THE RIMINI CENTRE FOR ECONOMIC ANALYSIS

WP 48_13

Maria Christidou
University of Macedonia, Greece

Theodore Panagiotidis
University of Macedonia, Greece
The Rimini Centre for Economic Research (RCEA), Italy

Abhijit Sharma
University of Bradford, UK

ON THE STATIONARITY OF PER CAPITA CARBON DIOXIDE EMISSIONS OVER A CENTURY

The Rimini Centre for Economic Analysis
Legal address: Via Angherà, 22 – Head office: Via Patara, 3 - 47900 Rimini (RN) – Italy
www.rcfea.org - secretary@rcfea.org

On the stationarity of per capita carbon dioxide emissions over a century

Maria Christidou (University of Macedonia),
Theodore Panagiotidis (University of Macedonia)
& Abhijit Sharma (University of Bradford School of Management)

May 2013

On the stationarity of per capita carbon dioxide emissions over a century

Abstract

This paper examines the stationarity of carbon dioxide (CO_2) emissions per capita for a set of 36 countries covering the period 1870-2006. We employ recently developed unit root and stationarity tests that allow for the mean reverting process to be nonlinear and take into account cross sectional dependence. By grouping countries according to their geographical proximity the importance of cross sectional dependence in panel unit root and stationarity tests is revealed. Using a recently developed nonlinear panel unit root test, we find strong evidence that the per capita carbon dioxide emissions over the last one hundred and fifty years are stationary. Our nonlinear specification captures the dynamics of the emissions time series data more effectively and we obtain evidence supporting stationarity for all country groups under study.

JEL Codes:C32, C33, Q28, Q54
Keywords: convergence, nonlinear unit roots, panel unit roots, heterogeneous panels, cross-section dependence

1 Introduction

The stationarity properties of carbon dioxide (CO_2) emissions per capita have assumed increasing importance in recent empirical work and policy debates. There has been increasing concern about rising emissions and the resulting policy challenges that are required on a global level. Stationary CO_2 emissions could imply gains in efficiency for the period under investigation (1870-2006) since there has been a significant increase in industrial production during this period. Nonetheless, stationarity evidence could imply that the greenhouse effect could potentially be mitigated. Stationarity is a concept that is closely related to the notion of convergence. Time series tests of convergence typically test for stationarity or for the presence of a unit root (see, for instance, **?**).

In this paper we employ a dataset of 36 countries that contains both developed and developing countries. These economies are at different stages of economic development. Within our set of countries, developed countries are experiencing a shift of economic focus usually from the industrial (and manufacturing) sector to the services sector. One would expect such a process to result in reduced emissions, as manufacturing activity reduces. Such a reduction in emissions in developed countries coexists with increased emissions in developing economies, as the agricultural sector in developing economies decreases in size and importance, and as the industrial (and manufacturing) sector increases in size and importance. As a result, it is of interest to investigate emissions based evidence closely linked to such a process of industrial structural change, with a focus on both developed and developing economies.

We employ recently developed unit root and stationarity tests that allow for cross sectional dependence. For the latter, countries are also grouped according to their geographical proximity. Our analysis also allows for the possibility that the mean reverting process is nonlinear, rather than assuming a linear mean-reverting process. Using a recently developed nonlinear panel unit root test, we find evidence that the per capita carbon dioxide emissions over the last one hundred and fifty years are stationary. Our nonlinear specification captures the dynamics of the emissions time series data more effectively and we obtain evidence supporting stationarity for all country groups under study.

To carry out our empirical analysis, we operate along two dimensions. On the time series dimension, we employ traditional unit root and stationarity tests. From the unit root tests we obtain estimates of half lives, as a measure of convergence. Half lives indicate the number of years that are required for half of the gap in the emissions level between the cross-sectional average and the country j to be eliminated. Nonlinear unit root tests allow us to examine the possibility that the mean reverting process is nonlinear. This is an important (and often overlooked distinction) because we have no reason to assume that the mean reverting process is, or has to be, linear[1]. On the panel dimension, we employ econometric procedures that take into account cross-sectional dependence. In particular, we make use of both unit root and stationarity tests. We employ a recently developed nonlinear panel unit root test which allows for the mean reverting process to be nonlinear in the panel.

Within the intertemporal budget constraint literature, **?** argues that stationarity and cointegration tests are incapable of rejecting sustainabilty. Although the above named literature examines different research question, the methodological tools are identical. For this reason, we will employ the term stationarity and we will not use the term sustainability.

The remainder of the paper is organized as follows: Section 2 presents the literature, Section 3 the data, whereas Section 4 discusses the econometric methodology. Section 5 provides the empirical results and Section 6 concludes.

[1] Many relationships are intrinsically nonlinear (in this context see for instance **?**)

2 Literature

A growing literature examines the stationarity properties of carbon dioxide emissions for both individual countries and groups, using univariate and multivariate time series techniques. Consideration of stationarity properties is an integral part of such empirical research. **?** analyses data for per capita carbon dioxide emissions for 109 countries employing seven regional panels (based on geographical proximity) between the period 1971-2003. They employ panel seemingly unrelated regressions augmented unit root tests. This allows them to take into account any cross-country correlations present in the data and they allow their panel specification to vary between countries. They conclude that carbon dioxide emissions exhibit evidence supporting stationarity and nonstationarity, depending on particular cases. They argue that seemingly unrelated regressions augmented Dickey-Fuller (SURADF) type tests that they employ are superior to other panel unit root tests employed in the literature. In related research, **?** apply a methodology proposed by **?** in order to carry out panel data stationarity tests for per capita carbon dioxide emissions for a panel of 21 Organisation for Economic Co-operation and Development (OECD) countries between 1950-2002. They find that relative per capita CO_2 emissions are stationary once they include structural breaks and allow for cross-sectional dependence in their model. In particular, structural breaks are identified in the 1960s and between 1970-1982.

