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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 (EKC) for total primary energy supply and for CO2 emissions for the period 1971-2014.
Our approach has two distinguishing features. Firstly, it adopts a robustness approach by (a) using both parametric and semi-parametric methods, and (b) analysing different scale, namely, the world as a whole, a panel of 115 units, some sub-samples of it, and single countries. Secondly, it strictly adheres to the original EKC narrative by not using control variables and taking Energy and CO2 in absolute rather than in per capita terms. The latter is standard in theoretical articles and consistent with the fact that "Nature cares" about absolute and not per capita pressures.
The analysis has both methodological and empirical outcomes. We show how the model specification, the sample, and the variables that are used affect the evidence about the EKC hypothesis. Hence this paper contributes to explain why the literature on the EKC produces very mixed results.
However, the multiscale perspective and some theoretical considerations give precise indications about the correct way of performing the analysis. Thus, we can safely affirm that, both for CO2 and Energy, the fragile evidence of EKC patterns emerging at the end of the past century has vanished after the new wave of globalization. Currently, there is only some evidence of decreasing elasticities for very-high income levels.
Interestingly, the great recession (2007-12) might have produced structural reductions in energy consumption and emissions in the affected countries. Finally, the case of Germany, which shows EKC patterns, suggests that active energy policies can successfully reduce energy consumption without harming the economy.

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

1 Introduction

As 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. For instance, since 2010 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.

As well known, the 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, the 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 logically 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). ‘Environmental degradation’ has to be measured in absolute terms because ‘Nature’ is affected by total human pressure, and not per capita. This is standard in theoretical contributions (see, for instance, the “green Solow model” by Brock and Taylor 2010). Investigating a reduced form in which per capita income is taken as the only ‘explanatory’ variable (Azomahou et al. 2006, 1348) also derives from the EKC original idea that was about exploring the relationship between income and environmental degradation and not looking for 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 (CO2). Our analysis cover more than one hundred counties for the time span 1971-2014.

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 fewer cases, for instance Bento and Moutinho (2016) for Italy, Pilatowska et al. (2015) for Poland, 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, besides CO_2 emissions 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 mixed as in the previous one, due to differences in the chosen dependent variable (e.g. CO_2 or Energy) and/or group of countries. Specifically, an EKC does not emerge according 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 having taken into account the issue of (non) stationarity of the series. On the contrary, an EKC shape is supported for CO_2 emissions by Zaman et al. (2016), Kais and Sami (2016), Apergis and Ozturk (2015), Pilatowska et al. (2015), Fahrani et al. (2014), Saboori and Sulaiman (2013) and Iwata et al. (2010), and both for CO_2 emissions and energy by Bento and Moutinho (2016) and Heidari et al. (2015). Finally, some works show differences in the results depending on the groups of analysis. In particular, according to Beck and Joshi (2015) an EKC emerges for African and Asian countries, while it does not emerge 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 CO_2, 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 of 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 fuels use are at the basis of most forms of pollutions[1].

In the present paper, the time span is significantly longer, covering both the process of globalization started with the WTO, the economic growth of emerging countries like China, the impressive technological change occurred in recent years, and the Great Recession (2007-2012). Finally, the analysis of the CO_2-income relationship allows us also to assess the re-carbonization due to the increasing consumption of carbon rich fuels of 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 “CO_2 Highlights” (IEA 2016). Series are available from 1971 for total energy supply (TPES), CO_2 and other variables derived from other sources including GDP and population. 145 countries and other regional aggregates are included; however, data cover the entire time span only for 113

[1] This is acknowledged by the most important national agencies and international institutions on the environment. See, e.g., https://www.epa.gov/environmental-topics/chemicals-and-toxics-topics

countries. By adding two aggregates, the countries belonging to former USSR and Yugoslavia respectively, we ended up with 115 series[2].

GDP is taken in purchasing power parity[3] due to the cross-country nature of the analysis. GDP is expressed in thousand dollars, TPES in PJoules and CO2 emissions in million tons. Figure 1 gives a snapshot of the dataset. Per capita income is on the x-axis, while on the y-axis are reported respectively the total TPES and CO2. Values are in logarithm for a better visualization of the data.

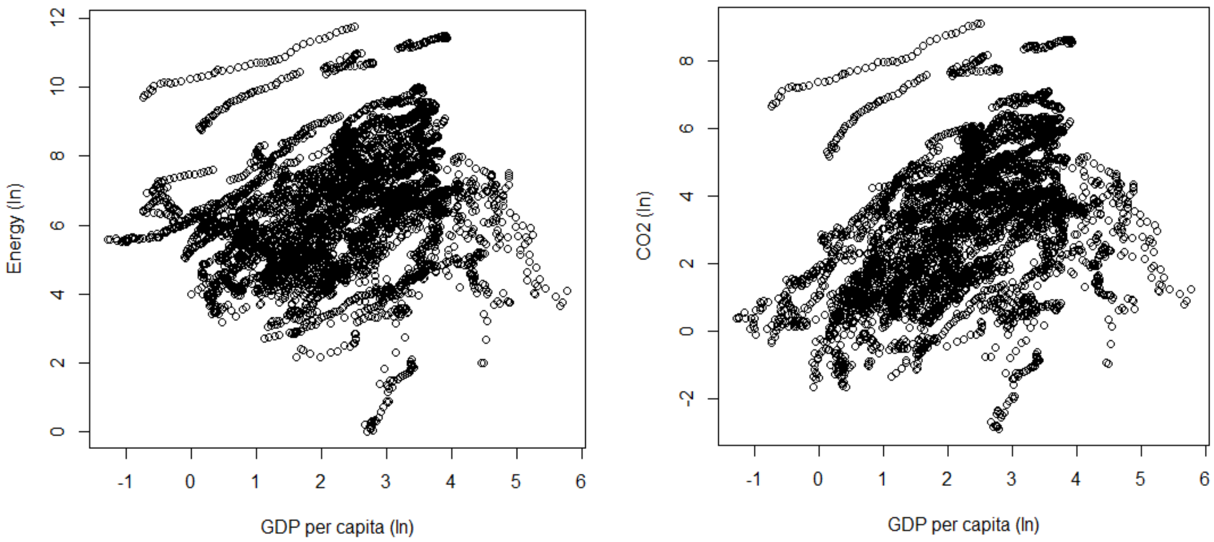

Figure 1. A snapshot of the dataset: Energy and CO2 vs GPD p.c. (1971-2014)

A preliminary look at the series suggested the presence of potential outliers, that is, observations that differ markedly from other observations 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 and/or force to change the 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 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 did a preliminary selection of the outliers by visual inspection of the scatter plots and then we arrived to a final decision with the help of a cluster analysis. When estimating regressions, data can be used in absolute terms since the different size of countries is accounted for by the intercepts. Graphical comparisons, however, require to standardise values. To this purpose TPES in Figure 2 is divided by the mean population over the period. Obviously, other rescaling can be used, as done in Figure 9 where TPES is divided by the size of the areas with population density >5 per square km for reasons that will be discussed below. Figure 2 shows that most of the potential outliers belong to

[2] 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.

