S. dollar has in the United States. The IEA 2017 dataset refers to GDP in 2010 US$. For details see the technical notes of the IEA (2016, p. 141)

econometric textbooks highlight (e.g. Gujarati 2004, 540 ff.), including or excluding them can strongly affect the estimates/specification, also when using semi-parametric methods (Alimadad and Salibian-Barrera, 2011).

We made a preliminary selection of the outliers by visual inspection of the scatter plots and then we took a final decision with the help of a cluster analysis. While in econometric estimates data can be used in absolute terms since the different size of countries is accounted for by the intercepts, graphical comparisons require standardising values. To this end, in Figure 2 TPES is divided by the mean population over the period. Other rescaling can be used, as in Figure 11 where TPES is divided by the size of the areas with population density >5 inhabitants per square km for reasons that will be discussed below. Figure 2 shows that most of the potential outliers belong to very peculiar (and often small) countries, whose economy is mainly based on oil. The changes in oil price made their income disproportionately high in the 70s during the oil shocks[5] but later strongly decreased. In the meantime, their oil abundance allowed them to support strongly increasing patterns in energy consumption. Of course, some countries showed special patterns only for some years (e.g. Iran), and not all of them are rich in oil. This is the case of Iceland that has a peculiar pattern deriving from the strong growth in the use of its geothermal energy potential.

In any case, we decided to keep the number of excluded countries as low as possible. Following the cluster analysis (see Appendix, 9.4), we ended up with 10 outliers. Countries that look rather peculiar, like Libya or Luxembourg[6], but belong to clusters that include "normal" countries, have not been excluded. Table 1 shows maximum and mean values of TPES p.c., GDP p.c., and population of the excluded countries.

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[5] This is visualised in Figure 2 by the right parts of the series that indicate the 1970s values.

[6] Libya has several observations that look very special. Hence, we run all the regressions both including and excluding it. Including Libya causes a reduction in the turning points, if existing, and in the slope of the fitted curves. One strong peculiarity of Luxembourg is its high numbers of commuters, nearly half of the labour force (Schmitz et al., 2012).

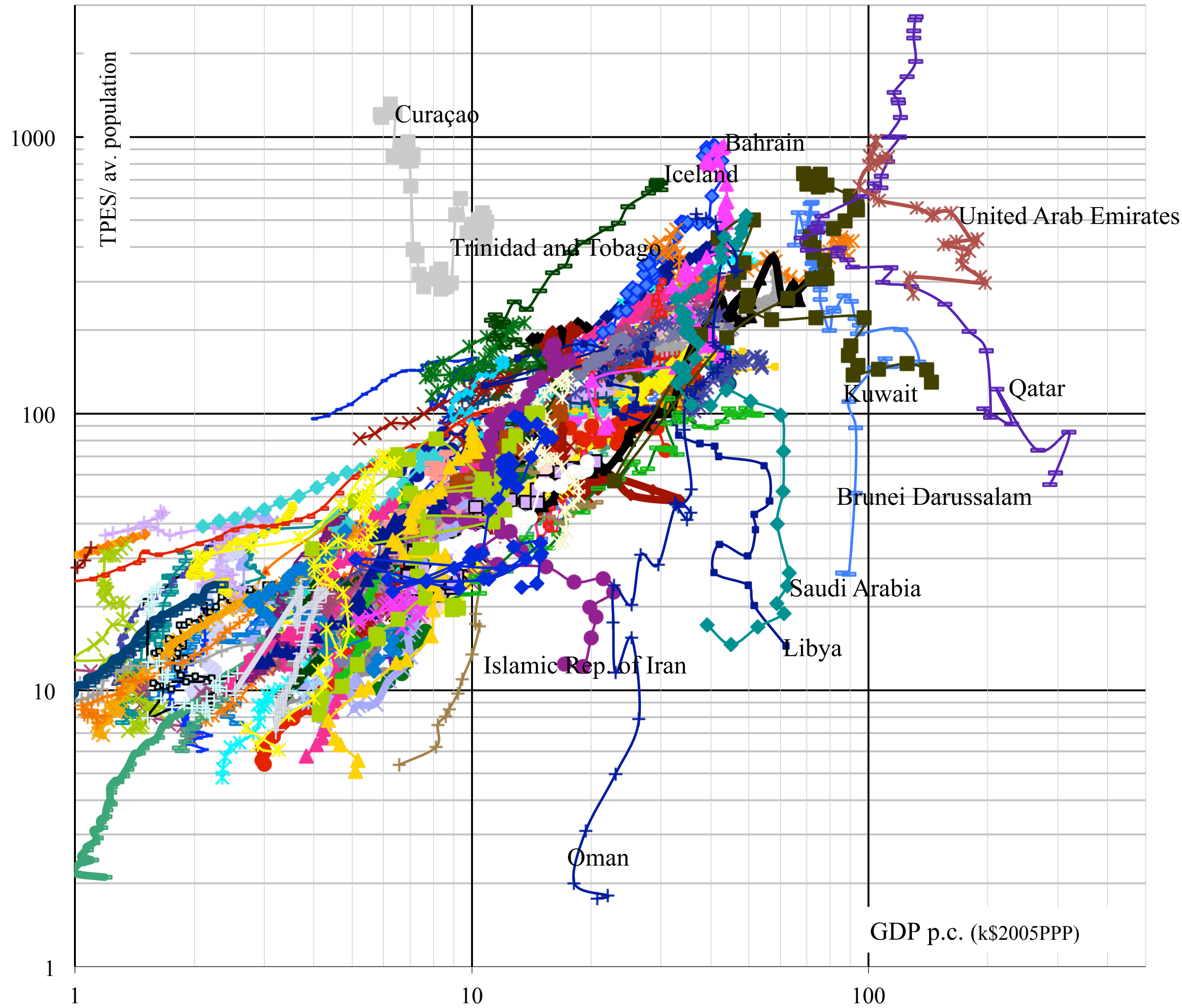

Figure 2. Looking for potential outliers: the relationship between GPD p.c. (k$2010PPP) and TPES/average population (GJoule)

Table 1: Statistics on energy, income, and population for the outliers

Country	Mean TPES p.c. (GJ)	Max TPES p.c. (GJ)	Mean GDP p.c. (k$2010 PPP)	Max GDP p.c. (k$2010 PPP)	Mean population (M)	Max population (M)
Bahrain	422	516	38.452	44.232	0.645	1.377
Brunei Darussalam	280	406	82.605	133.952	0.280	0.423
Curaçao	610	1518	8.539	10.916	0.190	0.229
Iceland	408	761	30.130	43.116	0.265	0.331
Kuwait	355	486	75.172	144.209	1.970	3.892
Oman	119	287	34.720	46.663	2.015	4.491
Qatar	664	953	134.664	320.113	0.700	2.235
Saudi Arabia	172	294	43.140	63.024	17.917	31.540
Trinidad and Tobago	302	633	18.089	29.963	1.204	1.360

3 The world patterns

As a first step, we investigated the EKC hypothesis by looking at the time series of the world as a single unit. This allows neutralising the effects of two countervailing forces - namely the transfer of cleaner technologies and "environmental displacement" (pollution haven hypothesis) between rich and poor countries - that have been considered crucial since the beginning of the EKC debate (Grossman and Krueger, 1991).

Figure 3 gives a first snapshot of the patterns of Energy, GDP per capita, Population and Energy efficiency. The increase in efficiency[7] has been more than offset by the growth of energy and population. As a consequence, the energy – GDP p.c. ratio remains higher than in the 1970s, despite the fact that some reductions have been occurring since the mid-1990s. Still, in 2014 energy was 2.5 times higher than half a century ago. CO2 emissions also grew relevantly since 1971 (2.25 times).

The trend of the CO2 content of energy is shown in Figure 4. After a prolonged period of decrease, it became stable in the 1990s and started to rise again at the beginning of the XXI century. Such an evolution reflects the changes in the energy mix that occurred during the period and that can be summarised by Figure 5 and Figure 6. They show the trends of CO2 emissions from fuel combustion by type of fuel, respectively in absolute terms (logarithmic scale) and as a percentage of total emissions. By comparing growth rates (the slope of the patterns in Figure 5) it emerges that emissions from gas increased more rapidly than those from oil and coal until the turn of the century. In the 1980s and 1990s the coal-CO2 emission share remained stable. Later, the "renaissance of coal" (e.g. Steckel et al., 2015), which has occurred in many fast-growing countries, particularly India and China, stopped the increase of the share of natural gas-CO2 emissions and the coal share started to increase again.

[7] GDP energy intensity has almost halved since 1971.