? consider the link between environment and development, including the possible existence of a Kuznets curve for CO_2 emissions, focusing in particular on non-OECD countries. They do not find evidence supporting an environmental Kuznets curve, but two regimes are identified (i) first a low-income regime where emissions accelerate with economic growth and (ii) second, a middle to high-income regime associated with a deceleration in environmental degradation. **?** study CO_2 emissions in OECD countries and the link to energy consumption (especially nuclear energy) and make use of an autoregressive distributed lag approach to cointegration for estimation. They find that use of nuclear power reduces CO_2 emissions in some countries and little support for an environmental Kuznets curve. **?** considers alternative government policies aimed at reducing pollution emissions using an overlapping generations model.

? analyze CO_2 emissions for a set of 128 countries between 1960-2003. Their analysis makes use of the method proposed by **?** which basically allows for several alternative time paths and individual heterogeneity. They assess evidence for club convergence which basically involves identification of groups of countries that converge to different equilibria. **?** postulate a common and an individual specific component in their model, thereby allowing idiosyncratic behaviour to be modeled appropriately while at the same time an element of commonality is preserved across the panel by making use of an unknown growth component. This panel commonality in turn leads to an analogue of the notion of sigma convergence within a panel context which allows for a representation of panel convergence. **?** find that per capita carbon dioxide emissions in the early years of their sample converge, while later on (time period corresponding to more recent years) they find evidence supporting two separate convergence clubs. Each convergence club converges to a different steady state. Their research also finds support for transition between the two clubs (or states). Our study also looks into convergence by looking at evidence for stationarity for groups of countries in order to empirically examine evidence on convergence keeping in mind both the panel and time series dimensions of the data, as well as making use of recently developed linear and nonlinear unit root tests.

In an econometric framework of analysis analogous to our paper, **?** analyze the income convergence hypothesis by employing nonlinear unit root test proposed by **?** based on testing for the presence of a unit root using a nonlinear smooth transition autoregressive

(STAR) framework. **?** find, for a set of twelve OECD countries for which nonlinearity within income gaps is detected, two cases of long-run convergence and four cases of catching up.

? analyses evidence of stochastic convergence for both carbon dioxide and sulphur dioxide emissions. In particular, annual fossil-fuel carbon dioxide emissions data for the period 1751-2003 is employed. A pairwise convergence methodology is employed whereby all possible pairs of log per capita emission gaps are analyzed for all countries in the sample. Mixed evidence on stochastic convergence is observed depending on which particular unit root test is employed. To resolve such conflicts, **?** makes use of specific critical values obtained from ADF-KPSS (Augmented Dickey-Fuller (**?**) and the Kwiatkowski, Phillips, Schmidt and Shin (**?**)) joint tests which point towards small percentages of stationary pairs around a constant mean. Thus evidence against stochastic convergence is found for both types of emissions and this includes tests for OECD countries also.

? re-examine evidence on convergence within per capita emissions of carbon dioxide based on a sample of OECD countries spanning 1950-2002. They make use of a battery of stationarity and unit root tests, allowing for panel cross-sectional dependence, taking particular care to avoid the sort of misspecification observed in some previous studies related to trend stationarity. Their study fails to find support for convergence in CO_2 emissions for OECD countries.

? investigate per capita carbon dioxide emissions (and per capita GDP) for 86 countries between 1960-2000. They employ a panel KPSS test based on **?**. They conclude that per capita carbon dioxide emissions globally are regime-wise trend stationary. As far as particular country-groups are concerned, **?** find that for Africa and Asia per capita CO_2 emissions appear to be nonstationary, while evidence supporting regime-wise trend stationarity is found for America, Europe and Oceania. However, in a related paper **?** analyze evidence relating to stochastic and deterministic convergence in carbon dioxide emissions for a sample of 23 countries between 1960-2002, using the methodology proposed in **?**. Allowing for cross-sectional dependence and finite sample biases by making use of bootstrap methods, **?** finds evidence supporting both stochastic and deterministic convergence in carbon dioxide emissions which is in line with the results obtained by **?**.

? finds evidence for convergence in per capita carbon dioxide emissions for a set of 23 OECD countries, but evidence against convergence is obtained for a set of 88 countries in a global sample between 1960-2000. **?** investigate stationarity evidence for a cross country panel per capita carbon dioxide emissions based on annual observations for 88 countries between 1960-1990. Using the method for stationarity testing in heterogeneous panels proposed by **?**, **?** find the time series of per capita carbon dioxide emissions to be nonstationary for the case of most country groups.

? test for convergence in per capita carbon dioxide emissions for a set of countries (both developed and developing) using a data set between 1870-2002. They explicitly allow for cross-sectional dependence amongst countries in their sample and employ three distinct panel unit root tests for their empirical assessment. Their method is motivated by previous work by **?** and **?** where the basic idea is to first estimate and remove a common component from the data and thereafter test for convergence in the remaining idiosyncratic part. **?** find support for convergence within the panel as a whole and they also provide estimates for speed of convergence.

As we can see from the brief overview provided above, it is of critical importance to take into account possible cross sectional dependence and to allow for the possibility that the mean reverting process is nonlinear. Our paper makes a contribution to the literature by taking into account both these aspects.