[3] PPP GDP 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 2016 dataset refers to GDP in 2010 US$. For details see the technical notes of the IEA (2016, p. 141)

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 but strongly decreased after. 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. Actually, Iceland shows a peculiar pattern that comes from a strong growth in the use of its geothermal energy potential.

Despite many countries have very special patterns (for instance, those countries whose label in Figure 2 has no emphasis), we decided to keep the number of excluded countries as lowest as possible and ended up with 10 countries. The cluster analysis (see appendix) guided our choice since we included all countries belonging to four close clusters, two of which contains only one country. Countries which looks rather special, as Lybia[4], 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.

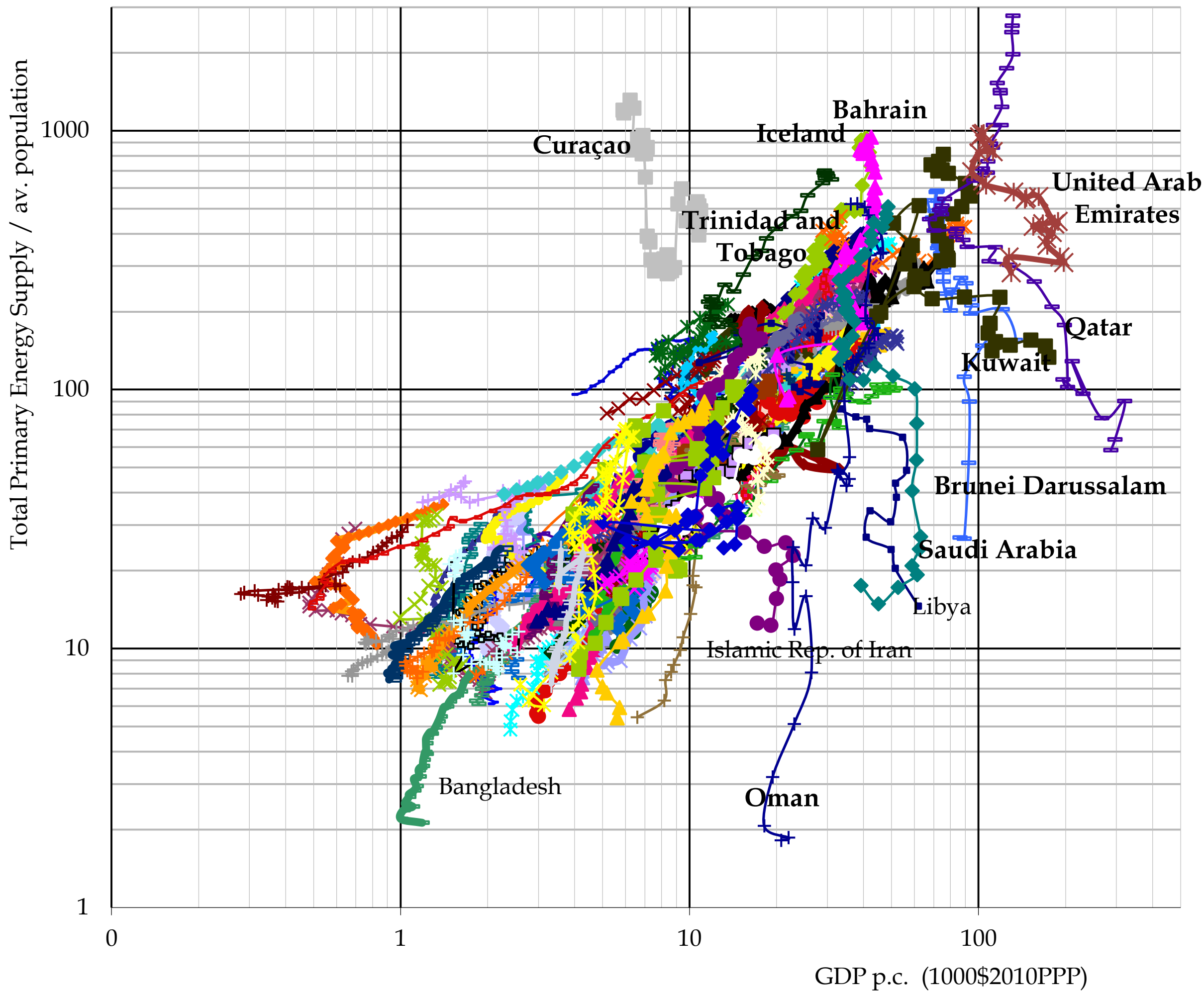

Figure 2. Looking for potential outliers: the relationship between GPD p.c. and TPES per average population

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[4] Lybia has several observations that look very special. Hence, we run all the regressions both including and excluding Lybia. Including it causes a reduction in the turning points, if existing, and in the slope of the fitted curves.

Table 1: Statistics about energy, income, and population for outliers

Country	mean TPES p.c.	max TPES p.c.	mean GDP p.c.	max GDP p.c.	mean population	max population
Brunei Darussalam	281	406	82.994	133.952	0.277	0.417
Trinidad and Tobago	295	633	18.336	30.988	1.200	1.354
Oman	116	287	34.614	46.663	1.959	4.236
Saudi Arabia	170	289	43.001	63.024	17.607	30.887
Iceland	401	761	29.597	42.344	0.264	0.327
Bahrain	421	516	38.345	44.232	0.629	1.362
Kuwait	357	486	82.893	174.959	1.924	3.753
United Arab Emirates	369	523	115.658	197.084	3.029	9.086
Curaçao	611	1518	8.495	10.916	0.191	0.229
Qatar	660	953	134.754	320.113	0.665	2.172

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 us neutralising the effects of two countervailing forces - namely the transfer of cleaner technologies and the “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 of efficiency (GDP energy intensity has almost halved since 1971) was more than offset by the growth of energy and population. As a consequence, the energy-GDPpc ratio remains higher than in 1970s, despite some reductions have been occurring since the mid of the 1990s. However, in 2014 energy was 2.5 times higher than half a century ago. CO2 emissions also grew relevantly since 1971 (2.25 times). The CO2 content of energy decreased until the beginning of the XXI century, due to the increase in the use of natural gas, which occurred particularly in the 1980s and the 1990s. After that, due to a new impulse in the use of coal in the emerging countries, the CO2 content of energy has started to grow again (Figure 4)