Figure 3: Changes in key indicators since 1971 (index numbers, 1971=100)

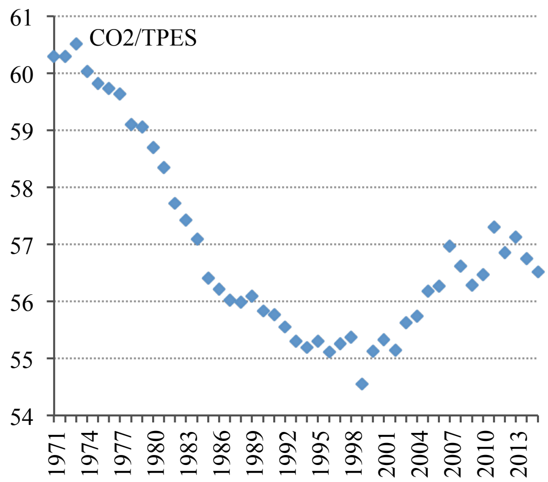

Figure 4: CO2 content of primary energy supply (t/TJ)

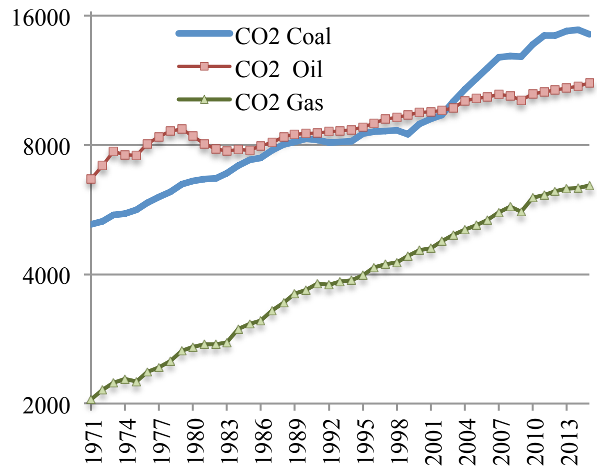

Figure 5: Trends of CO2 emissions by fuel (million tonnes, logarithmic scale)

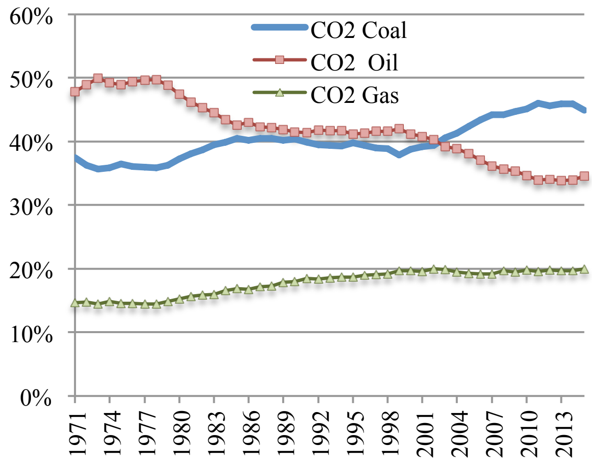

Figure 6: Trends of the fuel shares of CO2 emissions

The Kaya identity (Kaya, 1990) provides some suggestions about the drivers of change in CO2 emissions. Kaya identity is expressed as follows:

$$\text{CO2 emissions} = population \times \frac{GDP}{population} \times \frac{energy}{GDP} \times \frac{CO_2}{energy}$$

The contribution of each term to the annual change of world CO2 emissions is obtained by differencing the identity. For instance, the contribution of population to annual change was calculated multiplying (mid-point) population by the (mid-point) annual growth rate. The result is shown in Figure 7, where the length of each bar represents the part of the annual change of CO2 that is attributable to each term, while the horizontal grey dashes indicate the total annual change of

CO2. Bars below zero indicate reductions. By comparing the length of the different bars one notices that the growth of GDP per capita (the second term of the Kaya identity) was in most years the main driver of CO2 emission, stronger than the increase of emissions attributable to population growth, accounting from 280 to 380 Mtonnes of the annual change. One also notices that the reductions in CO2 attributable to improvements in the energy intensity of GDP (third term of the Kaya identity) were generally not enough to offset the increases due to other components.

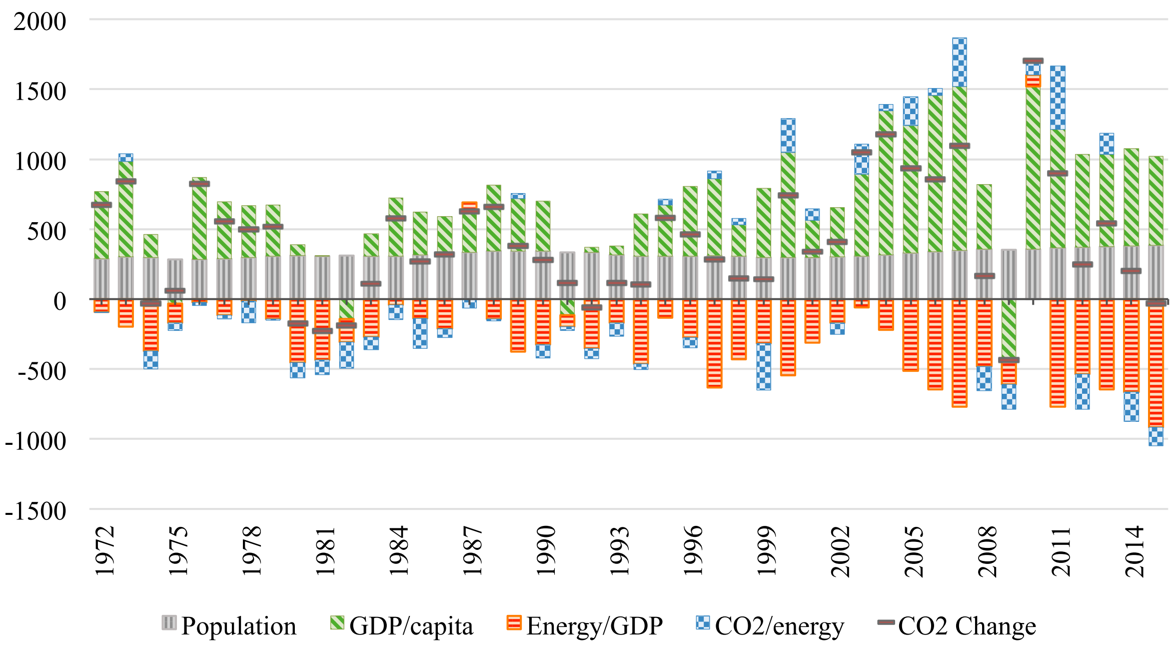

Figure 7. Kaya decomposition of CO_2 emissions annual change in the world (million tonnes)

When moving to the EKC-curve hypothesis, scatter plots (Figure 8) suggest that an inverted-U relationship at the world level has not emerged.

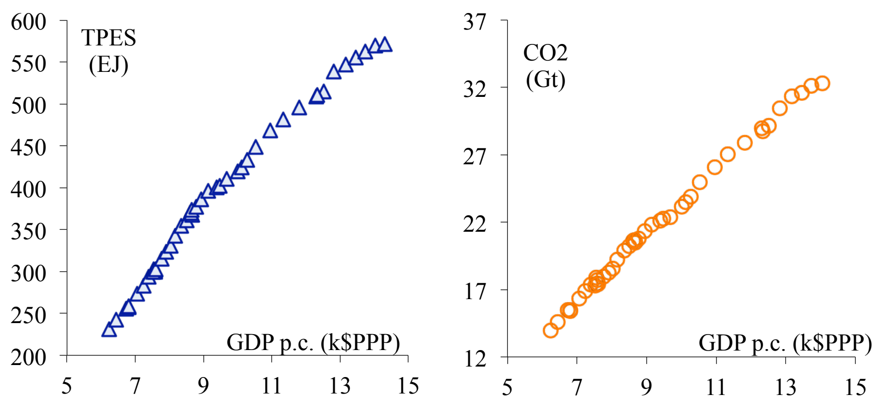

Figure 8. The Energy-GDP p.c. and CO2-GDP p.c. relationships at the world level

This is confirmed by the co-integration analysis[8], which is reported below. Since the augmented Dicky-Fueller test shows that all series are integrated of order 1, we looked for cointegrating relationships. Our results indicate that both CO2 and Energy showed a linear relationship with per capita income until 1990. After the break-up of communist regimes in Eastern Europe the relationship became moderately concave. Over all the period, the elasticities were bigger than one[9], that is, energy and CO2 emissions increased proportionally more than income.[10]

More specifically, the following are our best fit of the data (variables are in natural logarithms)[11, 12]:

$$Energy = 1.439\ GDPpc + (0.455\ GDPpc - 0.209 GDPpc^2)\ D9115 + + (9.716 - 0.012\ D7384 - 0.016\ D9802 - 0.014\ D0708) \quad \text{(eq. 1)}$$

n=45, ADF(3) regression: $\tau_{nc} = -5.19$, $p<0.01$ (MacKinnon, 1996)

$$CO2 = 1.265\ GDPpc + (0.245\ GDPpc - 0.114\ GDPpc^2)\ D9115 + + (7.204 + 0.024\ D7180 - 0.025\ D9902 - 0.010\ D0809) \quad \text{(eq. 2)}$$

n=45, ADF(1) regression $\tau_{nc} = -5.302$ $p<0.01$ (MacKinnon, 1996)

"*Dxxyy*" are intercept dummies going from year 'xx' to year 'yy'. For instance, *D9115* is equal to one for the period 1991-2015 and zero for the other years. Since all coefficients are significant, we can draw the following inference.

