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Convergence in Per Capita Carbon Dioxide Emissions Among G7 Countries: A TAR Panel Unit Root Approach

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Abstract The subject of this paper is the examination the convergence of per capita carbon dioxide emissions of the G7 countries during the 1960–2005 period in a nonlinear panel analysis framework. In this approach, first the linearity of the series was tested, and when the linearity was rejected, the threshold autoregressive (TAR) panel unit root test, which splits the data into two regimes, was employed to examine the stationarity properties of the series. Because the null of linearity was rejected in the first step, we tested the stationarity of the series using the TAR panel unit root test. In the TAR panel unit root test, we found that the United Kingdom was the transition country whose per capita carbon dioxide (CO_2) emissions determined the switch from one regime to the other. The results showed that convergence existed in the first regime and divergence, in the second. When we tested whether absolute or conditional convergence existed, we found that the per capita CO_2 emissions were conditionally converging in the first regime.

Keywords Carbon dioxide emissions · Convergence · G7 countries · Nonlinearity · Threshold autoregressive panel unit root test

1 Introduction

The need for using energy as an input for various economic activities (Chang and Lee 2008) together with increasing economic activities, especially in the developed countries, causes an increase in energy consumption. This increase in energy consumption in turn results in an increasing amount of gases that cause a greenhouse effect in the atmosphere, which ends up increasing global warming. The major gas causing the greenhouse effect in the atmosphere

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is carbon dioxide (CO_2), which is emitted through the use of fossil fuels such as petroleum, coal, and natural gas.

Several debates have taken place among countries to address global warming, which has become a serious threat in our age. During the Earth Summit in Rio de Janeiro in 1992, the developed countries agreed to balance their greenhouse gas emissions in 2000 to the 1990 level. The countries that undersigned the Kyoto Protocol of 1997 adopted stricter measures. These countries agreed that their CO_2 emissions in 2012 should be 6–8 % lower than those at the 1990 level. However, developing countries asserted that developed countries were responsible for the increase in greenhouse gases and objected to certain sections of the protocol, emphasizing that developed countries should lead in controlling CO_2 emissions, as well as controlling five other gas emissions. Thus, the change in CO_2 emissions of developed countries is critical.

Numerous measures have been taken, especially by developed countries, to meet the goals set by the Kyoto Protocol. One of the important measures is the stationarity of per capita CO_2 emissions. The necessity of using per capita measures in the analysis of CO_2 emissions has been emphasized by Soz (1997) in the Kyoto Protocol: "per capita basis . . . is a direct measure of human welfare." Also, as mentioned by Stegman (2005), individual activities such as car use cause greenhouse gases, so it can be assured that a per capita measure is necessary.