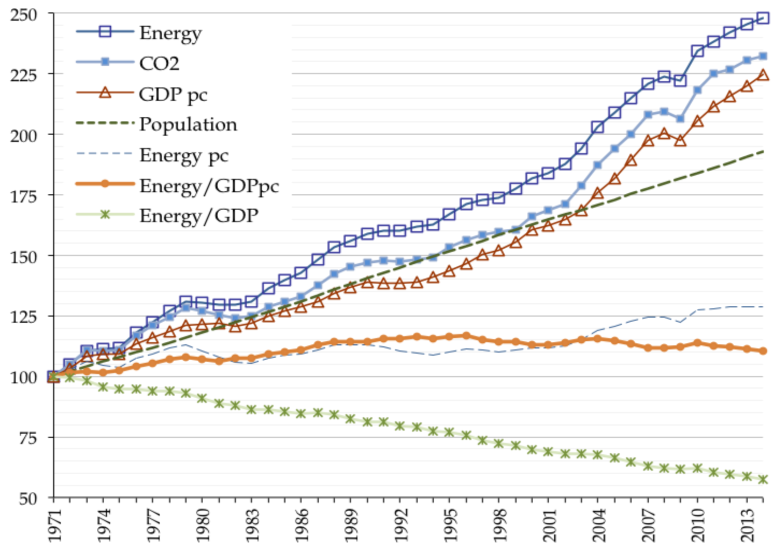

Figure 3: Changes in key indicators since 1971 (index numbers, 1971=100)

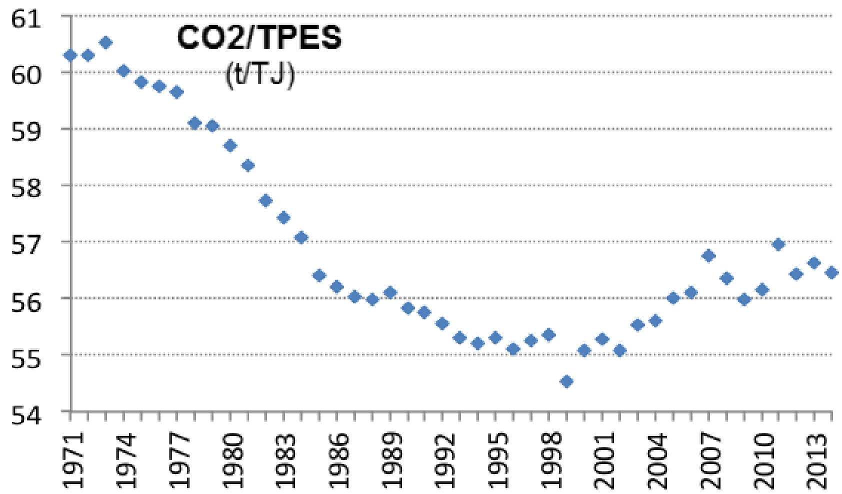

Figure 4: CO2 Content of primary energy (t/TJ)

The Kaya identity (Kaya 1990) can help in getting some intuitions about the drivers of change in the CO2 emissions. Kaya identity is expressed as follows:

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

Figure 5 shows the relative contribution of each terms of the Kaya identity to the annual change of world CO2 emissions. 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. Hence emissions have increased despite the improvements in the energy intensity of GDP (third term).

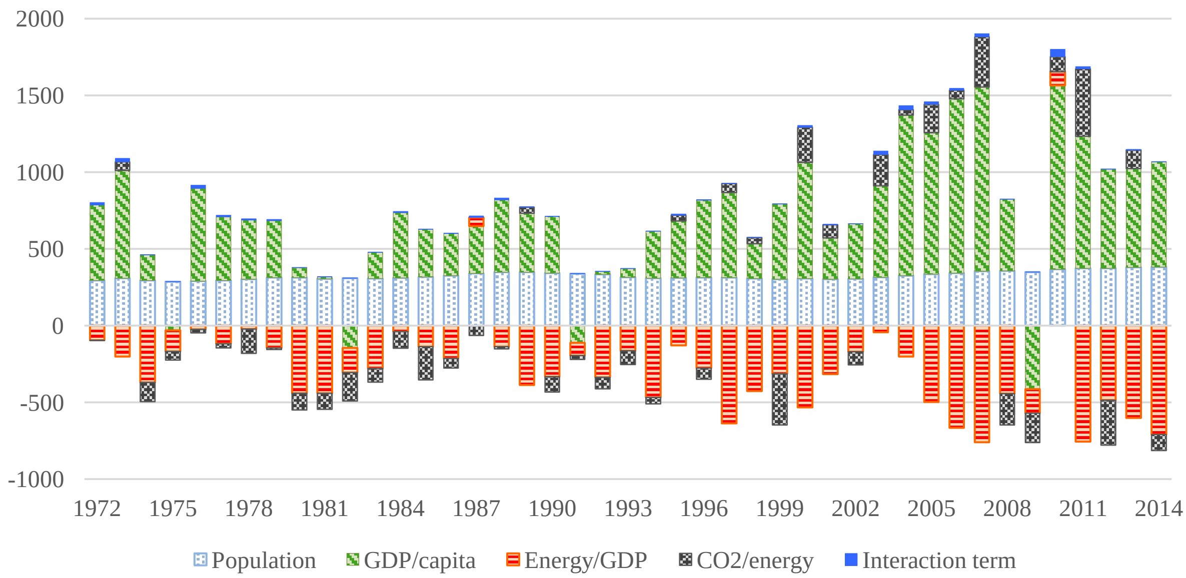

Figure 5. Kaya decomposition of CO_2 emissions change in the world, 1971-2014

When moving to the EKC-curve hypothesis, the scatter plots (Figure 6) suggest that an inverted-U relationship is not plausible. This is confirmed by the co-integration analysis[5] which is reported below.

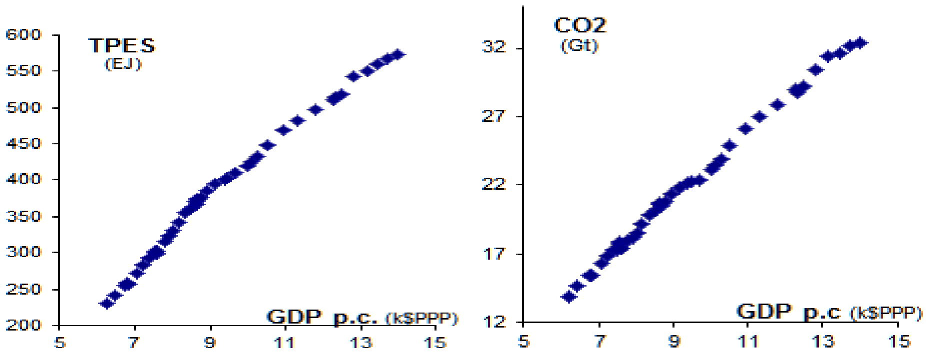

Figure 6. The Energy-GDPpc and CO2-GDPpc relationships at the world level.