The intercepts became temporarily lower between 1998 and 2002, when the CO2 energy content reached its minimum, and around the great recession (2007-2009). Also, the oil shocks of the 1970s significantly reduced primary energy, while the opposite occurred for CO2 because of the abovementioned predominance of oil and coal in that period.

[8] We followed Engle and Granger two stage method.

[9] The lowest value of the estimated elasticities is in 2015. Their values are 1.410 and 1.247, respectively for TPES and CO2.

[10] When looking for the short run relationship, we got the following "error correction model" estimates:

$\Delta Energy(t) = -0.552\ ect(t-1) + 1.234\ \Delta GDPpc(t) - 0.357\ D9114\ \Delta GDPpc(t-1)$

t-statistic: *-2.33* *18.67* *-4.30*

n=44, Adj.R^2=0.77 *ect* : error correction term (residuals of the l.r. estimate)

$\Delta CO2(t) = -0.110\ ect(t-1) + 1.203\ \Delta GDPpc(t) - 0.284\ D9114\ \Delta GDPpc(t-1)$

t-statistic: *-0.46* *15.88* *-2.97*

n=44, Adj.R^2=0.77 *ect* : error correction term (residuals of the l.r. estimate)

[11] The number of lagged difference terms in the ADF equations (number in brackets) was determined by minimizing the Akaike and Schwarz criterion and by checking the Breusch-Godfrey Serial Correlation LM Test.

[12] A cubic form gives a worse fit of the data.

Only for the sake of completeness, we also analysed the relationships using per capita energy and per capita emissions as dependent variables (see the Appendix, 9.2). In this case evidence of an EKC emerges. However, because of population growth, this does not imply absolute reductions in human impacts.

4 A Panel data analysis

In this section, our time-series cross-section dataset will be exploited to understand to what extent the picture that emerges for the world at the aggregate level holds also when single countries, independently of their size, are simultaneously considered in the panel data analysis.

4.1 Methods

The panel data analysis followed a standard EKC regression model, that is,

$$Y_{it} = \alpha_i + g(GDP_{it}/\text{pop}) + \varepsilon_{it}$$

where Y is either $TPES$ or $CO2$ and α_i are country-specific intercepts capturing differences that are independent of income.

Natural logarithm values were used in our estimates. In order to choose the appropriate functional form, we started from a semi-parametric analysis that lets the fit be a non-linear function of the regressors.[13] The results suggested using a standard cubic specification for the parametric estimates, which also allows for more flexibility than the quadratic one (see, e.g., de Bruyn and Heintz, 1999, 659).

The Hausman test (Hausman, 1978) is inconclusive both for TPES and CO2.[14] In the paper we report the results for the random effect models, which, however, are very similar to those obtained with the fixed effect models. Autocorrelation was checked by using the test discussed by Wooldridge (2002, 282) for serial correlation (order 1) in the idiosyncratic errors of a panel-data model[15]. The null hypothesis of no first order autocorrelation has to be rejected. Furthermore, a likelihood ratio test

[13] We used the MGCV package for R (Wood, 2006).

[14] The reason is that the differences in the coefficients estimated by the two models are very small so that the matrix of the differences of the variances of the coefficients is not positive definite.

[15] Drukker (2003) presents simulation evidence that this test has good size and power properties in reasonable sample sizes.

detected the presence of heteroskedasticity[16]. Thus, we fitted our models using feasible generalized least squares (FGLS). Series stationarity was checked with the tests developed by Levin, Lin and Chu (2002) and by Im, Pesaran, and Shin (2003)[17].

4.2 Semi-parametric estimates

Figure 9 shows the semi-parametric estimate respectively for TPES and CO2 (natural logarithm scales). The overall relationship is non-linear. For very low and very high-income levels the steepness of the relation is lower. At the same time, due to the presence of few observations, the confidence bands are bigger and make inference uncertain. Actually, both for CO2 and TPES, only the lower confidence band gives evidence in favour of an EKC pattern. In any case, the slope becomes lower at income thresholds of approximately 10000$ and 27000$ (at values of respectively 2.3 and 3.2 in Figure 9).

At the same time, EKC patterns can be obtained with a different setup. A first possibility is to include outliers in the estimates. In this case turning points emerge at about 50000$ and 45000$ respectively for TPES and CO2. (Figure A1 in the Appendix, 9.1). A second one is to use TPES per capita and emissions per capita (see, e.g., the world estimates in the Appendix, 9.2); evidence in favour of the EKC emerges because the growth of population progressively decreases the values of the regressands. In the introduction, we discussed why energy and emissions have to be taken in absolute terms rather than per capita. Third, one can introduce a time trend in the regression, as shown in Figure A2 and A3 in the Appendix, 9.2. A time trend is often used to proxy technological progress, which is believed to contribute reducing environmental pressures and impacts. Unfortunately, in this case the time trend has a positive effect, that is, energy and CO2 emissions increase in time, which is in contrast with the idea of beneficial effects of technological

[16]Since iterated GLS with only heteroscedasticity produces maximum-likelihood parameter estimates, it is possible to conduct an LR test quite easily just by comparing the estimates from a model fitted with panel-level heteroscedasticity and a model without heteroscedasticity.

[17] Only according to the Levin-Lin-Chu test there is evidence for the series to be I(1) (TPES and CO2 modelled without constant, which is consistent with the findings for the world as a single unit). For a discussion on differences in panel unit root tests see, e.g., the survey by Caporale and Cerrato (2004)

advancements. For this theoretical reason, we did not add a time trend.[18]

A question that attracted our attention is to assess the effects of the new wave of globalization that started at the turn of the new century. Hence, we ran new estimates for the period 1971-2001[19], which are shown in Figure 10, and compared them with those for the whole period (Figure 9). Clearly, some evidence of EKC that was emerging before 2001 was lost due to globalization.[20]

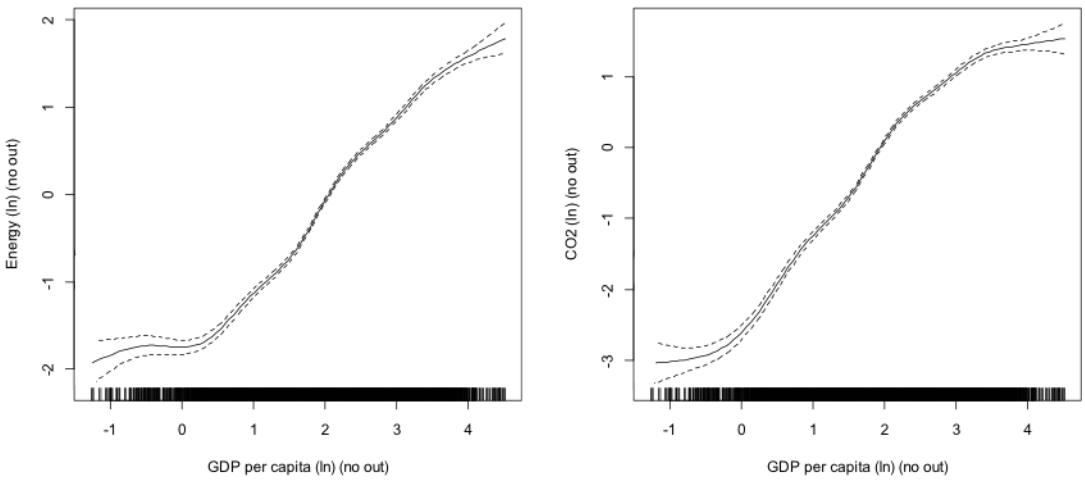

Figure 9: TPES vs. GDP p.c. and CO2 vs. GDP p.c.: semi-parametric regression without outlier, confidence band (5%) (variables in logarithms), 1971-2015.