3 Data

The data we use comprise the total fossil fuel carbon dioxide (CO_2) emissions from **?** and are in logarithmic form. In order to derive the per capita CO_2 emissions we used the population data from Maddison (2009), following **?**. Data for 36 countries are used in the analysis, namely Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Colombia, Cuba, Denmark, Ecuador, Finland, France, Germany, Hong Kong, India, Indonesia, Italy, Japan, Mexico, Netherlands, New Zealand, Norway, Peru, Philippines, Portugal, Spain, Sweden, Switzerland, Taiwan, Thailand, UK, Uruguay, USA and Venezuela.

4 Methodology

4.1 Country groupings used and motivation

In order to account for cross-sectional dependence we group the countries into four panels. The first group (see Table 1) consists of 16 developed countries, which is the same as the group considered in **?**, and will be referred to as the D16 group. The second group comprises 14 west European countries. The per capita CO_2 emissions data for these two groups cover the period 1870-2006. The other two groups of countries consist of eight Latin American and eight Asian countries, though the data span is shorter and covers the period 1921-2006 and 1907-2006, for the two groups respectively.

Table 1: Country groupings

D16	Western Europe	Latin America	Asia and Oceania
Australia	Austria	Argentina	Australia
Austria	Belgium	Brazil	China
Belgium	Denmark	Chile	India
Canada	Finland	Colombia	Indonesia
Denmark	France	Ecuador	Japan
Finland	Germany	Mexico	New Zealand
France	Italy	Peru	Philippines
Germany	Netherlands	Venezuela	Taiwan
Italy	Norway		
Japan	Portugal		
Netherlands	Spain		
Spain	Sweden		
Sweden	Switzerland		
Switzerland	UK		
UK			
USA			

4.2 Univariate unit root tests

First, five alternative univariate unit root and stationarity tests were applied to the per capita CO_2 emissions, namely the Augmented Dickey-Fuller (**?**) unit root test (ADF), the Kwiatkowski, Phillips, Schmidt, and Shin (**?**) stationarity test (KPSS), the Kapetanios, Shin and Snell (**?**) nonlinear unit root test (KSS), the Chong, Hinich, Liew and Lim (**?**) nonlinear unit root test (CHLL) and the **?** nonlinear unit root test. The first two are well know in the literature so we will only discuss the three most recent below.

? develop a new technique for the null hypothesis of a unit root against an alternative of nonlinear stationary smooth transition. Their test is based on the following exponential smooth transition autoregressive (ESTAR) specification:

$$\Delta y_t = \gamma y_{t-1}\left[1 - \exp\left\{\ -\theta y_{t-1}^2\right\}\right] + \varepsilon_t, \theta \geq 0, \tag{1}$$

where $\left[1 - \exp\left\{\ -\theta y_{t-1}^2\right\}\right]$ is the exponential transition function adopted in the test to present the nonlinear adjustment. The null hypothesis of a unit root in y_t implies that $\theta = 0$, hence we test

$$H_0 : \theta = 0$$

against the alternative

$$H_A : \theta > 0.$$

Because γ in equation (1) is not identified under the null, we cannot directly test $H_0 : \theta = 0$. To deal with this issue, KSS suggest reparameterisation of equation (1) by computing a first-order Taylor series approximation to specification (1) to obtain the auxiliary regression:

$$\Delta y_t = \delta y_{t-1}^3 + \varepsilon_t. \tag{2}$$

Assuming a more general case where the errors are serially correlated, regression (2) is extended to:

$$\Delta y_t = \sum_{j=1}^{p} \rho_j \Delta y_{t-j} + \delta y_{t-1}^3 + \varepsilon_t, \tag{3}$$

with the p augmentations used to correct for serially correlated errors. The null hypothesis of nonstationarity to be tested with either equation (2) or (3) is:

$$H_0 : \delta = 0$$

against the alternative

$$H_A : \delta < 0$$

and the t-statistic is

$$t_{NL} = \frac{\hat{\delta}}{se\left(\hat{\delta}\right)}. \tag{4}$$

KSS show that the t_{NL} statistic does not have an asymptotic standard normal distribution (the subscript NL indicates a nonlinear test). They tabulate the asymptotic critical values of the t_{NL} statistics via stochastic simulations.

To accommodate stochastic processes with nonzero means and/or linear deterministic trends, KSS modify the data as follows. In the case where the data has nonzero mean, the demeaned data are used, while for the case with nonzero mean and nonzero linear trend the demeaned and detrended data is under examination. To obtain the demeaned or detrended data, we first regress each series on a constant or on both a constant and a time trend, respectively, and then we save the residuals, which are used to carry out the test.

? propose a modification of the KSS by adding an intercept and a trend component into equation (3) to yield:

$$\Delta y_t = \mu + \sum_{j=1}^{p} \rho_j \Delta y_{t-j} + \delta y_{t-1}^3 + \phi G(trend) + \varepsilon_t, \tag{5}$$

where y_t is the original series and $G(trend)$ is the trend component, which can be a linear or quadratic trend. In the linear case the corresponding t-statistic is denoted as t_L and in the nonlinear case as t_{SQ}. The null and alternative hypotheses are given as in KSS and critical values are simulated by CHLL.