Since the augmented Dicky-Fueller test shows that all series are integrated of order 1, we looked for cointegrating relationships. The following are best fit of the data we could find (variables are in natural logarithms)[6 7]:

$$Energy = 1.434GDPpc + D9114(0.433GDPpc - 0.199GDPpc^2) + 9.726 - 0.012D7384 - 0.016D9802 - 0.014D0708 \quad \text{(eq. 1)}$$

n=44, ADF(6) regression: $\tau_{nc} = -5.387$, $p<0.01$ (MacKinnon, 1996)

$$CO2 = 1.264GDPpc + D9114(0.246GDPpc - 0.113GDPpc^2) + 7.205 + 0.025D7180 - 0.025D9802 - 0.010D0709 \quad \text{(eq. 2)}$$

n=44, ADF(3) regression $\tau_{nc} = -4.695$ $p<0.01$ (MacKinnon, 1996)

"*Dxxyy*" are intercept dummies going from year 'xx' to year 'yy'. For instance, *D9114* is equal to one for the period 1991-2014 and zero for the other years. Since all coefficients are significant, we can draw the following inference. Both CO2 and Energy showed a linear relationship with per capita income until 1990 and moderately concave after, which is consistent with the break-up of communist regimes in Eastern Europe. The elasticities were bigger than one[8], that is, energy and CO2 emissions increased proportionally more than income.[9]

The intercepts became temporarily lower between 1998 and 2002, when the CO2 energy content reached its minimum, and around the great recession (2007-2012). Also, the oil shocks of

[5] We followed Engle and Granger two stage method.
[6] The number of lagged difference terms in the ADF equations (number in brackets) was determined by minimizing the Aikake and Schwarz criterion and by checking the Breusch-Godfrey Serial Correlation LM Test.
[7] A cubic form gives a worse fit of the data.
[8] The lowest values of elasticities is in 2014. Their values are 1.410 and 1.269, respectively for energy and CO2.
[9] When looking for the short run relationship, we got the following "error correction model! estimates:

$\Delta Energy(t) = -0.708 \times ect(t-1) + 1.258 \times \Delta GDPpc(t) - 0.326 \times D9114 \times \Delta GDPpc(t-1)$

t-statistic: -3.07 19.74 -4.08

n=43, Adj.R^2=0.77 *ect* : error correction term (residuals of the l.r. estimate)

$\Delta CO2(t) = -0.734 \times ect(t-1) + 1.228 \times \Delta GDPpc(t) - 0.250 \times D9114 \times \Delta GDPpc(t-1)$

t-statistic: -3.34 19.10 -3.07

n=43, Adj.R^2=0.79 *ect* : error correction term (residuals of the l.r. estimate) the 1970s significantly reduced primary energy, while the opposite occurred for CO2 because of the abovementioned predominance of oil and coal in that period.

Only for the sake of completeness, we also analysed the relationships using per capita energy and per capita emissions as dependent variables (see appendix). 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 which 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. Variables are often taken in logarithms.

Natural logarithm values were used in all the estimates. In order to choose the appropriate functional form, we started from a semi-parametric analysis that lets the fit to be a non-linear function of the regressors.[10] The results suggested to use 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) suggested to use the fixed effects model for CO2, while for TPES Hausman test is inconclusive.[11] In the paper we present the estimates using the random effects model, which, however, are very similar to those obtained with the fixed effects model. 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[12]. The null hypothesis of no first order autocorrelation has to be rejected. Furthermore, a likelihood ratio test detected the presence of heteroskedasticity[13]. Thus, we fitted our models using feasible generalized least squares (FGLS).

[10] We used the MGCV package for R, see Wood, 2006.

[11] 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.

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

[13] 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.

Series stationarity was checked with the tests developed by Levin, Lin and Chu (2002) and by Im, Pesaran, and Shin (2003)[14].

4.2 Semi-parametric estimates

Figure 7 shows the semi-parametric estimate respectively for TPES and CO2 (logarithms). The overall relationship is non-linear. For very low and very high income levels the steepness 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 10,000$ and 27,000$ (respectively 2.3 and 3.2 in Figure 7).

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 emerges at about 50.000$ e 45.000$ respectively for TPES and CO2. (Figure A1 in the appendix). A second one is to use TPES per capita and emissions per capita (see, e.g., the world estimates in the appendix); 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. 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 advancements. For this theoretical reason, we did not add a time trend.[15]

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[16], which are shown in Figure 8, and compared them with those for the whole period (Figure 7). Clearly, some evidence of EKC that was emerging before 2001 was lost due to globalization.[17]

[14] 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)

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

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

[17] 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.

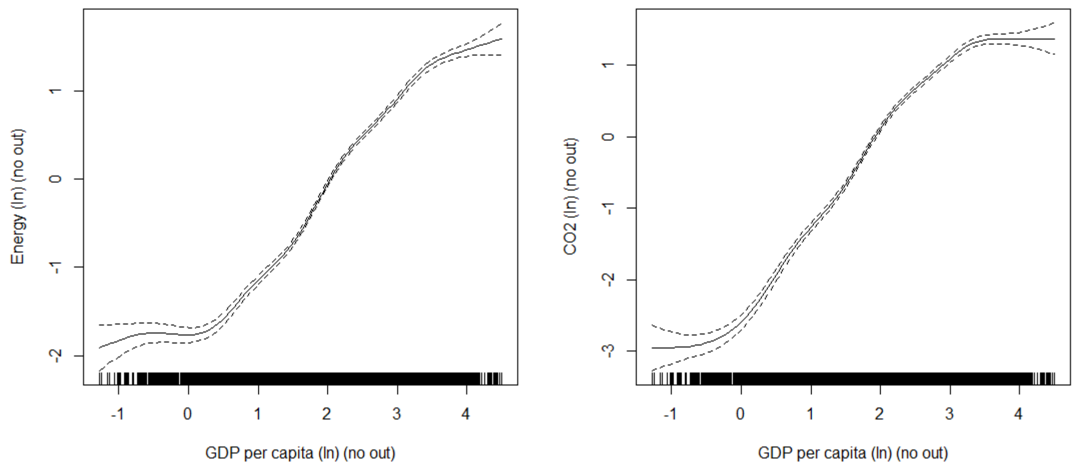

Figure 7: TPES vs GDPPC and CO2 vs GDPpc: semi-parametric regression without outlier, confidence band (5%) (variables in logarithms), 1971-2014.