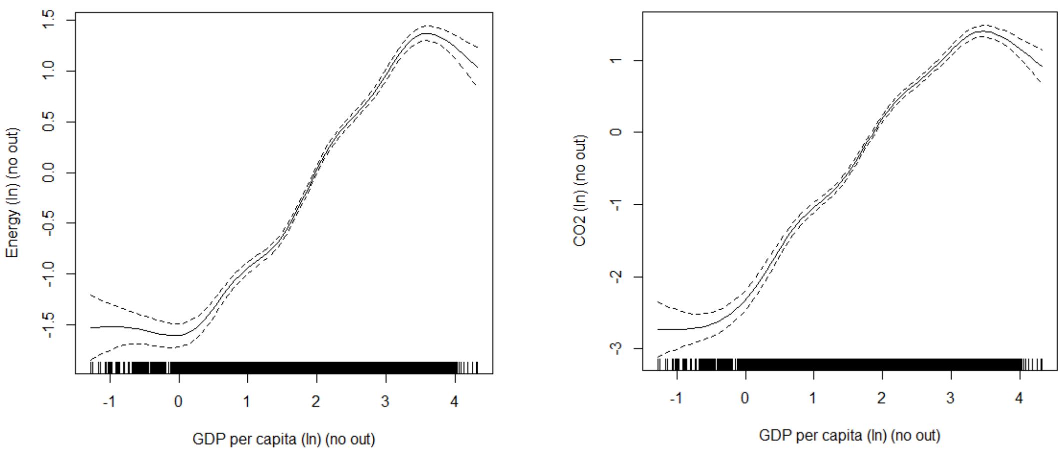

Figure 10: TPES vs. GDP p.c. and CO2 vs. GDP p.c.: semi-parametric regression without outlier, confidence band (5%) (variables in logarithms), 1971-2001.

[18] The stationarity tests also do not suggest the existence of deterministic trends.

[19] We took 2001 since at the end of that year China entered WTO.

[20] This is not in contrast with the findings of no EKC in Luzzati Orsini (2009) for two reasons. First, their time span was 1971-2004, second, they were stricter in excluding outliers, for instance Lybia. which is influential in the estimates.

4.3 Parametric estimates

4.3.1 All countries

The parametric estimations for all countries are shown in Table 2[21]. All the coefficients are strongly significant ($p<0.001$). A possible EKC pattern emerges for CO2 emissions, for which the calculated turning point is within the domain of the dataset, although at a rather high level of income, namely at $ 62224 (C.I. 95%: 15731 – 711949)[22]. The calculated turning point for TPES is $ 502863 (C.I. 95%: 45073 - 43.7 million). Consistently with the semi-parametric estimates, both the confidence bands at high-income levels are very large, and including outlier countries and/or time trend makes the relationship “more concave”, reducing the calculated turning points (not shown).

Table 2. Parametric estimates (FGLS)

Dep. variable		**ln *GDPpc***	**(ln *GDPpc*)^2**	**(ln *GDPpc*)^3**	**Turning points ($)** C.I. 95% ($)
ln TPES	Coeff.	0.077	0.172	-0.019	502 863
	Std. Err.	0.028	0.016	0.003	45 073 - 43.2 million
	p.	0.006	0.000	0.000	
ln CO2	Coeff.	0.892	0.120	-0.037	62 224
	Std. Err.	0.067	0.032	0.005	15 731-711 949
	p.	0.000	0.000	0.000	

4.3.2 Subsets of countries

Since the parametric specification constrains data into a specific shape, we also tested the EKC by pooling the countries in three groups according to their income level, namely, low, middle and high[23] and running the regressions with dummy variables for allowing different slope coefficients. The outcome is shown in Table 3. Again, the results are consistent with the semi-parametric ones. Low-income countries show a convex relationship for TPES, increasing from around $500, while a linear increasing one for CO2. Middle-income countries show an EKC pattern, although with turning points above the actual income range, particularly for TPES. For high-income countries an

[21] As mentioned above, random effects and fixed effects give similar results.

[22] These figures are affected by the estimates for 2015 that indicate a decrease in CO2 emissions at the world level. As customary, the most recent estimates are not yet fully reliable and subject to future revisions. When excluding 2015 the estimated T.P. is consistently higher

[23] Countries are divided into 3 groups of similar size. Since the aim was assessing the EKC hypothesis, countries were ranked according to their maximum income level. Then, we preliminarily divided them into three groups of 35 countries each. Finally, we checked whether countries with very similar maximum levels were assigned to different group and modified the group compositions accordingly.

EKC pattern is somehow more plausible only for TPES, for which the T.P. is at \$72660 while for CO2 the T.P. is at \$240285, outside the income range. However, the number of observations with very high levels of income makes the confidence bands too large to draw any reliable inference (see also Figure 9).

Table 3. Parametric estimates (FGLS): differences among group of countries

Estimations	**low** (34)			**middle** (35)			**high** (36)		
	Coeff.	*St. err.*	*p.*	*Coeff.*	*St. err.*	*p.*	*Coeff.*	*St. err.*	*p.*
ln TPES									
ln *GDPpc*	**-0.113**	0.033	0.001	-0.090	0.086	0.297	-0.272	0.149	0.067
$(\ln GDPpc)^2$	-0.025	0.023	0.253	**0.443**	0.063	0.000	**0.470**	0.084	0.000
$(\ln GDPpc)^3$	**0.054**	0.012	0.000	**-0.081**	0.013	0.000	**-0.068**	0.012	0.000
TPES turning points C.I. 95% (\$)	Relationship is increasing from 498 (434-581)			33 951 (4 194 – 919 122)			72 660 (0 – 15.547 million)		
ln CO2									
ln *GDPpc*	**0.489**	0.076	0.000	**1.728**	0.145	0.000	**1.865**	0.175	0.000
$(\ln GDPpc)^2$	-0.016	0.064	0.804	-0.088	0.098	0.368	**-0.259**	0.094	0.006
$(\ln GDPpc)^3$	0.033	0.026	0.207	**-0.036**	0.019	0.063	0.011	0.014	0.424
CO2 turning points C.I. 95% (\$)	none (2 730 - none)			26 454 (4 894 - none)			N-shaped: T.P.= 242 285 increasing from 34.210 million (4 879 - none)		
Data									
Range of GDP p.c. of obs. (\$)	280 – 8 997			481 – 24 799			2 703 – 91 310		
GDP p.c. mean (st. dev.) \$	3 135 (1 841)			9 917 (45 304)			28 942 (15 392)		

5 Single Countries

Consistency at different scales involves also a country level analysis (see, e.g. de Bruyn and Heintz (1999, pp. 671-672) and Stern et al. (1996, p. 1159)). Three main facts emerge from this analysis.

First, for most countries the relationship between TPES or CO2 and GDP p.c. is roughly linear and increasing, however with different slopes. Other countries show "non-linear" relationships due to wars or to their dependence on raw material exports. In particular, oil based economies show prolonged negative relationships (some examples are evident from Figure 2, others in Figure 11). The reason is that the abundance of energy sources made possible a marked growth in

TPES (and CO2 emissions) along the process of development, while income was very high in the 70s only because of high oil prices, which soon started to decline. Very few countries exhibit EKC patterns.

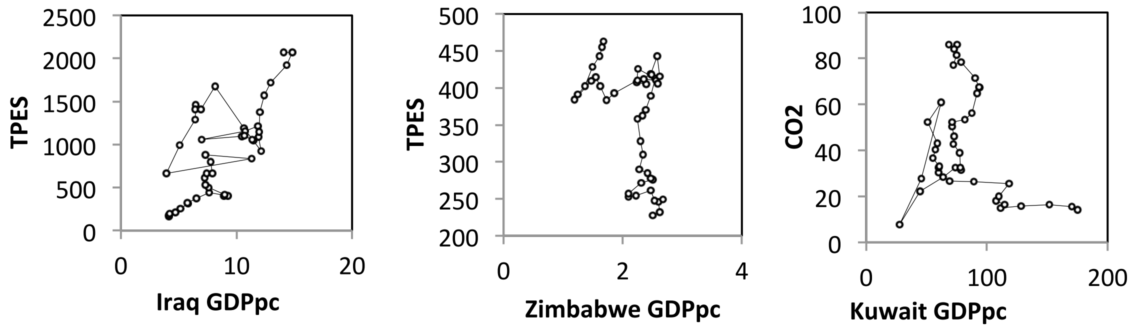

Figure 11. The relationship GPD p.c. - TPES or GDP p.c. - CO2: typical patterns of countries with war periods and natural resource based economies (TPES in PJoule, CO2 in Mtonnes GDP p.c. in k$PPP)

Second, in countries affected by the great recession TPES and CO2 emissions declined more than the decline in income and did not go back to pre-crisis level during the recovery (see Figures 12 and 13). Examples are Austria, Belgium, the Czech Republic, Denmark, Italy, Japan, Hungary, Spain, Sweden, Switzerland, the United Kingdom, and the USA. In other words, the crisis might have produced structural reductions in energy consumption and emissions. Only new data will tell whether some of those countries have actually entered EKC patterns.

