

1 **Convergence and Club Convergence of CO<sub>2</sub> Emissions at State Levels:**  
2 **A Nonlinear Analysis of the USA**

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14 **Abstract:** This study examined the convergence of CO<sub>2</sub> emissions at state-level in the USA, for  
15 the period from 1976 to 2014, based on a nonlinear and novel empirical framework. In so doing,  
16 we have applied Pesaran's (2007) test of pair-wise approach to testing convergence which gives in  
17 general what are the rejection frequencies and thus provides evidence of convergence. At the  
18 aggregate level, we also applied Chi-Young et al. (2006) half-life convergence test and the KPSS  
19 test with Fourier transformation which states are converging towards a cross-section average.  
20 Finally, we also adopted club convergence approach developed by Phillips and Sul (2007) to  
21 identify if the states are converging towards a club and last but not least we applied Schnurbus et  
22 al. (2016) test to find if there is possible evidence if club merging. We make two contributions to  
23 the literature: (i) we conduct a country-specific analysis by focusing on the US; (ii) we consider  
24 both convergence and club convergence. Our overall results from the Pesaran's (2007) pair-wise  
25 approach of convergence indicates that about 35% of the time the null of a unit root is rejected  
26 when ADF test is used and about 22% of the time null is rejected when ADF-GLS is used  
27 (irrespective of AIC or SBIC criterion). These results are also supported by KPSS stationary test  
28 which shows that null is rejected about 70 to 80% times. However, when Fourier function is  
29 incorporated in the KPSS test we find that the null hypothesis of stationarity is rejected only for  
30 Florida, Massachusetts, Montana, Nevada, New Mexico, Rhode Island, Texas indicating that only  
31 these states are non-convergent. Our overall results from club convergence (after club merging)  
32 show that USA states are forming 4 clubs. Our findings provide new insight into the convergence  
33 of CO<sub>2</sub> emissions at the state level in the USA and thus have profound implications in terms of  
34 environmental policy setting and Per Capita Emission (PCE) allocations.

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37 **Keywords:** CO<sub>2</sub> Emissions, Environmental Management, Convergence, Energy Policy, Club  
38 Convergence

39 **JEL Classification:** Q51, Q52, Q54, Q57, Q58, R11

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1 **1. Introduction**

2 Over the past few decades, two issues have conspicuously stood out: (i) unprecedented growth in  
3 the global economy and (ii) increasing rate of pollution. The statistics on carbon dioxide (CO<sub>2</sub>)  
4 emissions related to energy consumption suggest an increase of over 100% from 15.51 gigaton in  
5 1975 to 32.1 gigaton in 2016 (IEA, 2017). Among the attendant effects of emission is the threat of  
6 global warming and climate change. The general position in the literature is that global warming is  
7 predominantly caused by the emissions of Greenhouse Gases (GHGs) due to excessive  
8 consumption and dependence on the fossil energy sources to fuel economic development (Chiu,  
9 2017)<sup>1</sup>.

10 There have been international concerted efforts to tame the rising wave of GHGs. For instance, a  
11 number of treaties and accords have signed by governments of sovereign nations, which include  
12 the Intergovernmental Panel on Climate Change (IPCC) founded in 1988, the Kyoto protocol  
13 initiated in Kyoto, Japan in 1997 and more recently, the Paris Climate Conference Agreement 2015  
14 (COP21). Three factors have been identified to aid in the reduction of GHGs: mobilization and  
15 provision of financial resources; new technology adoption; and enhanced capacity building. The  
16 financial requirements to achieve these goals are enormous, thus serves as a discouraging factor.  
17 Other factors that can potentially impede the progress of this agreement include no legal bindings  
18 on emission targets; no specific financial supports; no change in specific policy premise; and no  
19 liability provision linked to financial compensation (Clemencon, 2016; Isa and Ganda, 2018).

20 Convergence in CO<sub>2</sub> emissions has been identified as an important tool that could help reduce  
21 GHGs. The fundamental problem of this approach related to the anticipated international policy  
22 agreement and allocation rules. For instance, countries with a relatively lower level of Per Capita

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<sup>1</sup> EAP (2020) reveals that a total of 6,677 Million Metric Tons of CO<sub>2</sub> was emitted in the US between 1990 and 2018. The five contributors are: Transportation (28%), Electricity (27%), Industry (22%), Commercial and Residential (12%) and Agriculture (10%).