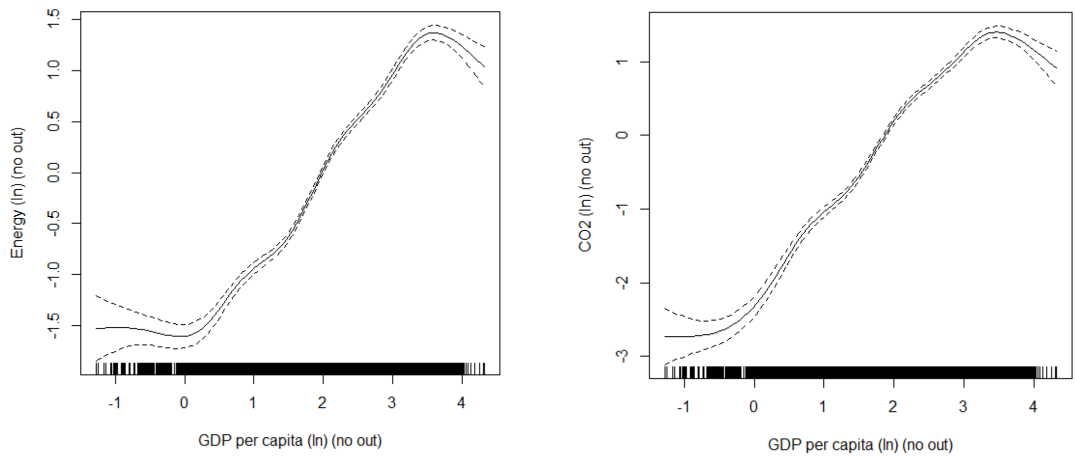

Figure 8: TPES vs GDPPC and CO2 vs GDPpc: semi-parametric regression without outlier, confidence band (5%) (variables in logarithms), 1971-2001.

4.3 Parametric estimates

4.3.1 All countries

The parametric estimations for all countries are shown in Table 2[18]. 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 56,606$ (C.I. 95%: 18,327-331,083). The calculated turning point for TPES is almost a 1,3 million$ (C.I. 95%: 57,725-1.475 million). Consistently with the semi-parametric results, including also outlier countries and/or time trend makes the relationship "more concave", reducing the calculated turning points (not shown).

[18] As mentioned above, we used random effects for TPES and fixed effect for CO2.

Table 2. Parametric estimates (FGLS)

Dep. variable		ln *GDPpc*	(ln *GDPpc*)^2	(ln *GDPpc*)^3	Turning points ($) C.I. 95% ($)
ln TPES	Coeff.	0.085	0.156	-0.015	1.272 millions
(Fixed effects)	Std. Err.	0.026	0.015	0.003	57,725 $-1.475 millions
	p.	0.001	0.000	0.000	
ln CO2	Coeff.	1.021	0.107	-0.039	56,606
(Random effects)	Std. Err.	0.062	0.029	0.004	18,327-331,083
	p.	0.001	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[19] 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. The relationship between per capita income and energy in the three different groups of countries was as follows. Low-income countries showed a convex relationship for TPES, increasing from around 2860$, while a linear increasing one for CO2. Middle-income countries showed an EKC pattern, although with turning points above the actual income range. A similar outcome holds for high-income countries, for which evidence of a CO2-EKC is even weaker.

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*	**-0.151**	0.031	0.000	-0.131	0.084	0.118	-0.282	0.155	0.254
(ln *GDPpc*)^2	-0.031	0.020	0.119	**0.452**	0.062	0.000	**0.455**	0.090	0.000
(ln *GDPpc*)^3	**0.066**	0.011	0.000	**-0.081**	0.013	0.000	**-0.064**	0.013	0.000
ln CO2									
ln *GDPpc*	**0.473**	0.075	0.000	**1.670**	0.147	0.000	**1.864**	0.182	0.000
(ln *GDPpc*)^2	-0.041	0.063	0.512	-0.066	0.099	0.505	**-0.288**	0.099	0.004
(ln *GDPpc*)^3	0.045	0.026	0.081	**-0.038**	0.020	0.051	0.018	0.015	0.228
TPES turning points C.I. 95% ($)	The rel. is increasing from 2,860 (1,743-6,901)			35,725 (4,089 - 1,053,960)			91,898 (0 - 101,488,422)		
CO2 turning points C.I. 95% ($)	none (2,568 - none)			26,610 (4,792 - none)			none (4,415 - none)		
Data									
Range of GDP p.c. of obs. ($)	280 – 9,089			481 – 23,965			2703 – 89,917		
GDP p.c. mean (st.dev) $	3,085 (1,838)			9,818 (4,257)			28,598 (12,581)		

[19] 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.

5 Single Countries

Consistency at different scales involves also a country level analysis (see, e.g. de Bruyn and Heintz (1999,671-672) and Stern et al. (1996,1159). 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 materials exports. In particular, oil based economies show prolonged negative relationships (see Figure 2 for some examples). 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.

Second, in some countries affected by the great recession (see Figures 9 and 10) TPES and CO2 emissions declined more than the decline in income and did not go to pre-crisis level during the recovery. Examples are Austria, Belgium, Czech Republic, Denmark, Japan, Hungary, Sweden, Switzerland, United Kingdom, USA. A stronger decline of TPES and CO2 was experienced also by those countries for which data do not show a recovery, e.g. Italy and Spain. 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 9 are standardised dividing by the size of the areas with population density >5 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 10, 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 which shows a EKC patterns. TPES declined after the reunification due to the economic collapse of the Eastern regions, was then stable until the Great Recession, during which started again to decline. At the same time, it has to be noted that the p.c. TPES in Germany are still very high, both in terms of inhabited land and population. It is outside the scope of the present paper to establish why this has occurred. The purpose of this section was only to validate the evidence found for the world as a single unit and for the cross-country time-series analysis.

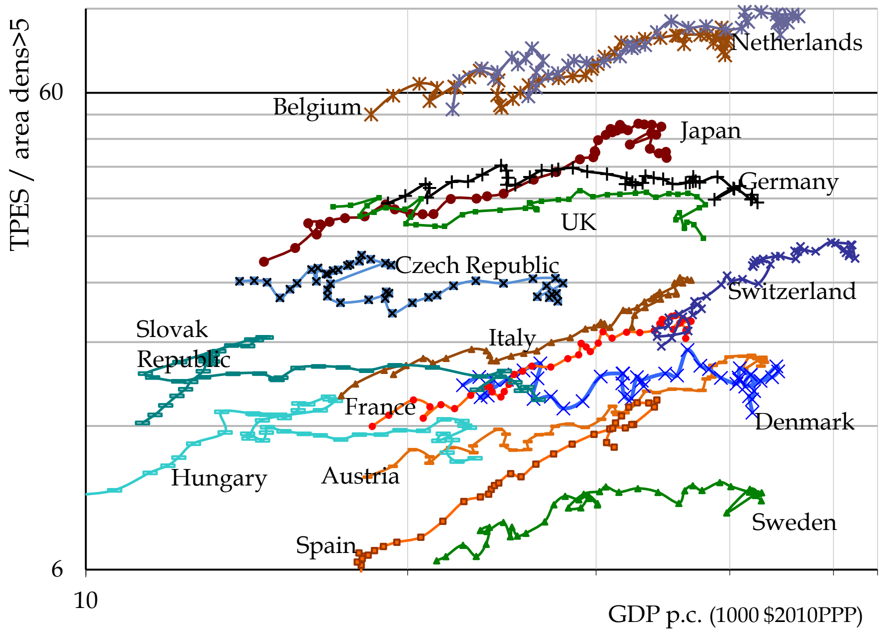

Figure 9. The relationship between GPD p.c. and TPES per inhabited areas with density > 5 per sq.m. population Countries affected by the great recession.