An assumption that implicitly is made by all the above mentioned unit root tests, both linear and nonlinear, is that mean reversion is symmetric at any point. In other words the parameters are identical for both negative and positive deviations. **?** relaxed this assumption and developed a unit root test against the alternative of symmetric or asymmetric ESTAR nonlinearity and for that reason he proposed an extension of the KSS test, by adding another term in equation (3) to yield:

$$\Delta y_t = \phi_1 y_{t-1}^3 + \phi_2 y_{t-1}^4 + \sum_{i=1}^{k} k_i \Delta y_{t-i} + \varepsilon_t, \tag{6}$$

where y_t is either the original series or the demeaned or detrended series, for the case where the data has nonzero mean or/and linear trend, respectively, defined as in the KSS test.

The null hypothesis of nonstationarity to be tested is:

$$H_0 : \phi_1 = \phi_2 = 0.$$

? derives the asymptotic critical values of the F-statistic via stochastic simulations. An additional feature of this approach is that if the unit root null is rejected then the null hypothesis of symmetric ESTAR can be tested against the alternative of asymmetric ESTAR using equation (6) where:

$H_0 : \phi_2 = 0$ against $H_1 : \phi_2 \neq 0$ with a standard F-test.

4.3 Panel unit root tests

Adding the cross-sectional dimension to the usual time dimension is very important in the context of nonstationary series, because it allows overcoming the low power issue of unit root tests in small samples[2]. However, the issue of heterogeneity in the parameters is introduced, when using panel data instead of individual time series and needs to be taken into account. Five types of panel unit root and stationarity tests were applied to the data. Such tests are the Im, Pesaran and Shin (**?**), the **?** and the Chiang, Kuan and Lo (**?** 2007) panel unit root tests, as well as the **?** and the **?** panel stationarity tests. With the exception of the **?** test, all employ the assumption of heterogeneity in the parameters.

The **?** (IPS) test is based on:

$$\Delta y_{i,t} = \alpha_i + b_i y_{i,t-1} + \sum_{j=1}^{p} \phi_{i,j} \Delta y_{i,t-j} + \varepsilon_{i,t}, \tag{7}$$

where $i = 1, 2, ..., N$ cross-section units or series, that are observed over periods $t = 1, 2, ..., T$. The null hypothesis of a unit root can be now defined as:

$$H_0 : b_i = 0, \forall i$$

against the alternative

$$H_A = \begin{cases} b_i < 0 & \text{for} \quad \text{i =1, 2, ...,} \ N_0 \\ b_i = 0 & \text{for} \quad \text{i =} \ N_0\text{+1, ..., N,} \quad \text{with} \quad 0 \text{ ¡ } N_0 \leq \text{N} \end{cases}$$

The alternative hypothesis allows unit roots for some of the individual series. Therefore, the IPS test evaluates the null hypothesis that all the series contain a unit root against

[2] *Wagner* (2008) demonstrated the importance of cross-sectional dependence in the data.

the alternative that some of the series are stationary. After estimating the separate ADF regressions, the average of the t-statistics for b_i from the individual ADF regressions, t_{iTi}, is defined as:

$$\bar{t}_{NT} = \frac{1}{N}\sum_{i=1}^{N} t_{iTi} \tag{8}$$

Under the assumption of cross-sectional independence, this statistic is shown to converge to a normal distribution. IPS propose a standardized statistic, denoted $W_{\bar{t}}$, which is based on the theoretical means and variances of t_{iTi}, $E(t_{iTi})$ and $Var(t_{iTi})$ respectively.

The IPS test assumes that the time series are independent across i. However, in many macroeconomic applications using country or regional data it is found that the time series are contemporaneously correlated. **?** (PES) relaxes the cross-sectional independence assumption and considers a one-factor model with heterogeneous loading factors for residuals and suggests augmenting the standard ADF regression with the cross-section averages of lagged levels and first differences of the individual series. The cross-sectional augmented ADF equation (CADF) is given by:

$$\Delta y_{i,t} = \alpha_i + b_i y_{i,t-1} + c_i \overline{y}_{t-1} + \sum_{j=0}^{p} d_{i,j} \Delta \overline{y}_{t-j} + \sum_{j=1}^{p} \delta_{i,j} \Delta y_{i,t-j} + \varepsilon_{i,t}, \tag{9}$$

where $\overline{y}_{t-1} = N^{-1}\sum_{i=1}^{N} y_{i,t-1}$ and $\Delta\overline{y}_{t-1} = N^{-1}\sum_{i=1}^{N}\left(\overline{y}_t - \overline{y}_{t-1}\right)$. Let $t_i(N,T)$ be the t-statistic of the OLS estimate of b_i. The panel unit root test is then based on the average of the individual cross-sectionally augmented ADF statistics (CADF). PES builds a modified version of IPS $\bar{t}_{NT}$ test:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T). \tag{10}$$

Pesaran proposes simulated critical values of CIPS for various sample sizes.
The **?** 2007 (CKL) test detects nonstationarity against nonlinear but globally stationary exponential smooth transition autoregressive (ESTAR) dynamic panels. For that reason, CKL first apply the KSS nonlinear unit root test to each cross-section and then form the simple average of these individual unit root test statistics:

$$t_\delta = \frac{1}{N}\sum_{i=1}^{N} t_{iNL}, \tag{11}$$

where t_{iNL} is the KSS statistic, given in equation (4) where the subscript NL indicates a nonlinear test. CKL tabulate asymptotic critical values of the t_δ statistics via stochastic simulations with the raw, the demeaned and the detrended data.