1 Emissions (PCE), usually the developing countries, will favour egalitarian policy agreements  
2 because the allocation rule asserts that countries with higher PCE will carry a broader burden of  
3 the mitigation cost (Apergis and Payne, 2017; Rios and Gianmoena, 2018). This allocation problem  
4 becomes obvious and acute in a decentralized, developed and fiscal federalism practising countries-  
5 such as the United States- because of the concern over equitable and fair schemes of emissions  
6 allocation associated with the ongoing discussion at the Framework Convention on Climate  
7 Change. Although the fair share and contributions by each country (or state) to deal with the  
8 emissions is a debatable subject with a crucial political dimension, an important aspect to note at  
9 this juncture is that some scholars in the recent past (for instance, Aldy 2006, Barassi et al. 2008,  
10 Barassi et al. 2011 and Payne et al. 2014) have posited that PCE allocation schemes could cause  
11 limited concerns if emissions tend to converge over the passage of time. In fact, Apergis and Payne  
12 (2017) argue that the convergence of CO<sub>2</sub> emissions is the key conjecture to postulate many climate  
13 change models and thus policies. Achieving equilibrium in CO<sub>2</sub> emissions using such earlier cited  
14 approaches may resort to costly trade-offs i.e. higher adjustment costs and wealth transfers. Thus,  
15 it becomes imperative that CO<sub>2</sub> emissions must converge to specific target levels to meet the  
16 objective of curbing down the emissions level.

17 Hence, unravelling the convergence dynamics of CO<sub>2</sub> emissions, PCE has gained considerable  
18 interest in the recent literature. Furthermore, understanding the CO<sub>2</sub> emissions stochastic dynamics  
19 has also become inevitable to aid policymakers in designing the climate change proposals in the  
20 most efficient way (Panopoulou and Pantelidis, 2009). Acknowledging the importance of this issue  
21 in a recent study, Burnett (2016) argued that understanding the CO<sub>2</sub> emissions dynamics is of  
22 paramount importance to formulate an optimal mitigation policy. It implies that even in the case of  
23 persisting differences in regional emissions, a mitigation policy could be framed in a way that the  
24 underlying economic structure is least adversely impacted and abatement costs could also be  
25 optimized.

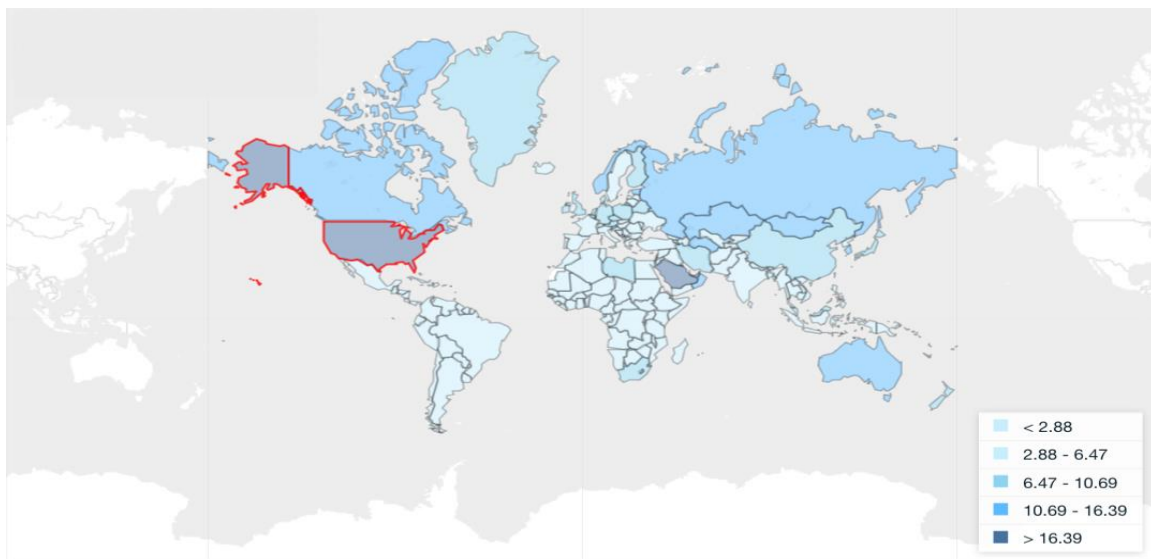
1 Digging deeper, a strand of the literature had shown that there is the need to account for the  
2 importance of club convergence. There is a need to look at the source and distribution of emission  
3 within a country to formulate new or ratify existing international agreements (Burnett, 2016).  
4 Hence, policymakers are interested in seeing the changing dynamics of the distribution of emission  
5 at the state level. The essence of this disaggregation is to determine whether the tail of the  
6 distribution of emission is widening or shrinking. It will also provide information on whether the  
7 policy has been effective or there is a need to make changes to it.