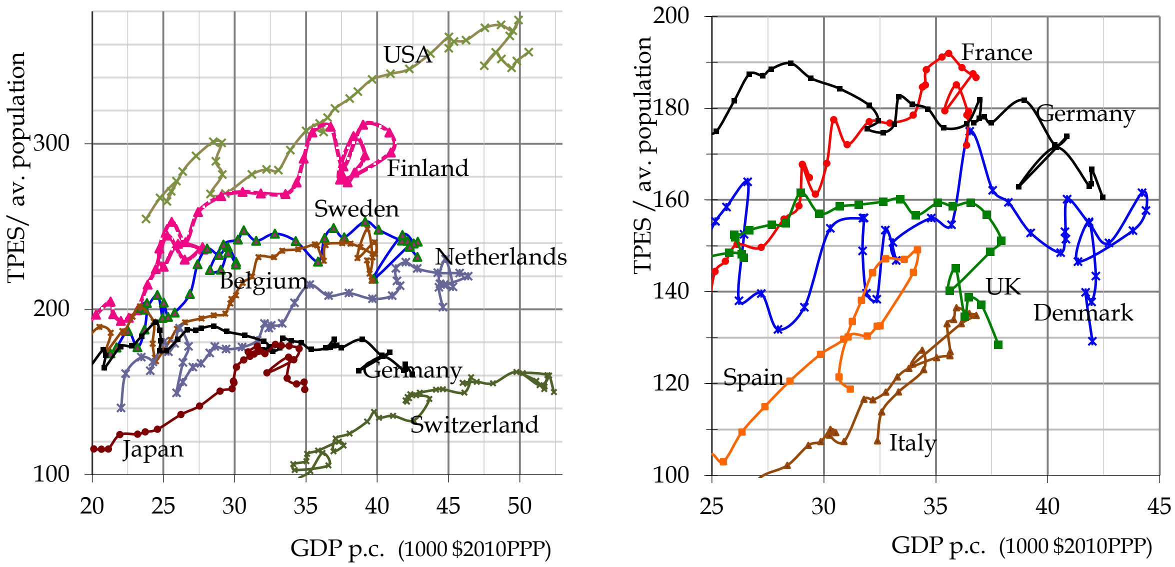

Figure 10. The relationship between GPD p.c. and TPES per average population. Countries affected by the great recession.

6 Conclusion

This piece of research uses a robustness approach to empirically test the EKC hypothesis for CO2 emissions and energy (TPES) for a long time-span, 1971-2014.

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 1971-2000, there is some evidence of EKC, stronger for CO2 emissions than for energy,

(3) such a piece of evidence does not hold for the whole period, 1971-2014, which includes the new

wave of globalization,
(4) the energy consumption and CO2 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 evident.

The robustness approach both helps reducing the perils of statistical artefacts involved in cross-country analysis, and contributes explaining the mixed evidence that the EKC literature produces. Actually, even if the analysis concerns a single variable, support in favour of EKC patterns can be produced. We showed that this is the case when very special countries are included into 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 semiparametric and parametric techniques make us confident to affirm that, both for energy and CO2 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. Globalization has not helped, as was reasonable to expect. Hence, we need strong and active policies of 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 energy that is used.

The pattern of Germany, where active energy policies have been implemented, suggests that energy consumption can be reduced without harming the economy. Whether this is a ‘true’ absolute reduction, or has caused higher energy consumption 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 connected with local territories.

7 Acknowledgements

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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		

* Outliers countries

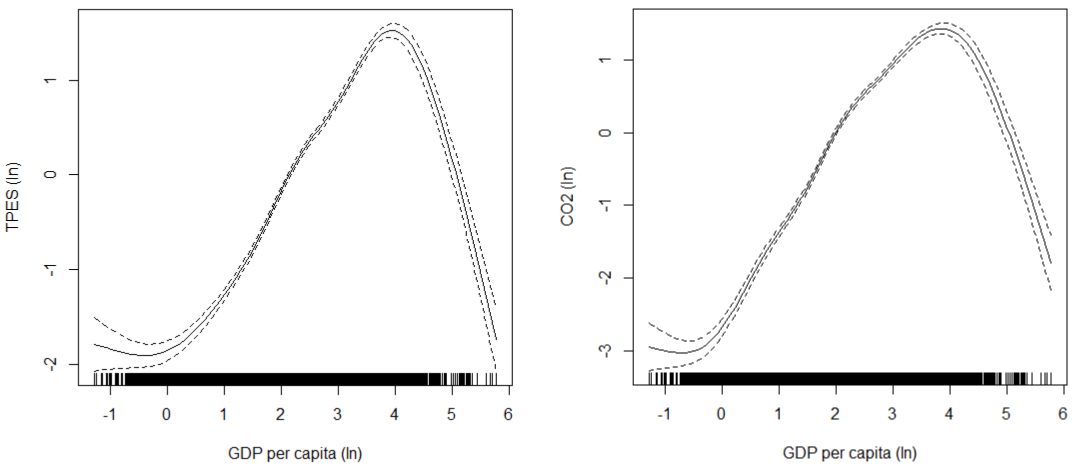

Figure A1: TPES vs GDPPC and CO2 vs GDPpc: semi-parametric regression without outlier, confidence band (5%), all countries, including outliers.