The per capita CO_2 emissions should be stationary in order to provide guidance for overcoming global warming (Lee et al. 2008). If the per capita CO_2 emissions include a unit root (integrated of order one [I(1)]), then shocks that affect the series have a permanent effect; if the per capita CO_2 emissions are stationary (integrated of order zero [I(0)]), then the effects of the shocks are transitory and implementation of policy decisions concerning the environment are partially compulsory (Lee and Chang 2009). In this study, by examining whether the effects of temporary shocks on relative emissions disappear over time, we tested the convergence hypothesis of CO_2 emissions. The seminal study belongs to Strazicich and List (2003). They analyzed the CO_2 emission convergence of 21 industrialized countries between the years 1960 and 1997 using Im et al. (2003) panel unit root test. The results of this study supported evidence of stochastic convergence of per capita CO_2 emissions over the sample period. Aldy (2006) investigated whether CO_2 emissions converged for two data sets. Although he found no evidence of convergence among 88 countries for the 1960–2000 period, he did find convergence among 23 Organisation for Economic Co-operation and Development (OECD) countries over this period, although the evidence for stochastic convergence is mixed. Ezcurra (2007) analyzed the spatial distribution of per capita CO_2 emissions in 87 countries from 1960 to 1999 by using a nonparametric approach and ascertained that there was a convergence process in this period though the process would not continue indefinitely. Lee and Chang (2008) utilized seemingly unrelated panel regressions augmented Dickey-Fuller unit root tests and analyzed whether there was convergence among 21 OECD countries. The results revealed that 14 out of 21 countries exhibited divergence. Chang and Lee (2008) investigated the convergence of per capita CO_2 emissions for 21 OECD countries during the 1960–2000 period by employing the Lagrange multiplier unit root test, which endogenously determines structural breaks. Their empirical findings provided evidence that the CO_2 emissions of these countries were stochastically converging. Barassi et al. (2008) investigated the same issue for the period from 1950 to 2002 by employing panel stationarity and unit root tests, and the results of the analysis suggested that per capita CO_2 emissions did not converge during the sample period. Utilizing the suite of test statistics proposed by Sen (2003), Lee et al. (2008) investigated the CO_2 convergence issue for 21 OECD countries during the 1960–2000 period and concluded that the relative per capita CO_2 emissions were stationary, indicating that the per capita CO_2 emissions were stochastically converging. Romero-Ávila (2008) examined the existence of stochastic and deterministic convergence of CO_2 emissions in 23 countries over the period 1960–2002, employing a panel stationarity test of Carrion-i-Silvestre et al. (2005). The results of their study provided strong evidence for supporting both stochastic and deterministic convergence in CO_2 emissions. Westerlund and Basher (2008) tested the convergence in the CO_2 emissions for 28 developed and developing countries using data spanning the period 1870–2002. They used three panel unit root tests, and the results showed evidence in favor of convergence for the period as a whole. Panopoulou and Pantelidis (2009) examined the hypothesis of stochastic convergence among 128 countries for the period 1960–2003, and the results of the study favored the existence of convergence for all countries in the early period of the sample. But for the recent years of the sample, there are two convergence clubs. One of the clubs contains countries with high per capita CO_2 emissions, and the other club contains countries with low per capita CO_2 emissions. Also a transition between the clubs exists. Lee and Chang (2009) applied a panel stationarity test developed by Carrion-i-Silvestre et al. (2005) for 21 OECD countries from 1950 to 2002 and found evidence for stochastic convergence. They also emphasized that the structural breaks that occurred in the 1960s and over the 1970–1982 period corresponded to time periods when fossil fuel became the main source of productivity. Jobert et al. (2010) investigated whether the emissions were converging across 22 European countries over the 1971–2006 period by employing the Bayesian shrinkage estimation method and found evidence for the absolute convergence.

Findings from the previous literature showed that different econometric methods and different samples provide different results for the CO_2 convergence phenomenon. In this study, we contributed to the existing literature by examining the convergence of per capita CO_2 emissions in a nonlinear framework. To the best of our knowledge, only one study considers nonlinearity while investigating the convergence of CO_2 emissions. Camarero et al. (2011) investigated the CO_2 convergence of 23 OECD countries by using the individual unit root test of Kapetianos et al. (2003), which tests the null hypothesis of unit root against the alternative of the globally stationary exponential smooth transition autoregressive process.

However, as indicated by Maddala and Wu (1999), individual unit root tests generally lack power, and one way of increasing this power is to use panel data unit root tests. Thus, in this study, we employed a recently proposed panel nonlinear unit root test. One advantage of the TAR panel unit root approach over the techniques used by the researchers in the previous studies is that by employing this approach at the first step, we tested the linearity against the nonlinearity, and in the case of finding nonlinearity, we continued analysis in a nonlinear framework. Moreover, this approach allowed us to split the data into two regimes. The decision of rejection or nonrejection of the null hypothesis of divergence in regime 1 is independent of the status in regime 2. That is, rejection of the null of divergence hypothesis in regime 1 does not affect the rejection or nonrejection of the null in the second regime. So we let the data have different characteristics in different regimes.

The disadvantage that occurs in the standard panel unit root tests (e.g., Im et al. 2003; Levin et al. 2002) can also be seen as a disadvantage for this approach. The rejection of the null hypothesis at the first step indicates that the panel is characterized by nonlinearity, but a small number of series might maintain the rejection of the null (e.g., Breuer et al. 2001, 2002; Wu and Lee 2009). Another disadvantage of the TAR panel unit root test is that it allows only two regimes and it is possible that data should be characterized by a three-regime threshold autoregressive model (see Kapetanios and Shin 2006).