The **?** (HAD) test is similar to the KPSS test and has a null hypothesis of no unit root in any of the series in the panel. Like the KPSS test, the HAD test is based on the residuals from the individual OLS regressions of $y_{i,t}$ on a constant:

$$y_{i,t} = \alpha_i + u_{i,t},\ u_{i,t} = \phi_i u_{i,t-1} + \varepsilon_{i,t}. \tag{12}$$

Assuming that $\varepsilon_{i,t}$ are $I(0)$ for all i and that $\varepsilon_{i,t}$ are $iid(0,\sigma_\varepsilon^2)$ and cross-sectionally independent, the null hypothesis of the test is:

$$H_0 : |\phi_i| < 1, \forall i.$$

Given the residuals, the HAD test is defined by:

$$LM = \frac{1}{\hat{\sigma}_i{}^2 NT^2}\left(\sum_{i=1}^{N}\sum_{t=1}^{T} S_{i,t}^2\right), \tag{13}$$

where $S_{i,t}$ is the partial sum of the residuals and $\hat{\sigma}_i{}^2$ is an estimate of the long run variance of $y_{i,t}$. HAD shows that under mild assumptions:

$$Z = \frac{\sqrt{N}\,(LM - \xi)}{\zeta} \to \mathrm{N}\,(0,1)\,, \tag{14}$$

where $\xi = 1/6$ and $\zeta^2 = 1/45$. Thus, we should use the right-hand tail of a standard normal distribution for critical values of the HAD test. Following **?** we employed the quadratic spectral kernel method.

Finally, **?** (HAK) developed a stationarity test that takes into account cross-sectional dependence. Their test is basically the same as the KPSS test with the regression augmented by cross-sectional average of the observations, in the spirit of PES that augments the standard ADF regression. The limiting null distribution is the same as the HAD test. In a modified version for serial correlation, the HAK test proposes augmenting equation (12) as follows:

$$y_{i,t} = \alpha_i + \sum_{j=1}^{p} \phi_{i,j} y_{i,t-j} + \sum_{j=0}^{p} \psi_{i,j} \overline{y}_{t-j} + \varepsilon_{i,t}, \tag{15}$$

where $\overline{y}_t = N^{-1} \sum_{i=1}^{N} y_{i,t}$. The test statistic is then constructed in the same way as HAD, that is:

$$Z_A = \frac{\sqrt{N}\,\left(\overline{ST} - \xi\right)}{\zeta} \to \mathrm{N}\,(0,1)\,, \tag{16}$$

where $\overline{ST}$ is the average of the KPSS test statistic across i.

5 Empirical Results

Tables 2 and 3 provide results of the linear tests, while Tables 4 and 5 present the results obtained from nonlinear tests[3]. The ADF test statistic appears in the first column and the corresponding half lives in the following column. The following countries have stationary per capita CO_2 emissions (reject unit root null): Australia, Belgium, Canada, Colombia, Cuba, Denmark, Germany, Hong Kong, Japan, Peru, Portugal, Switzerland, UK, USA, Venezuela. That is 15 out of 36 countries. In this group, we have some of the biggest polluters (USA as well as large European states). On the other hand, we observe quite high p-values from China and India who are the most populous nations (0.341 and 0.873 respectively). This insignificance suggests that the per capita CO_2 emissions are not stationary in these countries, if we were to assume that the mean reverting process is a linear one. Table 2 also reports half-lives that appear to be high although one needs to bear in mind that linearity is assumed. The KPSS test statistic examining the null of stationarity is presented in the last columns of Tables 2 and 3. All the tests statistics are significant suggesting that we reject the null of stationarity in all cases.

The three KSS statistics are also presented in Tables 4 and 5. These are for the raw data, for the demeaned and for the detrended. Let us start with the countries that the null of a unit root can not be rejected in neither of the three cases. They are New Zealand,

[3]Our interest on the stationarity of the per capita CO2 emissions is stationarity around a constant. For that reason the ADF (**?**), KPSS (**?**), IPS (**?**), PES (**?**), HAD (**?**) and HAK (**?**) tests were performed only with intercept and no trend. However, in the KSS (**?**) test we modified the data to get the demeaned and detrended data, following Kapetanios, Shin and Snell (2003). Consequently, in the Sollis (2009) and the CKL (**?**[2007]) tests, which are extensions of the KSS test, we also modified the data in the same way. Finally, the CHLL (**?**) test is a modification of the KSS test, which takes into account a trend, using the original data, without any transformation.

Table 2: Linear tests

Countries	ADF	Half-lives	KPSS
Argentina	-1.600	18.668	1.170**
(1902-2006)	(0.478)		
Australia	-2.805*	35.149	1.514**
(1860-2006)	(0.060)		
Austria	-2.401	8.548	0.865**
(1860-2006)	(0.143)		
Belgium	-2.608*	10.719	1.388**
(1860-2006)	-0.093		
Brazil	-0.760	82.417	1.228**
(1902-2006)	(0.825)		
Canada	-4.052**	18.199	1.212**
(1870-2006)	(0.001)		
Chile	-0.987	34.986	1.207**
(1902-2006)	(0.755)		
China	-1.877	21.637	1.301**
(1902-2006)	(0.341)		
Colombia	-2.888*	6.019	1.106**
(1921-2006)	(0.051)		
Cuba	-18.393**	0.545	0.640**
(1941-2006)	(0.000)		
Denmark	-2.758*	27.709	1.545**
(1860-2006)	(0.066)		
Ecuador	-2.572	16.565	1.075**
(1917-2006)	(0.102)		
Finland	-1.287	37.321	1.579**
(1860-2006)	(0.634)		
France	-2.241	22.756	1.449**
(1860-2006)	(0.192)		
Germany	-2.816*	11.119	1.363**
(1860-2006)	(0.058)		
Hong Kong	-3.989**	4.277	1.174**
(1938-2006)	(0.002)		