8 Based on the foregoing, the broad objective of this study is to examine the existence of convergence  
9 in CO<sub>2</sub> emissions for the United States of America. Also, we are investigating if there is  
10 convergence at club levels where the states can be grouped together in clubs. To empirically support  
11 our endeavour we are employing a very rich and novel set of empirical approaches. This is a major  
12 theoretical as well empirical contribution to the existing literature on the subject. Specifically, in  
13 this study, we are applying Pesaran's (2007) test of a pair-wise approach to testing convergence.  
14 Furthermore, the half-life convergence test suggested by Choi et al. (2004) is applied. At the  
15 aggregate level, we use the KPSS test with Fourier transformation as proposed by Becker et al.  
16 (2006). Thereafter, in order to identify the club convergence phenomenon, the approach developed  
17 by Phillips and Sul (2007) is adopted.

18 This literature adds two main innovations to the literature on CO<sub>2</sub> emissions. First, we conduct a  
19 country-specific analysis by focusing on the US. The need to account for country analysis stems  
20 from the failure to achieve convergence at a wider and larger scope. In fact the COP21 agreement  
21 proposes that member countries adopt a "Nationally Determined Contribution" to CO<sub>2</sub> emissions  
22 reduction based on countries specific characteristics, circumstance and nature. This exercise is in  
23 sharp contrast to Rios and Gianmoena (2018) who focused on 141 countries. Second, we consider  
24 both convergence and club convergence. Existing studies have individually analyses both  
25 convergence and club-convergence. In this study, we take a more comprehensive and rigorous

1 approach by examining convergence and club-convergence simultaneously. The club convergence  
2 adopted in this study is applied with states in America. This is in contrast to club convergence  
3 obtained along regional lines (e.g. Caramero et al., 2014; Morales-Lage et al., 2019 for EU  
4 countries).

5 The choice of the US is based fact that the country is a major emitter of carbon. Statistics show that  
6 as of 2013, US's CO<sub>2</sub> emissions in the world with per capita emission of 16.40 metric tons (see  
7 Figure-1). The propelling American industrial growth, coupled up with its natural endowment of  
8 fossil fuels such as coal reserves (27% of the world's aggregate) besides petroleum and natural  
9 gases have led to emissions on a massive scale. The Federal government has expressed deep  
10 concerns over the issue in the recent past and commitment to curb CO<sub>2</sub> emissions to 26-28% below  
11 2005 levels by the year 2025(Whitehouse, 2015). Moreover, academics and scholars have also  
12 repeatedly voiced the legitimate and reasonable concerns while analysing the dynamics of CO<sub>2</sub>  
13 emissions in the USA (see, for instance, Aldy 2006, Payne et al. 2014, Li et al. 2014, Burnett 2016).



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15 **Figure-1.** Carbon dioxide (CO<sub>2</sub>) emissions around the world in 2013 (in per capita metric tons)  
16 **Note:** The area highlighted with red borders represents the USA, **Source:** The World Bank  
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1 Our key findings suggested that the result of Pesaran's (2007) test depicts an impending state of  
2 convergence. The half-life convergence test showed a point estimate of the unbiased half-life of  
3 5.8 years with a 95% confidence interval of 4.8-7.2 years. The KPSS stationary test shows that the  
4 null of a unit root is rejected about 70-80% times. Overall, Phillips and Sul's (2007) approach  
5 identifies 4 clubs and the rest of the states are put together into another single club, in total five  
6 clubs. Concomitantly, these findings have profound implications for the formulation of climate  
7 policy based on per capita emissions.

8 The rest of the paper is structured as follows. The section 2 briefly reflect on the existing evidence  
9 on the subject to contextualise the argument and in the existing debate on the subject, section 3 sets  
10 out the empirical methodology and data employed as a mean to test the convergence and club  
11 convergence in the USA. The section 4 will present the findings which will lead us to conclude in  
12 the section 5.