The rest of this study is organized as follows: The next section defines the econometric methodology used in this study, the third section analyzes the empirical results, and the fourth section concludes the paper.

2 Econometric Methodology

In this study, we used a new unit root test introduced by Beyaert and Camacho (2008) that combines three main approaches: the threshold model, the panel data unit root tests, and the computation of critical values by bootstrap simulation. Using this test, we tested the null hypothesis of linearity against the alternative of nonlinearity at the first step. Next, on the condition that we rejected the null of linearity, we tested nonlinear divergence versus nonlinear convergence. If we rejected the null, then we tested absolute convergence against the conditional convergence.

We used the following model in this study:

$$\Delta c_{n,t} = \begin{array}{l} \left[\delta_n^I + \rho_n^I c_{n,t-1} + \sum_{i=1}^{p} \varphi_{n,i}^I \Delta c_{n,t-i}\right] I_{\{z_{t-1}<\lambda\}} \\ + \left[\delta_n^{II} + \rho_n^{II} c_{n,t-1} + \sum_{i=1}^{p} \varphi_{n,i}^{II} \Delta c_{n,t-i}\right] I_{\{z_{t-1}\geq\lambda\}} + \varepsilon_{n,t} \end{array} \quad \mathrm{n} = 1, \ldots, \mathrm{N}, \mathrm{t} = 1, \ldots, \mathrm{T}, \qquad (1)$$

where the subscript n refers to unit, the superscript t refers to the time period, and $c_{n,t} = \log(X_{n,t}) - (1/n)\sum_{n=1}^{N}\log(X_{n,t})$ shows the difference between log of per capita CO_2 emission of country n in year t $(\log(X_{n,t}))$ and the countrywide average log of per capita CO_2 emission at time $t((1/n)\sum_{n=1}^{N}\log(X_{n,t}))$. In Eq. 1 $I\,\{x\}$ is an indicator function that takes value 1 when x is true and takes value 0 otherwise. Therefore, it can be considered as a dummy variable that takes a unit value if the condition $I_{\{z_{t-1}<\lambda\}}$ is fulfilled. So Eq. 1 indicates that there are two different regimes that the dynamics of per capita CO_2 emissions follow, one of them at any t. When $z_{t-1} < \lambda$, the indicator function takes the value 1, the model is $\Delta c_{n,t} = \delta_n^I + \rho_n^I c_{n,t-1} + \sum_{i=1}^{p} \varphi_{n,i}^I \Delta c_{n,t-i} + \varepsilon_{n,t}$, and the system stands in *regime 1*; otherwise the indicator takes the value 0, the model becomes $\Delta c_{n,t} = \delta_n^{II} + \rho_n^{II} c_{n,t-1} + \sum_{i=1}^{p} \varphi_{n,i}^{II} \Delta c_{n,t-i} + \varepsilon_{n,t}$, and the system is in *regime 2*. λ is called the *threshold parameter*, whose value is unknown and has to be estimated with the other coefficients of the model. z_t is called the *transition variable*, which can be either exogenous or endogenous. Following Beyaert and Camacho (2008), we take z_t as endogenous. That is, the values of the transition variable are obtained from $c_{n,t}$ variables, and as emphasized by Beyaert and Garcia-Solanesit (2009), the transition variable pushes the system at time t into one of the regimes depending on the value it took at time $(t-1)$ compared to the threshold parameters. We chose $z_t = c_{m,t} - c_{m,t-d}$ for some m and $0 < d \leq p$. So, whether the emissions converge or not, z_t would be stationary.

Model 1 can be estimated by the least squares. There are some variables (λ, m and d) whose values are unknown and the coefficients are dependent on these variables, so we employed the feasible generalized least squares (FGLS) with grid search procedure to estimate model 1.[1] By employing a grid search technique, we estimated model 1 with different values of unknown parameters ($\theta_0 = (\lambda_0, m_0, d_0)$) and obtained the corresponding weighted sum of squared residuals. We selected the values θ_0, which give rise to the lowest weighted sum of squared residuals. Briefly, the main reason for employing a grid search is to determine the values of unknown parameters.