As mentioned above, to facilitate comparisons the TPES values in Figure 13 are standardised by dividing them by the size of the areas with population density > 5 inhabitants per square km. We used this indicator for two reasons. The first is practical, namely its variability is rather high, which involves easier visual comparisons, the second is theoretical, that is, the more energy is used per unit of land, the higher can be considered its environmental impacts. In Figure 13, TPES is relative to the average population over the time span, as in Figure 2. Similar pictures can be drawn for CO2, which however shows more pattern variability due to strong differences in the mix of energy sources.

Third, Germany is the only country in our large panel that shows a clear EKC pattern. TPES declined after reunification due to the economic collapse of the Eastern regions, was then stable until the Great Recession, during which it started again to decline. At the same time, it has to be noted that TPES p.c. in Germany are still very high, both in terms of inhabited land and population. In the next section we will briefly discuss why this has occurred. Here it is sufficient to emphasise that the purpose of this section was only to check the evidence found for the world as a single unit and for the cross-country time-series analysis.

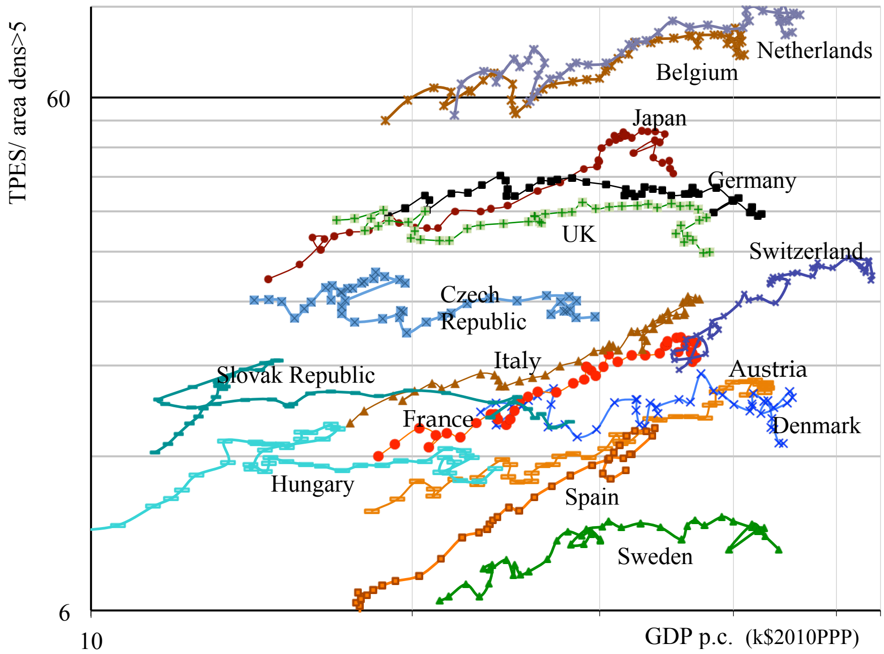

Figure 12. The relationship between GPD p.c. and TPES per inhabited areas with density > 5 inhab. per sq.km.: countries affected by the great recession

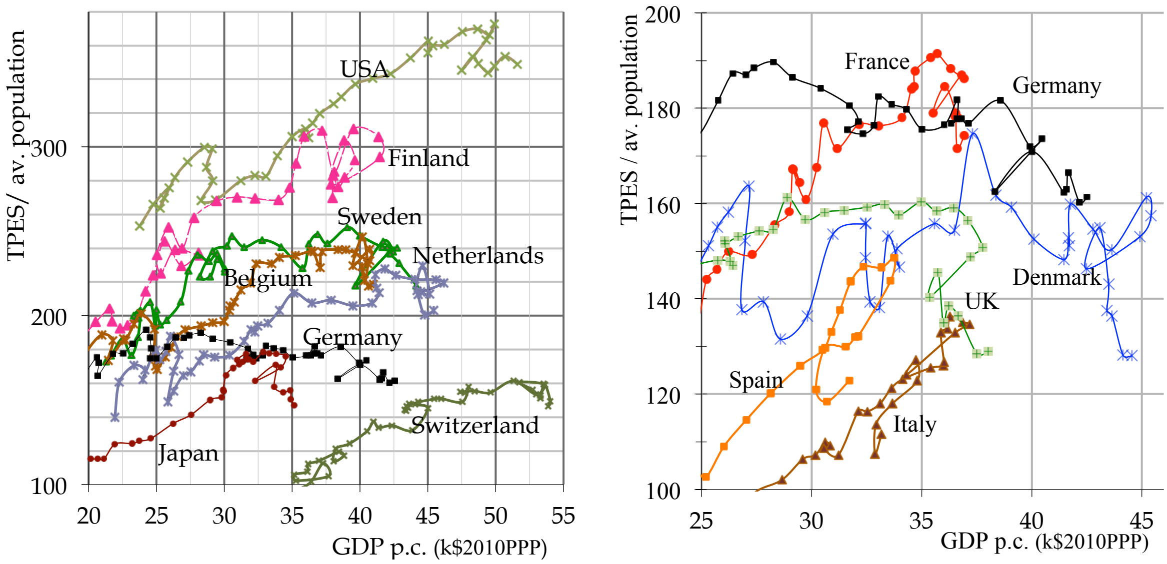

Figure 13. The relationship between GPD p.c. and TPES per average population: countries affected by the great recession

6 Conclusion

This piece of research adopted a robustness approach to empirically test the EKC hypothesis for CO_2 emissions and energy (TPES) over a long time-span, 1971-2015.

The length of the time span allows us to show that

(1) non-linear patterns emerged after the collapse of the USSR and the other communist countries in Eastern Europe,

(2) for the period 1971-2001, there was some weak evidence of EKC,

(3) such a piece of evidence does not hold for the whole period, 1971-2015, which includes the new wave of globalization, and the great recession,

(4) the energy consumption and CO_2 emissions decreased more than income during the great recession (2007-2012) for most of the affected countries,

(5) Germany is the only country in the dataset for which EKC patterns are clearly evident.

The robustness approach both helps reducing the perils of statistical artefacts involved in cross-country analysis, and contributes to explaining the mixed evidence that the EKC literature produces. Actually, changing the setup can produce support in favour of EKC patterns. We showed that this is the case when very special countries are included in the analysis, when energy and emissions are taken in per capita terms, when control variables are added to the analysis (time, in this case). Including influential outliers is simply wrong (see Section 2), while the other two routes are against the very nature of the EKC (see Section 1). Moreover, the estimated coefficient of time, which is usually interpreted as a proxy of technological advancement, would be positive rather than negative.

The above mentioned considerations, the several levels of analysis (the world, the whole panel of countries, three subsamples of it, and single countries), and the use of both semi parametric and parametric estimation techniques make us confident to affirm that, both for energy and CO_2 emissions, the evidence of EKC patterns is still missing. There is only evidence that both variables grew less proportionally than income p.c. for very high levels of it.

The policy implications of our findings are unambiguous. Income growth will not deliver reductions in energy use and CO2 emissions. Globalisation has not helped, as was reasonable to expect. Hence, we need strong and active policies for CO2 reductions. This holds also for energy because energy is the prime source of any human impact. For instance, water tables are irreversibly damaged by excessive drawdown, independently of the CO2 content of the type of primary energy that is used.

The patterns of Germany, where active energy policies have been implemented, suggest that energy consumption can be reduced without harming the economy. German Federal State policies were focused both on supply, working for a cleaner industrial sector production, and on demand, discouraging the consumption of CO2 at the individual level.