## 13 **2. Existing Literature on CO<sub>2</sub> Emission Convergence**

14 There are various alternative forms of convergence concepts which have been discussed in the  
15 recent literature to unveil CO<sub>2</sub> emissions convergence pattern. The use of convergence concepts  
16 such as Beta Convergence (Baumol, 1986), Sigma Convergence (Barro and Sala-i-Martin, 1990;  
17 Sala-i-Martin, 1996), Stochastic Convergence ( Quah,1990; Quah,1990; Carlino and Mills,1993;  
18 Carlino and Mills, 1996), Club Convergence (Apergis and Payne, 2017; Panopoulou and  
19 Pantelidis, 2009; Phillips and Sul, 2007) is prevalent in past and recent literature besides several  
20 econometric techniques (such as clustering algorithms, cross-sectional and distributional analysis,  
21 unit root tests etc.).

22 The broad base of scholarly contributions is complementary and overlapping in nature; however,  
23 an attempt has been made to segregate the studies based on their central themes. The segregation  
24 of literature closely follows, Apergis and Payne, (2017). However, a detailed review is presented

1 in this study. The existing evidence on the subject can be classified into two categories. The first  
2 strand of literature focuses on the convergence of CO<sub>2</sub> emissions across countries using parametric  
3 approaches, most often, using variants of unit root tests. These studies primarily use unit root tests  
4 to draw conclusions on the convergence in respective countries. Overall, the literature offers  
5 contradicting evidence on the subject. For instance, some studies ( Strazicich and List, 2003; Chang  
6 and Lee, 2008; Romero-Ávila. 2008; Westerlund and Basher, 2008; Christidou et al., 2013) have  
7 argued in favour of stochastic convergence of CO<sub>2</sub> emissions, on the other hand, some studies  
8 contradicted ( Barassi et al., 2008) and while others have come up with rather mixed and  
9 inconclusive results (contrast, for instance, Aldy, 2006; Barassi et al., 2011; Lee and Chang 2008;  
10 Yavuz and Yilanci, 2013; Nguyen, 2005; Ezcurra, 2007; Criado and Grether, 2011).

11 Among the noteworthy studies on the CO<sub>2</sub> convergence, Strazicich and List (2003) employed a  
12 panel unit root tests and cross-section regressions on a rich dataset of 21 developed (OECD)  
13 countries, their findings suggested that there exists evidence of considerable convergence of CO<sub>2</sub>  
14 emissions among the under analysis countries. Their findings were supported by the later study by  
15 Chang and Lee (2008) which employed a Lagrange Multiplier (LM) unit root test which also  
16 provided significant evidence that CO<sub>2</sub> emissions in the 21 OECD countries converged  
17 stochastically when the structural breaks were controlled for. Further support to findings by  
18 Strazicich and List (2003) was provided by an empirical study by Romero-Avila (2008) which  
19 employed a unit root test using panel stationary test proposed by Lluís Carrion-i-Silvestre (2005).  
20 It was concluded that there is a stochastic and deterministic convergence of CO<sub>2</sub> emissions in the  
21 sample of OECD countries. A study by Westerlund and Basher (2008) employed an extended data-  
22 set of 27 countries from 1870-2002 and employed a Panel unit root test. They reported that report  
23 the evidence of CO<sub>2</sub> emissions convergence for the developed and developing countries in the  
24 sample set. Their findings were supported by a later study by Christidou et al. (2013) as they  
25 employed even a longer data-set ranking from 1870-2006 and used a nonlinear panel unit root test

1 to account for the nonlinearities. They strongly argued for the existence convergence of CO<sub>2</sub>  
2 emissions for a sample period of over a hundred years. In a nutshell, the findings of the studies  
3 acknowledged in this para are complementary and in a broader sense, they conclude on the presence  
4 of CO<sub>2</sub> convergence.

5 Despite the considerable amount of evidence reported on the convergence of CO<sub>2</sub> emissions by a  
6 number of studies acknowledged in the above para, there are also a number of studies which  
7 reported contradictory and mixed results. For instance, Barassi et al. (2008) on 21 developed  
8 (OECD) countries, employing a panel unit root test reported non-convergence of CO<sub>2</sub> emissions.  
9 They critiqued the methodological inaccuracies in the previous studies and attempted to address  
10 them (see Barassi, et al., 2008; for details). Similarly, a study by Aldy (2006) employing an  
11 Augmented Dickey-Fuller- Generalized least square unit root test, found mixed results. It was  
12 reported that although there is evidence of converging CO<sub>2</sub> emissions for the 23 OECD countries,  
13 however, on the global scale of 88 countries, the emissions appear to diverge. Perhaps, one  
14 implication of the finding was country and development level heterogeneity. Nevertheless, the  
15 divergence is not limited to the OECD and None-OECD countries, Lee and Chang (2008)  
16 employing at panel seemingly unrelated regressions augmented Dickey-Fuller (SURADF) unit-  
17 root tests reported that 14 out of 21 OECD countries exhibit divergence. They argued that these  
18 results are more robust than the results of the conventional panel unit root tests. Similarly, Barassi  
19 et al. (2011) using a unit root test, Local Whittle estimator and its variants suggested that 13 out of  
20 the 18 developed countries in their sample exhibit impending signs of convergence. A study by  
21 Yavuz and Yilanci (2013) on G-7 countries employed a Threshold Autoregressive (TAR) panel  
22 unit root test and which involved splitting the data into two regimes using TAR. Interesting, their  
23 results showed the evidence of convergence in the first regime and divergence in the second regime.  
24 In evidence from the US and specifically on the regional/states level, a study by Bult (2007)  
25 analysing the emissions of Sulphur Dioxides (SO<sub>2</sub>) and Nitrogen Oxides (NO<sub>x</sub>), they reported