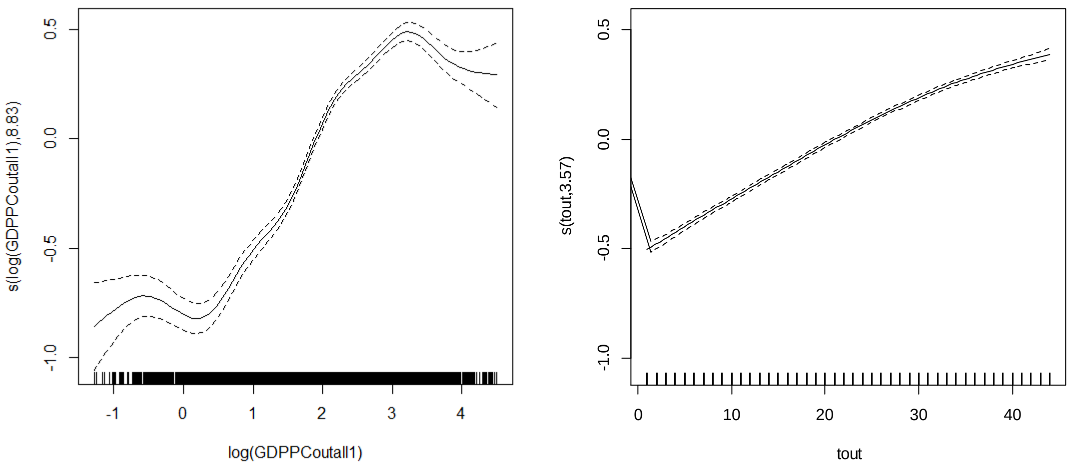

Figure A2: Semi-parametric regression of TPES on GDP p.c. with time trend (without outliers)

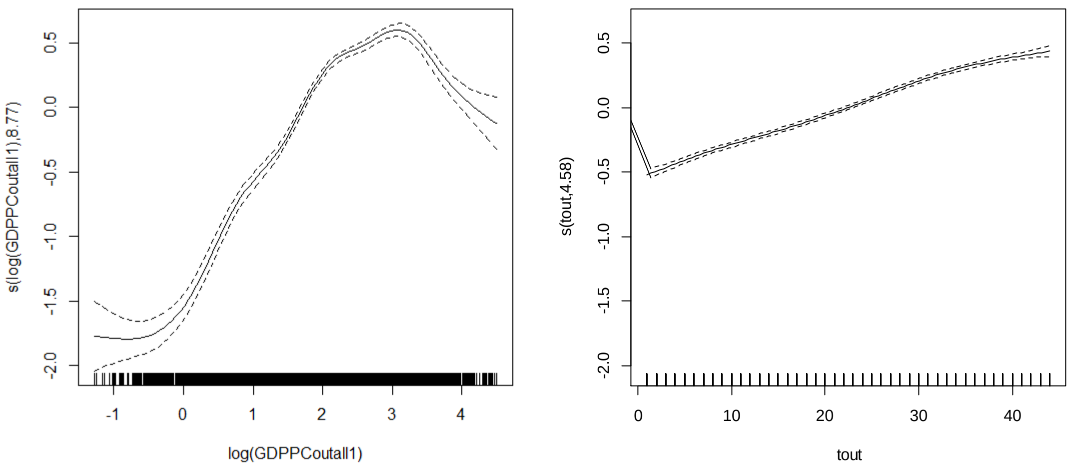

Figure A3: Semi-parametric regression of CO2 on GDP p.c. with time trend (without outliers)

9.2 World analysis: per capita energy and emissions

When taking energy and emissions in per capita terms, we get the cointegrating regressions 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, while after 1991 a cubic specification gives a good fit. The intercept is 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.

$$\boldsymbol{Epc} = 0.550 \times \boldsymbol{GDPpc} + D9114 \times (38.923 - 48.293 \times \boldsymbol{GDPpc} + 19.943 \times \boldsymbol{GDPpc}^2 - 2.749 \times \boldsymbol{GDPpc}^3) + 3.067 - 0.015 \times D9802 + D7180 \times 0.051$$

n=44, ADF(4) regression: τ_{nc}= -4.63, p<0.01 (MacKinnon, 1996)

$$\boldsymbol{CO2\_pc} = 0.363 \times \boldsymbol{GDPpc} + D9114 \times (54.573 - 68.180 \times \boldsymbol{GDPpc} + 28.271 \times \boldsymbol{GDPpc}^2 - 3.894 \times \boldsymbol{GDPpc}^3) + 0.584 + D7180 \times 0.077 - D9802 \times 0.018$$

n=44, ADF(0) regression: τ_{nc}= -6.51, p<0.01 (MacKinnon, 1996)

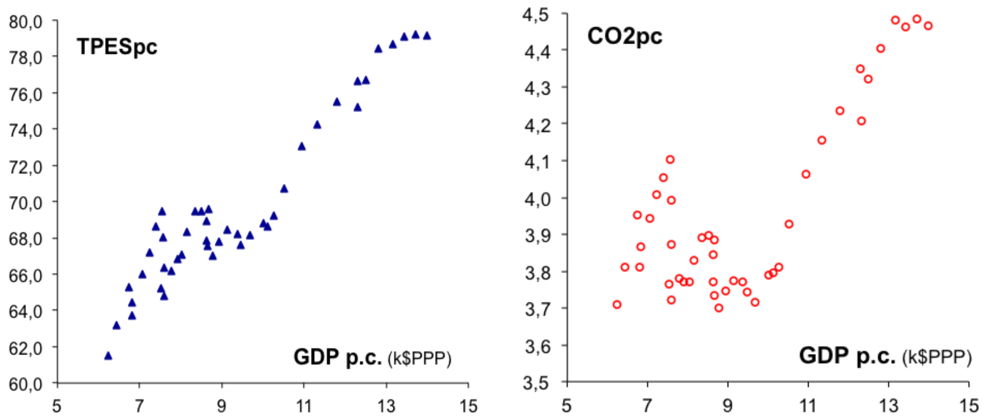

Figure A4: TPES and CO2 PER CAPITA versus income per capita at the world level

9.3 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[20] (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 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 of 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 pc GDP 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 are 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 A5 gives a visualization of the clustering. Two reasons suggested us to choose 8 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 600 (horizontal line), implying the identification of eight 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	0.50	0.25	0.26	0.27	0.31	0.43	0.23	**0.65**	0.58	0.28	0.34	0.41	0.39	0.58	0.30
Pseudo T squared	114.27	293.42	42.74	37.05	137.86	11.80	9.85	16.64	17.64	12.89	3.91	23.39	3.14	30.21	14.31

[20] 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.