Regarding the first aspect, between 2005 and 2017 the first two phases of the EU Emission Trading System (EU ETS) policy were implemented, with the aim of limiting CO2 emissions of about 11000 large installations within the EU (European Commission, 2003) that cannot operate without a greenhouse gas emission permit. Each authorized plant must annually offset its emissions with quotas that can be bought and sold by individual operators, even though international exchanges are allowed. This programme has been showing promising results for Germany, especially in terms of technological change of the power generation (Rogge and Hoffmann, 2010) and of registered participants (more than 1600 as of 2010). Furthermore, Germany has also negotiated voluntary agreements with different industrial associations to determine specific emission reduction targets. Although not legally binding, this policy seems to have led to positive tangible results, with an up to 30% reduction in CO2 emissions of industries participating in the voluntary agreement compared to the others for the period 1995-2010 (Parlow and Hövelmann, 2016). On top on these policies, in 2010 Germany launched a comprehensive long-term programme (the, so called, *Energiewende*) aimed at reducing emissions, leveraging on renewable energy, energy efficiency and energy demand management (BMWi-BMU 2010, Pegels and Lütkenhorst 2014). Despite that it is not yet certain that targets will be actually reached (Buchan, 2012), the path tracked so far seems to be exceptional worldwide (AGORA, 2015), also thanks to the direct involvement of residents and of small entrepreneurs at the local level (Reis, 2017) and the strong political and social consensus developed during the last years around this policy which makes the possibility of a path reversion rather unlikely (Hake et al., 2015).

Concerning demand policies, Germany has pushed towards the reduction of individual transport by car, while making walking and cycling more attractive and favouring the diffusion of public transport (Buehler, 2014). This set of policies was based on the one hand on decisions taken at federal level, such as the increase in taxation on gasoline which generated a 0.03€ per year rise in gasoline price between 1998 and 2003 (Buehler and Pucher, 2012), and on the other hand, the implementation of activities at the local level, such as the introduction of a high number of cycle paths and pedestrian routes, as well as the extension and integration of the public service, which contributed to the share of car trip reduction in the last 25 years in the main German cities (Buehler et al., 2017).

To what extent Germany has achieved a 'true' absolute reduction or caused higher energy consumption and emissions in other countries is a matter for further research. In any case, policies can be envisioned which stimulate the economy and reduce energy consumption without relying on energy increases abroad, namely policies promoting handicraft, repairing services, and activities strongly based on local territories.

7 Acknowledgements

We gratefully acknowledge precious comments and suggestions on earlier versions of this paper received from participants in the Biennial International Workshop Advances in Energy Studies: "Energy futures, environment and well-being" (Naples, Italy, 25-28 September 2017), in the 12th Conference of the European Society for Ecological Economics: "Ecological Economics in Action: Building a Reflective and Inclusive Community" (Budapest, Hungary, 20-23 June 2017), Lisa Gianmoena and the three anonymous referees. Errors remain our own. The present research was partially funded by the PRA 2017 grant of the University of Pisa. The paper is the outcome of joint work of the authors. Nonetheless, Sections 2, 3, 5, 9.2-3 were written by Luzzati, Section 4 and 9.1 by Orsini, Sections 1 and 9.4 by Gucciardi. Section 6 is equally attributable to Luzzati and Gucciardi.

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9 Appendix

9.1 Supplementary tables and figures

Table A.1: Countries in the dataset grouped according to their per capita income

HIGH: 32 (43 - 9 outliers)	**MEDIUM**: 35 (36 - 1 outlier)	**LOW**: 36
Australia	Albania	Angola
Austria	Algeria	Bangladesh
*Bahrain	Argentina	Benin
Belgium	Brazil	Bolivia
*Brunei Darussalam	Bulgaria	Cameroon
Canada	Chile	Congo
Chinese Taipei	Colombia	Côte d'Ivoire
Cyprus	Costa Rica	Dem. Rep. of Congo
Czech Republic	Cuba	DPR of Korea
Denmark	*Curaçao	El Salvador
Finland	Dominican Republic	Ethiopia
France	Ecuador	Ghana
Gabon	Egypt	Guatemala
Germany	Former Soviet Union	Haiti
Gibraltar	Former Yugoslavia	Honduras
Greece	Hungary	India
Hong Kong, China	Indonesia	Jamaica
*Iceland	Iraq	Kenya
Ireland	Islamic Rep. of Iran	Morocco
Israel	Jordan	Mozambique
Italy	Lebanon	Myanmar
Japan	Malaysia	Nepal
Korea	Mauritius	Nicaragua
*Kuwait	Mexico	Nigeria
Libya	Panama	Pakistan
Luxembourg	People's Rep. of China	Paraguay
Malta	Peru	Philippines
Netherlands	Poland	Senegal
New Zealand	Romania	Sudan
Norway	South Africa	Syrian Arab Republic
*Oman	Sri Lanka	Togo
Portugal	Thailand	United Rep. of Tanzania
*Qatar	Tunisia	Viet Nam
*Saudi Arabia	Turkey	Yemen
Singapore	Uruguay	Zambia
Slovak Republic	Venezuela	Zimbabwe
Spain		
Sweden		
Switzerland		
*Trinidad and Tobago		
*United Arab Emirates		
United Kingdom		

* Outlier countries

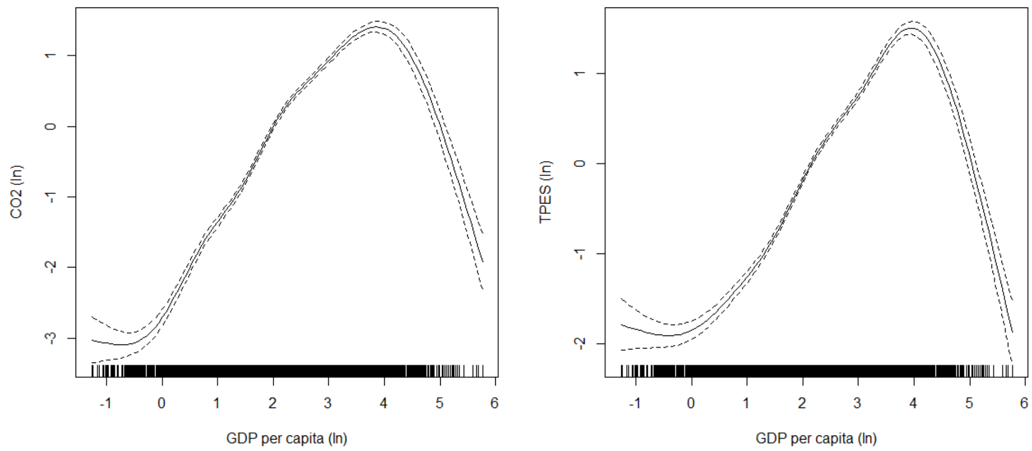

Figure A1: TPES vs. GDP p.c. and CO2 vs. GDP p.c.: semi-parametric regression without outlier, confidence band (5%), all countries (including outliers).

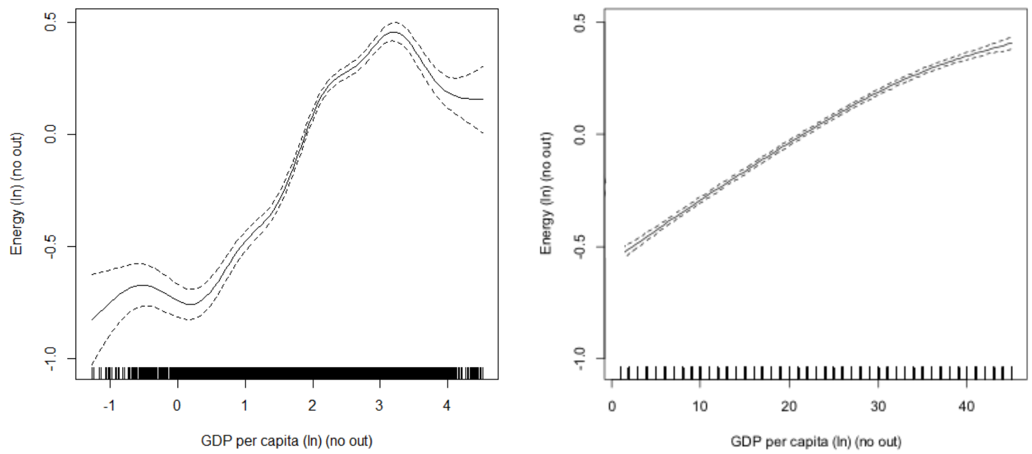

Figure A2: Semi-parametric regression of TPES on GDP p.c. with time trend (without outliers)