After estimating model 1, we tested the null hypothesis of the linear model against the alternative of model 1. However, some parameters were not defined under the null, so the linearity test, which is based on the likelihood-ratio principle, did not follow a standard distribution. Also, we do not know whether the series exhibits a unit root or not. We obtained

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[1] True value of variance-covariance is not known directly, so by employing estimated variance components instead of true values, we employed the FGLS method.

the critical values by bootstrapping, and the linearity test was carried out under considering both situations.

We tested the following null hypothesis against the alternative hypothesis that all coefficients are not equal:

$$H_{0,1} : \delta_n^I = \delta_n^{II}, \rho_n^I = \rho_n^{II}, \varphi_n^I = \varphi_n^{II}; \quad \forall n = 1, \ldots, N \text{ and } \forall i = 1, \ldots, p$$

If we could not reject this null hypothesis, we estimated the following linear Evans and Karras (1996) model:

$$\Delta c_{n,t} = \delta_n + \rho_n c_{n,t-1} + \sum_{i=1}^{p} \varphi_{n,i} \Delta c_{n,t-i} + \varepsilon_{n,t}; \quad n = 1, \ldots, N, \text{ and } t = 1, \ldots, T., \quad (2)$$

After estimating model 1, we calculated the likelihood function for both models and obtained $L_{1,2} = -2 \ln (L_2/L_1)$, where L_1 is the likelihood function of model 1 and L_2 shows the likelihood function of model 2. The null hypothesis is rejected if $L_{1,2}$ is too large, but because the size of $L_{1,2}$ is not known, Beyaert and Camacho (2008) obtained the critical value by mimicking Caner and Hansen's (2001) single equation bootstrap method. As mentioned above, we did not know whether the series had a unit root, so we carried out two sets of bootstrap simulations. The first set of simulations is based on an unrestricted estimation of model 2 and is called the *unrestricted bootstrap* simulation, and the second set of simulations is based on model 2 by imposing a unit root by restricting $\rho_n = 0$. If we could not reject the null of the linear model, we needed to test the convergence in a linear framework by estimating model 2, which is indeed a specification used by Evans and Karras (1996) and is extended with bootstrap simulations by Beyaert (2006). If we rejected the null hypothesis of divergence in the linear Evans–Karras methodology, then we had to test the null hypothesis of the conditional against the absolute convergence by testing $\delta_n = 0$ for all n.

When the null hypothesis of the linear model was rejected, we passed to the next step, where we tested the null hypothesis of convergence against the alternative of the divergence. The null and alternative hypotheses can be represented as:

$$H_{0,2} : \rho_n^I = \rho_n^{II} \quad \forall n, \quad (3)$$

$$H_{A,2a} : \rho_n^I < 0, \quad \rho_n^{II} < 0 \forall n, \quad (4a)$$

$$H_{A,2b} : \rho_n^I < 0, \quad \rho_n^{II} = 0 \forall n, \quad (4b)$$

$$H_{A,2c} : \rho_n^I = 0, \quad \rho_n^{II} < 0 \forall n. \quad (4c)$$

The null hypothesis in 3 shows the absence of the convergence under both regimes. The alternative hypothesis (4a) implies convergence of CO_2 emissions of the countries under both regimes. This case was called "full convergence" by Beyaert and Camacho (2008). The alternative hypotheses (4b) and (4c) denote *partial convergence*. That is, convergence took place under only one of the regimes.

Following Caner and Hansen (2001), Beyaert and Camacho (2008) proposed a Wald-type test statistic to test the null of full divergence against the alternative of full convergence:

$$R_2 = t_I^2 + t_{II}^2,$$

where $t_i = \frac{\hat{\rho}_n^i}{s_{\hat{\rho}_n^i}}$, for $i = I, II$ and $\hat{\rho}_n^i$ is the grid-FGLS estimation of ρ_n^i in model 1. Large values of R_2 are favorable to convergence. On the other hand, when $t_I (t_{II})$ is too small and $t_{II} (t_I)$ is not, we could not reject the hypothesis of convergence under regime 1 (2) and divergence under regime 2 (1). To find the appropriate probability values, bootstrap critical values had to be calculated.