*Notes: The optimal lag length is based on SIC. p-values in parentheses. **, * indicate rejection of the null hypothesis at 5% and 10% significance levels, respectively. KPSS critical values 5%=0.463, 10%=0.347.*

Uruguay and Venezuela. For the first two, there is an agreement across all three tests that the per capita CO_2 emissions are not stationary. For the third (Venezuela) KSS and KPSS point towards no-stationarity whereas ADF towards stationarity. For the rest 33 countries (out of a total of 36) one of the three KSS statistics is found to be significant at the conventional levels. The weakest cases are found to be Norway (demeaned at the 10%) and Philippines (detrended at the 10%). The CHLL has the same null as the KSS and stationarity can not be rejected in 6 out of the 36 cases. In particular stationarity can not be rejected in: Austria, Chile, Colombia, India, Indonesia and USA. These are cases where the conclusion is in line with the KSS (see Tables 4 and 5).

The **?** approach relaxes the assumption of a symmetric ESTAR nonlinearity and allows

Table 3: Linear tests (continued)

Countries	ADF	Half-lives	KPSS
India	-0.560	191.130	1.254**
(1900-2006)	(0.873)		
Indonesia	-0.010	31.977	1.246**
(1889-2006)	(0.954)		
Italy	-1.966	26.510	1.513**
(1860-2006)	(0.301)		
Japan	-5.448**	12.045	1.321**
(1868-2006)	(0.000)		
Mexico	-1.272	17.952	1.251**
(1902-2006)	(0.639)		
Netherlands	-1.409	28.920	1.528**
(1860-2006)	(0.576)		
New Zealand	-0.902	35.623	0.985**
(1900-2006)	(0.783)		
Norway	-2.065	25.026	1.477**
(1860-2006)	(0.259)		
Peru	-2.630*	8.373	1.166**
(1902-2006)	(0.090)		
Philippines	-0.991	32.940	1.095**
(1907-2006)	(0.753)		
Portugal	-4.374**	8.210	1.448**
(1870-2006)	(0.000)		
Spain	-0.574	125.543	1.536**
(1860-2006)	(0.871)		
Sweden	-2.080	21.759	1.448**
(1860-2006)	(0.253)		
Switzerland	-2.675*	16.952	1.423**
(1860-2006)	(0.080)		
Taiwan	-1.501	27.731	1.152**
(1898-2006)	(0.528)		
Thailand	-1.292	32.593	1.108**
(1931-2006)	(0.628)		
UK	-4.174**	3.268	0.857**
(1860-2006)	(0.001)		
Uruguay	-1.654	16.105	0.748**
(1932-2006)	(0.450)		
USA	-3.551**	25.326	1.311**
(1860-2006)	(0.008)		
Venezuela	-2.939**	6.234	1.445**
(1913-2006)	(0.045)		

Notes: see notes in Table 2.

for parameters to differ for positive and negative deviations of the series from its attractor of the same proportionate value. Looking at the three test statistics of the Sollis test, we reject the unit root null in 31 out of the 36 cases. Across all the three nonlinear unit root tests, we get strong evidence of nonstationarity in the cases of Australia, Cuba and New Zealand.

Table 4: Nonlinear tests

Countries	KSS			CHLL		Sollis		
	t_{NL}	t_{NL1}	t_{NL2}	t_L	t_{SQ}	F_{AE}	$F_{AE\mu}$	F_{AEt}
Argentina (1902-2006)	-2.789**	-2.707*	-2.921	-2.780	-2.716	4.042*	3.727	5.952*
Australia (1860-2006)	-1.908	-1.294	-1.481	-0.398	-0.669	1.124	1.151	1.461
Austria (1860-2006)	-4.252**	-4.272**	-4.755**	-4.961**	-4.428**	9.442**	9.542**	11.263**
Belgium (1860-2006)	-0.675	-2.856*	-3.997**	-2.375	-2.342	0.298	3.458	9.309**
Brazil (1902-2006)	-2.143*	-1.823	-4.069**	-1.726	-2.197	3.724*	5.441**	8.685**
Canada (1870-2006)	-0.371	-1.542	-2.318	-2.224	-2.852	50.746**	53.517**	52.789**
Chile (1902-2006)	-2.241**	-1.787	-3.312*	-3.550**	-2.862	4.036*	3.922	5.455
China (1902-2006)	-2.441**	-0.574	-5.147**	-2.312	-1.942	2.832	3.974	10.319**
Colombia (1921-2006)	-4.343**	-5.230**	-6.635**	-3.846**	-4.268**	42.985**	38.564**	37.092**
Cuba (1941-2006)	-0.972	-0.777	-3.068	-0.977	-0.994	0.463	1.394	4.352
Denmark (1860-2006)	-2.549**	-2.491	-1.463	-0.715	-0.903	3.258	3.182	1.408
Ecuador (1917-2006)	-2.819**	-2.008	-1.217	-1.039	-1.199	10.869**	3.771	0.911
Finland (1860-2006)	-2.410**	-1.802	-3.901**	-2.919	-2.337	3.876*	3.698	7.621**
France (1860-2006)	-1.911	-2.074	-4.368**	-1.212	-1.266	1.932	2.136	7.862**
Germany (1860-2006)	-0.827	-2.522	-4.828**	-1.554	-1.709	2.551	3.423	11.580**
Hong Kong (1938-2006)	-1.865	0.122	-0.127	1.149	1.065	6.107**	0.334	4.078