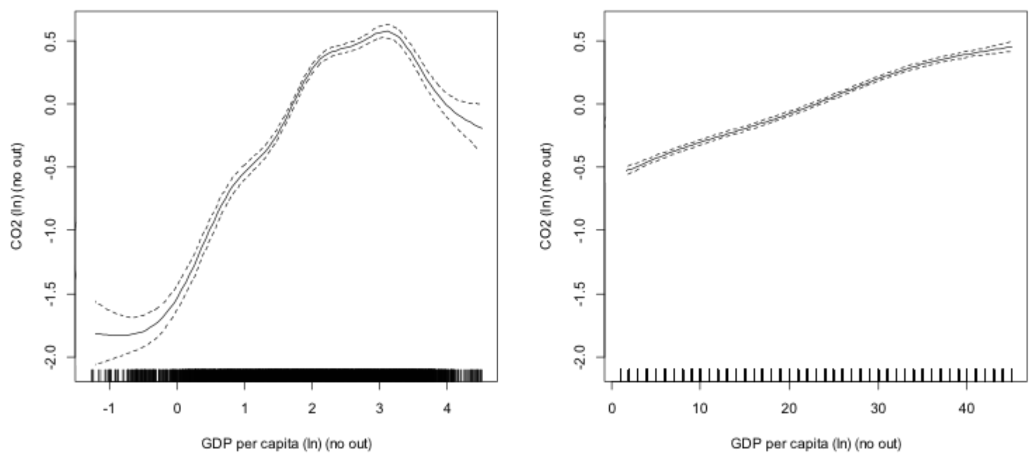

Figure A3: Semi-parametric regression of CO2 on GDP p.c. with time trend (without outliers)

9.2 World analysis: per capita energy and emissions

The cointegrating regressions when taking energy and emissions in per capita terms are shown below. As in the analysis in absolute terms, a structural break can be detected in 1991. Before 1991 the relationship is linear, although with a higher intercept in the 1970s. After a cubic specification provides a good fit. The intercepts are somehow lower between 1998 and 2002. Such evidence is consistent with the scatterplots represented in Figure A4. In the main text, it is discussed why the evidence of concavity after 1991 does not imply reductions in environmental pressures and is inconsistent with the original EKC narrative.

$$Epc = 0.550\,GDPpc + (42.667 - 53.087\,GDPpc + 21.995\,GDPpc^2 - 3.042\,GDPpc^3)\,D9115 + 3.067 + D7180 \times 0.051 - 0.014 \times D9802$$

n=45, ADF(4) regression: τ_{nc}= -5.05, p<0.01 (MacKinnon, 1996)

$$CO2pc = 0.363\,GDPpc + (58.896 - 73.575\,GDPpc + 30.507\,GDPpc^2 - 4.202\,GDPpc^3)\,D9115 + 0.584 + 0.077\,D7180 - 0.017\,D9902$$

n=45, ADF(1) regression: τ_{nc}= -5.99, p<0.01 (MacKinnon, 1996)

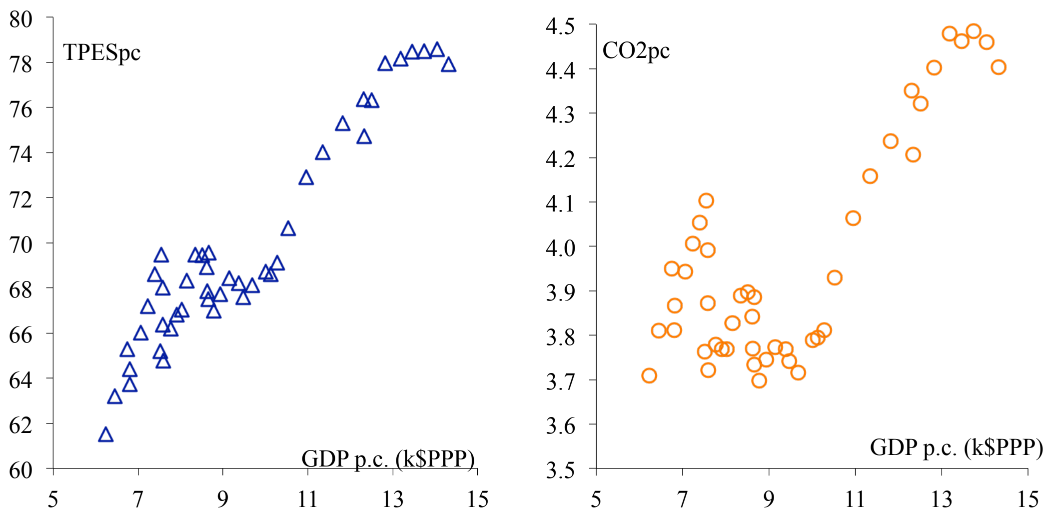

Figure A4: TPES and CO2 p.c. vs. GDP p.c.: world level

9.3 IEA vs. BP data

Dataset on energy are made available both by IEA and BP, which, however, use different accounting protocols (see section 2). Regarding primary energy sources, data are different in size (IEA data are about 10% higher than BP) but show similar variability, as evident from Figure A5 that compares world figures of IEA and BP.

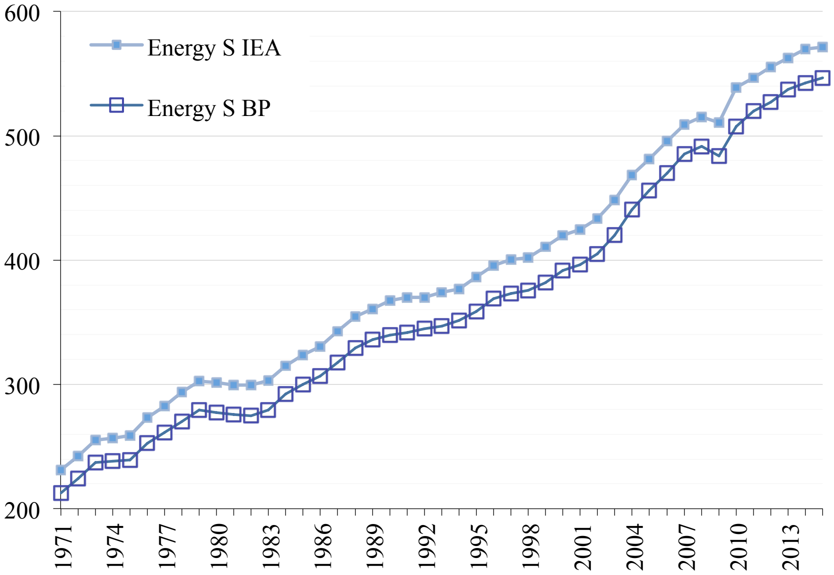

Figure A5: World energy primary supply: difference between IEA and BP figures (Ejoules)

9.4 Cluster Analysis

In order to identify different patterns of the relationships investigated in this paper and check for the outliers, we run a cluster analysis. However, a caveat is due because of the evolution in time of each country. While some countries showed rather stable patterns, others (for instance Iran) exhibited marked changes along the time span considered in this paper. Hence, it must be emphasised that the following results reflect average behaviours.

Since there are no theoretical reasons for testing an *ex-ante* given number of clusters, we used a hierarchical cluster approach. The metric of the clustering was the Euclidean distance[24] (see Nardo et al., 2008). The Ward's method (Ward, 1963) provided the linkage criterion to calculate the distance between sets of observations. According to this methodology, the objects whose merger provides the smallest possible increase of the overall within-group variance are iteratively combined.

We discuss now the analysis performed for TPES and per capita GDP. When using CO2

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[24] The Euclidean distance is defined as $D(x,y) = \sqrt{\left(\frac{\sum_{i=1}^{N_d}(x_i-y_i)^2}{N_d}\right)}$, where x and y are two different values for different countries over the N_d variables.

emissions instead of TPES, results are similar. To avoid the "difference in scales" bias we divided TPES values by the average population over the whole period. To identify the clusters, we used the maximum, average values and the standard deviation, calculated over the entire period of analysis. This gives an indication of the magnitude and variability of the variables. To take into account the patterns of the two variables over time, we also considered their yearly growth rates, their standard deviations, the number of years in which each rate of growth and TPES elasticity to GDP p.c. was positive.

We adopted the Duda and Hart's (1972) stopping rule to establish the number of clusters. This rule is based on the ratio between the dispersion in the next pair of clusters before and after combining, namely, the sum of squares in the two clusters divided by the sum of squares in the combined cluster. More distinct clustering is suggested by larger values of the ratio or smaller pseudo T-squared statistics. Table A2 shows the two statistics calculated for our dataset, while the dendrogram in Figure A6 gives a visualization of the clustering. Two reasons suggested us to choose 12 clusters. First, this number maximises the Duda-Hart statistic (the corresponding pseudo T-squared statistic is rather low); second, the dendrogram shows that the vertical distance before two countries are connected, which represents dissimilarity, makes the most sudden jump at a linkage distance close to 400 (horizontal line), implying the identification of twelve clusters.

Table A.2 - Duda–Hart stopping rule analysis.