The last step of the convergence analysis consists of discriminating between absolute and conditional convergence. Following Ferreira and Vieira (2009), we present the hypotheses as follows:

$$\begin{aligned} &H_{0,3} : \delta_n^i = 0, \quad \forall n \text{ and } \forall i, \\ &H_{A,3a} : \delta_n^i \neq 0, \\ &H_{A,3b} : \delta_n^I = 0, \quad \delta_n^{II} \neq 0 \\ &H_{A,3c} : \delta_n^I \neq 0, \quad \delta_n^{II} = 0 \end{aligned}$$

Under the maintained hypothesis $\rho_n^i < 0, \forall n$, $H_{0,3}$ shows the absolute convergence under both regimes, and the alternative in $H_{A,3a}$ reflects conditional convergence. The alternative hypotheses $H_{A,3b}$ and $H_{A,3c}$ imply conditional convergence in the first and second regimes and absolute convergence in the second regime and first regime, respectively. We tested the null hypothesis employing the tests ϕ_j, $j = a, b, c$ of Beyaert and Camacho (2008). The critical values were obtained by bootstrap simulations.

3 Empirical Results

In this study, we used per capita CO_2 emissions data (metric tons per capita) over the period of 1960–2005 for the G7 countries. We obtained our data set from World Development Indicators. For enabling a visual analysis of convergence, we present the data of per capita CO_2emissions in Fig. 1.

A visual inspection of Fig. 1 shows that the series tends to convergence on a common mean value, indicating a converging pattern among the CO_2 emission levels. To make a comparison for the TAR panel methodology, we first estimated the linear Evans–Karras model and presented the statistical results in Table 1. The results show that the per capita CO_2 emissions of G7 countries are converging because p value for the null of divergence is equal to 0.0000. We also conclude that there is absolute convergence among the countries because the p value for the absolute convergence is above the standard critical value $0.3310 > 0.05$.

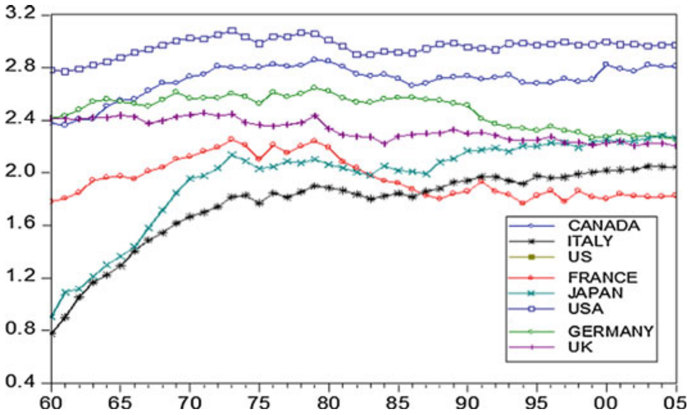

Fig. 1 Plot of logarithm of per capita CO_2 emissions for G7 countries

Table 1 Results of linear Evans–Karras model

Divergence versus convergence	Absolute versus conditional convergence
0.0000 Convergence	0.3310 Absolute convergence

Entries shows the bootstrap p values

Table 2 Results of TAR model

Linearity tests		Transition country	d	λ	% observations in regime I
Unrestricted	Restricted				
0.0050	0.0050	United Kingdom	1	1.2414	81.3953

Convergence tests

Divergence versus convergence			Absolute versus conditional convergence		
Regime I	Regime II	Both	Regime I	Regime II	Both
0.0000	0.6270	0.0010	0.0150	–	–
Partial convergence in regime I			Conditional in regime I		

Entries shows the bootstrap p values. d and λ indicate the delay and threshold parameters respectively