*Notes: The optimal lag length is based on SIC. t_{NL}, t_{NL1} and t_{NL2} refer to the model with the raw data, the demeaned data and the detrended data, respectively. t_L and t_{SQ} refer to the model with linear and squared trend, respectively. F_{AE}, $F_{AE\mu}$, F_{AEt} refer to the model with the raw data, the demeaned data and the detrended data, respectively. **, * indicate rejection of the null hypothesis at 5% and 10% significance levels, respectively, 5% critical values t_{NL}=-2.22, t_{NL1}=-2.93, t_{NL2}=-3.40, t_L=-3.35, t_{SQ}=-3.40, F_{AE}=4.365, $F_{AE\mu}$=4.954 and F_{AEt}=6.463, 10% critical values t_{NL}=-1.92, t_{NL1}=-2.66, t_{NL2}=-3.13, t_L=-3.05, t_{SQ}=-3.07, F_{AE}=3.527, $F_{AE\mu}$ =4.157 and F_{AEt}=5.460.*

Overall, the KSS test statistics were employed in order to examine the possibility that the mean reverting process is a nonlinear one (in particular an exponential smooth autoregressive process). The vast majority of the countries emissions (33 out of the 36) were found to be stationary at the conventional levels of significance. Within the CHLL the unit root null was rejected in 30 out of the 36 cases and with the Sollis test in 31 out of the 36. This is compared to 15 out of 36 with the ADF, so we can conclude that when allowing for

Table 5: Nonlinear tests (continued)

Countries	KSS			CHLL		Sollis		
	t_{NL}	t_{NL1}	t_{NL2}	t_L	t_{SQ}	F_{AE}	$F_{AE\mu}$	F_{AEt}
India (1900-2006)	-5.138**	-0.761	-3.292*	-3.331*	-3.178*	13.112**	9.466**	5.378
Indonesia (1889-2006)	-3.491**	-2.941**	-6.036**	-4.642**	-4.485**	30.863**	24.806**	41.318**
Italy (1860-2006)	-2.838**	-1.523	-3.922**	-2.125	-2.014	6.828**	6.657**	15.183**
Japan (1868-2006)	-1.610	0.161	-0.576	-0.817	-1.078	8.321**	0.075	0.355
Mexico (1902-2006)	-2.369**	-1.743	-5.716**	-1.529	-1.259	3.722*	3.789	6.381*
Netherlands (1860-2006)	-1.159	-2.050	-6.673**	-2.623	-2.304	2.014	2.352	18.031**
New Zealand (1900-2006)	-0.080	-1.062	-2.331	-1.405	-1.646	0.155	1.023	2.715
Norway (1860-2006)	-2.164*	-1.990	-3.843**	-1.186	-1.305	3.285	1.973	7.334**
Peru (1902-2006)	-2.241**	-3.790**	-3.802**	-2.363	-2.116	9.723**	9.944**	7.160**
Philippines (1907-2006)	-2.516**	-3.189**	-4.578**	-2.509	-2.178	10.936**	9.603**	13.741**
Portugal (1870-2006)	-3.025**	-0.005	-2.695	-2.747	-2.224	3.215	2.099	6.354*
Spain (1860-2006)	-2.620**	-0.573	-5.447**	-1.791	-1.516	3.416	2.494	22.457**
Sweden (1860-2006)	-1.924*	-1.638	-7.318**	-0.655	-0.808	4.023*	1.356	22.789**
Switzerland (1860-2006)	-3.606**	-3.186**	-7.554**	-2.720	-2.770	6.423**	5.594**	29.961**
Taiwan (1898-2006)	-3.714**	-2.282	-2.560	-2.080	-2.134	11.569**	10.523**	11.859**
Thailand (1931-2006)	-1.973*	-1.417	-1.787	-0.521	-0.412	3.317	1.419	1.765
UK (1860-2006)	0.267	-5.910**	-5.464**	-1.881	-2.447	1.669	18.732**	16.649**
Uruguay (1932-2006)	-1.727	-1.444	-1.359	-0.757	-0.768	4.966**	2.393	1.797
USA (1860-2006)	-0.018	-2.652	-2.167	-3.444**	-3.419**	0.142	5.422**	3.568
Venezuela (1913-2006)	-3.557**	-4.078**	-2.530	-2.637	-2.754	8.175**	8.487**	6.762**

Notes: see notes in Table 4.

the mean reversion process to be nonlinear there is increased evidence of stationarity.

At this point, it is important to repeat the argument that the evidence provided here do not point towards a sustainable $CO2$ per capita; stationarity and sustainability are

Table 6: Breusch-Pagan (1980) LM test of independence

	D16	Western Europe	Latin America	Asia and Oceania	All Countries
	(1870-2006)	(1870-2006)	(1921-2006)	(1907-2006)	(1921-2006)
LM	11571.831	8781.086	1756.972	2250.103	27178.833
p-value	0.00	0.00	0.00	0.00	0.00

different notions. On the contrary, we found evidence that most of the economies that have focused on the services sector provide stronger evidence for stationarity compared to emerging economies where traditional sectors like manufacturing and construction are more important. The increased evidence for stationarity that emerges when nonlinearity is taking into account again does not suggest sustainability. It, rather, suggests, from a policy point of view, that drastic (non-linear in a sense) measures could force the series to revert to their mean.

Next, we combine the time series with the cross section dimension. Testing for cross-sectional dependence is essential when dealing with panel data models, since it may lead to inconsistent or inefficient estimators and biased estimates. According to **?**, when $T > N$ the Lagrange multiplier (LM) test, developed by **?**, is adequate in order to test for cross-sectional dependence. Since the time dimension in our panel data is greater than the cross-sectional dimension, we employ the LM test and the results are shown in Table 6. According to our results, the null hypothesis of independence is rejected in all panels, providing evidence for cross-sectional dependence among all country groups.