N of clusters	1	2	3	4	5	6	7	8	9	10	11	**12**	13	14	15
Duda-Hart index	0.45	0.28	0.21	0.32	0.45	0.35	0.46	0.16	0.33	0.50	0.54	**0.60**	0.40	0.01	0.45
Pseudo T squared	140.50	262.09	40.29	21.31	43.07	116.07	6.91	10.51	6.15	48.40	10.12	14.19	12.16	148.14	16.03

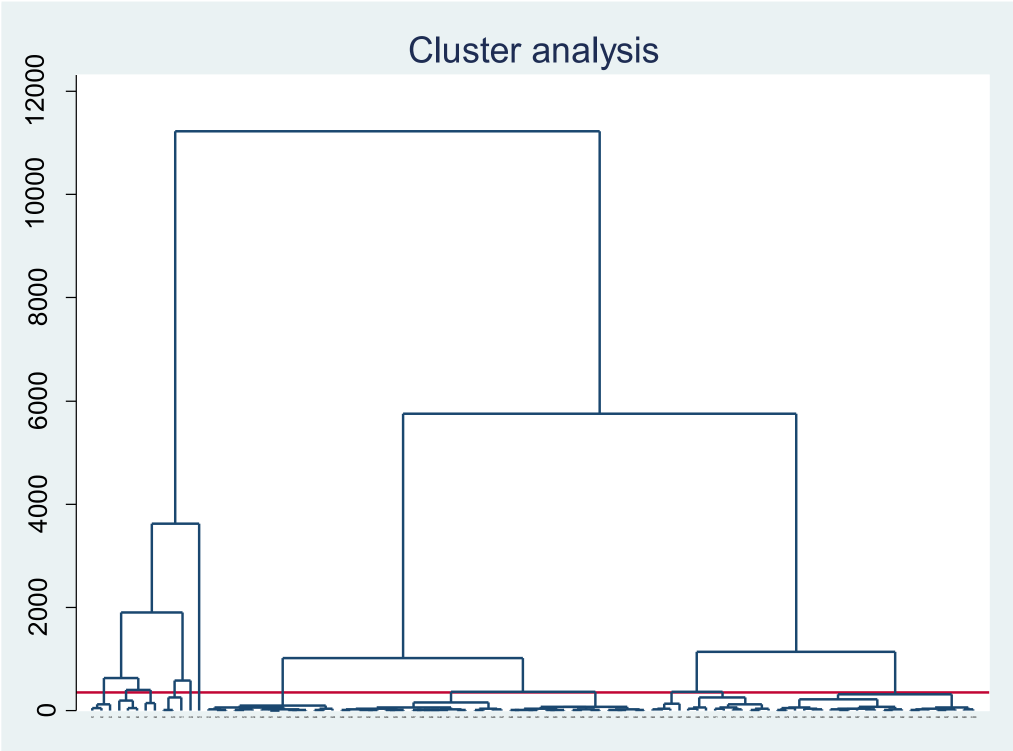

Fig. A6. The dendrogram of the hierarchical cluster analysis.

Table A3 shows the Countries included in each cluster. Cluster 1 and 10 include very rich and high-emission countries; units in clusters 7, 8, and 9 are developing countries with a geographical predominance of Africa and South America. The description of clusters 11 and 12 is slightly more difficult due to a high degree of infra-cluster dissimilarity. It includes both developed countries (mainly from Europe and Asia) and other countries whose average energy consumption (and emissions) and GDP p.c. are comparable to the others only because of temporary peaks (as it is witnessed by larger standard deviations, not shown).

Clusters 2,3,4, 5, and 6 include only economies that are strongly based on oil (geothermal energy for Iceland) and whose figures are markedly different from the others. This can be seen, for instance, by the statistics of energy consumption and GDP p.c. for each cluster, which are shown in Figure A7 and A8. Such evidence supports the idea that those countries can be considered as influential outliers as discussed in section 2.

Table A3 – Composition of the clusters

Cluster	Countries	n
1	Canada, United States, Luxembourg	3
2	Brunei Darussalam, Oman, Saudi Arabia	3
3	Kuwait, Trinidad and Tobago	2
4	Iceland, Bahrain, United Arab Emirates	3
5	Curaçao	1
6	Qatar	1
7	Chile, Mexico, Portugal, Turkey, Malta, Former Yugoslavia, Algeria, Thailand, People's Rep. of China, Hong Kong, Argentina, Brazil, Iraq, Jordan, Lebanon	15
8	Albania, Angola, Egypt, Mauritius, Nigeria, Tunisia, Zambia, Zimbabwe, DPR of Korea, Indonesia, Viet Nam, Bolivia, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Jamaica, Panama, Paraguay, Peru, Uruguay, Syrian Arab Republic	26
9	Benin, Cameroon, Congo, Côte d'Ivoire, Dem. Rep. of Congo, Ethiopia, Ghana, Kenya, Morocco, Mozambique, Senegal, Sudan, United Rep. of Tanzania, Togo, Bangladesh, India, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Haiti, Nicaragua, Yemen	24
10	Australia, Finland, Norway, Singapore	4
11	Korea, New Zealand, Belgium, Czech Republic, Germany, Netherlands, Sweden, Gibraltar, Former Soviet Union, Chinese Taipei	10
12	Israel, Japan, Austria, Denmark, France, Greece, Hungary, Ireland, Italy, Poland, Slovak Republic, Spain, Switzerland, United Kingdom, Bulgaria, Cyprus, Romania, Gabon, Libya, South Africa, Malaysia, Venezuela, Islamic Rep. of Iran	23

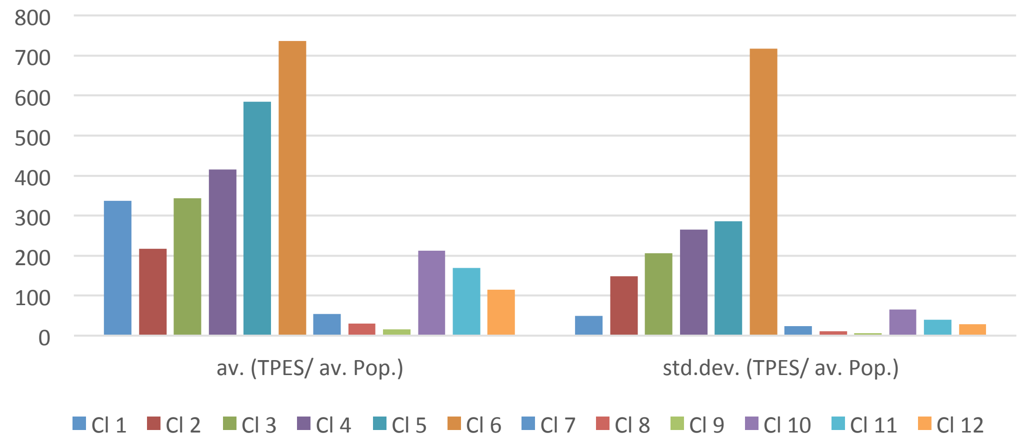

Fig. A7. Average TPES/Average population in each cluster and relative standard deviation

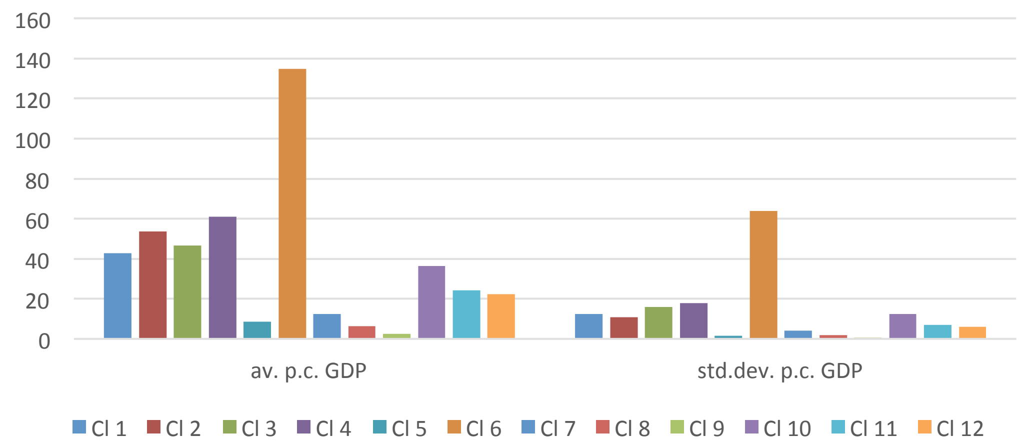

Fig. A8. Average GDP p.c. in each cluster and relative standard deviation