Table 2 shows the statistical results for the TAR model.[2] At the first step of the analysis, we rejected the null hypothesis of linearity because both the unrestricted and restricted bootstrap p values were below the 5 % critical value. We determined that the United Kingdom is the transition country whose per capita CO_2 emissions determine the switch from one regime to the other. It is also possible to choose the transition variable exogenously. For example, per capita energy consumption and per capita gross domestic product are among the possible transition variables. We estimated the threshold value as 1.2414 and the delay parameter $d$as 1. So it might be stated that the transition variable is $c_{UK,t} - c_{UK,t-1}$ and regime 1 corresponds to the years in which the difference between the growth rates of UK's per capita CO_2 emission and the average growth rate of the per capita CO_2 emissions of G7 countries was below 1.2414 %. However, regime 2 takes place when the relative growth of UK's per capita CO_2 emissions is above this level. Regime 1 has 81.3 % of the whole sample, whereas regime 2 corresponds to 18.7 % of observations of the sample.

The results of the convergence tests in the lower part of Table 2 show that convergence took place under only regime 1, suggesting that there was partial convergence. We reject the null of absolute convergence against the conditional convergence because the p value was 0.0150 in the first regime.

The graph of the TAR estimation is presented in Fig. 2. The visual information from Fig. 2 shows that regime 1 completely dominated the decades of the 1960s, 1990s, and 2000s and regime 2 partly dominates the 1970s and 1980s. This information can be interpreted as follows: per capita CO_2 emissions of G7 countries converged only during the decade of the 1960s and after 1990 but diverged partly between 1970 and 1990. The main reasons for this divergence is that fossil fuel became the main source of productivity, oil prices were higher, and nuclear power was later developed, as emphasized by Lee and Chang (2009). The convergence of CO_2 emissions, especially after 1990, shows that the developed countries started

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[2] To determine the optimal lag length in the linear and nonlinear TAR models, we employed Bayesian information criteria.

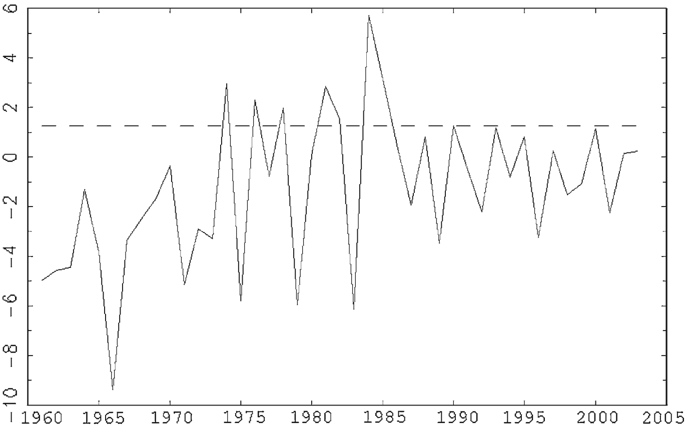

Fig. 2 Threshold variable for CO_2 emissions of G7 countries: *Horizontal line* refers to the threshold (1.2414). Threshold variable refers to the UK data (d = 1)

to consider the importance of global warming and to make decisions about reducing CO_2 emissions.

This condition implies that the energy consumption manners of developed countries changed under extraordinary circumstances, such as with oil crises, and these countries sought alternative energy sources. We suggest that developed countries should revise their energy consumption policies under such conditions. As CO_2 emissions converge except in crisis periods, those developing countries producing larger carbon emissions might be persuaded to stabilize their emissions and then reduce them, especially in the crisis periods. Shocks to the relative series are not permanent after 1990, so it is possible to forecast the future values of the series by examining past behavior. On the other hand, the existence of nonlinear convergence might be considered an important point to consider for nonlinearity for CO_2 projections.

4 Conclusion

Previous studies have used linear univariate or panel data methods to analyze the unit root properties of per capita CO_2 emissions. This study has used a recently introduced nonlinear panel unit root test that allows splitting data into two regimes depending on the threshold variable. By using the per capita CO_2 emissions of G7 countries from 1960 to 2005, we conclude that the CO_2 emissions of G7 countries diverged only when fossil fuel became the main source of productivity or in the case of an oil crisis. Apart from these situations, there is convergence among these countries, which can be an important point to which governments should pay attention. We also found that the emissions are nonlinear, which shows that testing nonlinearity for the convergence hypothesis should be considered before reaching any conclusions about convergence.

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