We now turn to the panel tests that are presented in Table 7. Countries in our sample are categorised in Table 1. The panel concerning all countries consists of 32 countries instead of 36, in order to ensure balanced panels are available for analysis in order to perform the various tests on our data. Summarising the tests we employ, IPS is a panel unit root tests for heterogeneous panels, PES is a panel unit root test that takes into account cross-sectional dependence and CKL is a nonlinear panel unit root test. HAD and HAK are stationarity tests where the former is a panel version of the KPSS and the latter is in the same spirit but takes into account cross-sectional dependence. Given the evidence for the presence of cross section dependence, we should focus on the PES approach which augments the simple ADF with the cross section averages of lagged levels and first-differences of the variables. Extensive simulation results support this test (see Pesaran 2007 for more on this). The latter approach does take into account cross section dependence but assumes linearity. To relax this assumption we also report the CKL test that examines the null of a unit root against the alternative of a unit root process with a panel exponential smooth transition autoregressive. Both PES and CKL are unit root tests so we also report HAK which is a stationarity test (in the spirit of the KPSS).

For the D16 countries, we get evidence in favour of stationarity by all the panel unit root tests (with the exception of HAD) whereas this is reinforced by the stationarity tests when we take into account cross-sectional dependence (HAK). The same conclusion is reached when we consider Western Europe: strong evidence of stationarity emerges across all the tests (with the exception of HAD again). In the case of Latin America, Asia and All countries the two panel tests that do not account for cross-sectional dependence (IPS and HAD) are the ones that provide evidence against stationarity. Overall strong evidence that the per capita CO_2 emissions are stationary emerges from both the unit root and the stationarity tests when cross-sectional dependence is taken into account.

Table 7: Panel tests

	D16 (1870-2006)	Western Europe (1870-2006)	Latin America (1921-2006)	Asia and Oceania (1907-2006)	All Countries (1921-2006)
IPS	-4.475**	-2.794**	-1.273	2.632	-0.932
	(0.000)	(0.002)	(0.101)	(0.995)	(0.175)
PES	-3.548**	-3.571**	-2.792**	-2.789**	-3.030**
HAD	32.821**	31.345**	18.667**	18.177**	37.887**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
HAK	-0.720	-0.630	0.204	-1.353	-1.018
	(0.764)	(0.735)	(0.419)	(0.911)	(0.845)
CKL					
$t\delta$	-1.778*	-2.090**	-2.398**	-1.941*	-1.965**
$t\delta_1$	-2.773**	-2.724**	-3.236**	-1.631**	-3.072**
$t\delta_2$	-4.390**	-4.812**	-3.511**	-3.582**	-3.973**

*Notes: The optimal lag length is based on SIC. IPS, PES, HAD, HAK and CKL denote the Im, Pesaran and Shin (2003), the Pesaran (2007), the Hadri (2000), the Hadri and Kurozumi (2008) and the Chiang, Kuan and Lo (2007) tests, respectively. Corresponding p-values in parentheses, $t\delta$, $t\delta_1$ and $t\delta_2$ refer to the model with the raw data, the demeaned data and the detrended data, respectively, **, * indicate rejection of the null hypothesis at 5% and 10% significance levels, respectively, 5% critical values: PES= -2.25 (D16 and Western Europe), -2.32 (Latin America and Asia), -2.16 (All Countries), $t\delta$ =-2.02, $t\delta_1$ =-1.56, $t\delta_2$ =-1.53, 10% critical values: PES= -2.15 (D16 and Western Europe), -2.21 (Latin America and Asia), -2.08 (All Countries), $t\delta$ =-1.68, $t\delta_1$ =-1.32, $t\delta_2$ =-1.28.*

6 Conclusions

This paper examines the stationarity properties of per capita CO_2 emissions for a set of 36 countries covering the period 1870-2006. Linear and nonlinear unit root and stationarity tests are employed within our analysis. Nonlinear unit root tests examine the case where the mean reverting process is nonlinear. The ADF test indicates evidence supporting stationarity for 15 out of the 36 countries, while the nonlinear KSS unit root test indicates stationarity for 33 out of 36 countries, suggesting an exponential smooth transition might more successfully capture the dynamics of the time series under investigation. The latter inference (of possible nonlinearities) is also supported by a nonlinear unit root tests that allows for asymmetric mean reversion. This study does not draw any conclusions about sustainability but focus only on stationarity. From a policy point of view, we do not make any statements about the sustainability of the CO_2 emissions per capita. However, we do observe that the evidence of stationarity is more clear in richer countries which have outsourced some of the industries that are characterised by higher emissions. The stronger evidence in favour of stationarity that we observe when nonlinear unit roots are employed suggests that drastic policy measures could force a nonlinear mean-reverting behaviour in the series.

This evidence in support of stationarity is also confirmed along the panel dimension. Recently developed panel unit root and stationarity tests are employed to analyse these results further. We include linear as well as nonlinear tests that account for cross sectional dependence. Once nonlinear tests are incorporated, evidence is obtained indicating per capita CO_2 emissions are stationary, for all the different country groups that we have considered.

Some policy implications arise from our analysis. Further international co-ordination for abatement and emissions reduction is likely to assist the process of emissions reduction. Any incentives or policy measures which enable developing countries to substitute technologies involving lower emissions would contribute further. Greater international co-operation and policy consensus in this regard would assist emissions abatement.