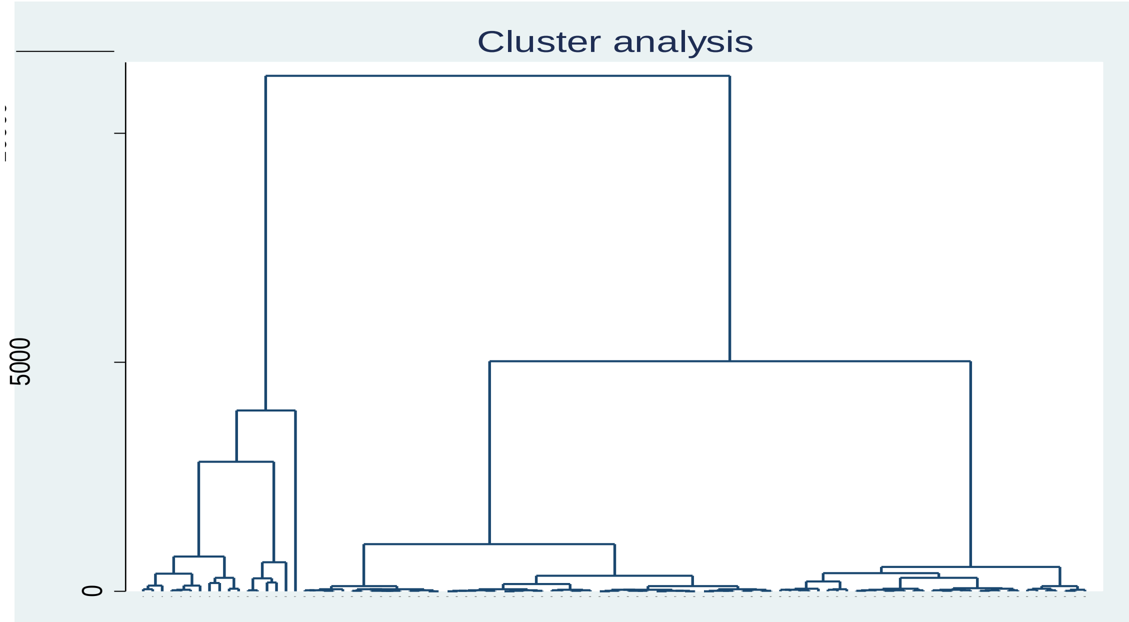

Fig. A5. The dendrogram of the hierarchical cluster analysis.

Table A3 shows the Countries included in each cluster. Cluster 1 includes very rich and high-emission countries; units in clusters 6 and 7 are developing countries with a geographical predominance of Africa and South America. The description of cluster 8 is slightly more difficult due to a high degree of infra-cluster dissimilarity. It includes both developed countries (predominantly from Europe and Asia) and other countries whose average energy consumption (and emissions) and GDP p.c. are comparable to the others mainly because temporary peaks (as it is witnessed by larger standard deviations, not shown).

Cluster 2,3,4, and 5 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 A6 and A7. Such evidence confirms 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, Australia, Finland, Luxembourg, Norway, Singapore	7
2	Brunei Darussalam, Trinidad and Tobago, Oman, Saudi Arabia	4
3	Iceland, Bahrain, Kuwait, United Arab Emirates	4
4	Curaçao	1
5	Qatar	1
6	Chile, Mexico, Portugal, Turkey, Malta, Former Yugoslavia, Algeria, DPR of Korea, Thailand, People's Rep. of China, Hong Kong, Argentina, Brazil, Cuba, Jamaica, Panama, Uruguay, Iraq, Jordan, Lebanon, Syrian Arab Republic	21
7	Albania, Angola, Benin, Cameroon, Congo, Côte d'Ivoire, Dem. Rep. of Congo, Egypt, Ethiopia, Ghana, Kenya, Mauritius, Morocco, Mozambique, Nigeria, Senegal, Sudan, United Rep. of Tanzania, Togo, Tunisia, Zambia, Zimbabwe, Bangladesh, India, Indonesia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Viet Nam, Bolivia, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Nicaragua, Paraguay, Peru, Yemen	44
8	Israel, Japan, Korea, New Zealand, Austria, Belgium, Czech Republic, Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Slovak Republic, Spain, Sweden, Switzerland, United Kingdom, Bulgaria, Cyprus, Gibraltar, Romania, Former Soviet Union, Gabon, Libya, South Africa, Malaysia, Chinese Taipei, Venezuela, Islamic Rep. of Iran	33

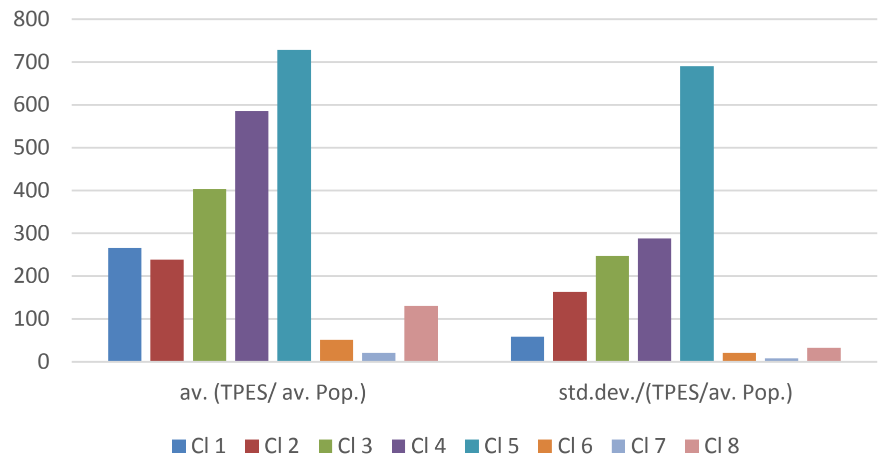

Fig. A6. Average TPES/Average population in each cluster and relative standard deviation

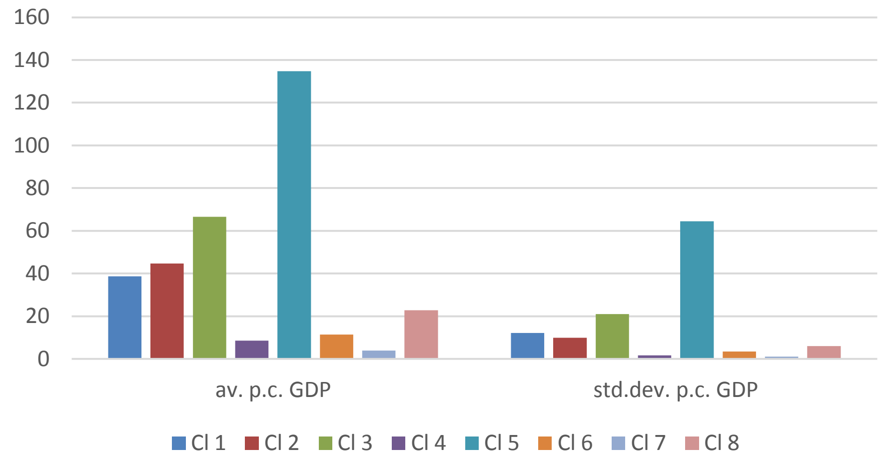

Fig. A7. Average GDP in each cluster and relative standard deviation