1 stronger evidence of converging emissions rates during the federal pollution control years (1970–  
2 1999) than during the local control years (1929–1969). In an earlier study on US List (1999) which  
3 was also focusing on SO<sub>2</sub> and NO<sub>2</sub> emissions in 10 US Environmental Protection Agency (EPA)  
4 regions reported some convergence. However, in this study we are focusing on Co2 emissions  
5 which are a big proportion of GHGs in the US, constituting around 82% of total annual GHG  
6 emissions (EPA, 2018).

7 In terms of empirical approaches to analyse the convergence, there is a strand of literature that  
8 employed non-parametric approaches. For instance, a study by Nguyen (2005) employed a rich  
9 dataset of 100 industrial countries and Conditional Distribution Estimation and Cross-Sectional  
10 Panel Regression. However, reported very limited evidence of CO<sub>2</sub> emissions convergence.  
11 Similarly, in another endeavour with even a richer data set (140 countries), a study by Ezcurra  
12 (2007) using the Stochastic kernel and Ergodic distribution documented some evidence of  
13 reductions in disparities of CO<sub>2</sub> emissions around the world. However, it was argued that such  
14 convergences may not persist indefinitely. In another study by Ezcurra (2007b) on 100 countries  
15 employing Stochastic Kernel and Ergodic distribution, it was claimed that there is some evidence  
16 of CO<sub>2</sub> emissions convergence. Later analysis by Criado and Grether (2011) employed the  
17 empirical approach but an extended dataset of 166 countries. They concluded that countries with  
18 higher PCE tend to exhibit more divergences. Furthermore, that before the oil price shocks of  
19 1970's the spatial distribution of CO<sub>2</sub> emissions exhibit a flattening, right-skewed and non-  
20 stationary pattern. The pattern becomes more stable after the 1970s. In evidence from 25 European  
21 countries, a study by Herrerias (2007) employed at Distribution Dynamics and Asymptotic half-  
22 life convergence approach. Furthermore, they complemented their analysis by investigating the  
23 asymptotic half-life of convergence, mobility indices and the continuous version of the Ergodic  
24 distributions. Their results supported the convergence hypothesis among the EU countries although  
25 they also observed differences between sub-periods. The existing evidence on the subject discussed

1 in this section is summarised in the following Table-1:-

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**Table 1: Literature on Cross-country CO<sub>2</sub> emissions**

Study	Period	Sample	Methodology	Key Findings
<i>(a) Studies using Unit Root Tests</i>				
Strazicich and List (2003)	1960-1997	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom (UK) and the USA.	Panel unit root tests and cross-section regressions.	The study concludes an evidence of considerable convergence of CO <sub>2</sub> emissions among the sample countries.
Chang and Lee (2008)	1960-2000	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK and USA.	Lagrange Multiplier (LM) unit root test.	The results of the study provide significant evidence that CO <sub>2</sub> emission in the 21 OECD countries convergence stochastically when the structural breaks are controlled for.
Romero-Avila (2008)	1960-2002	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK and USA.	Unit root test using panel stationary test of Lluís Carrion-i-Silvestre (2005).	The results support both stochastic and deterministic convergence of CO <sub>2</sub> emissions over the sample counties.
Westerlund and Basher (2008) [22]	1870-2002	Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Denmark, Finland, France, Germany, Greece, India, Indonesia, Italy, Japan, Mexico, Netherlands, New Zealand, Peru, Portugal, Spain, Sweden, Switzerland, UK and the USA.	Panel unit root test.	The authors report the evidence of CO <sub>2</sub> emissions convergence for the developed and developing countries in the sample set.
Christidou, Panagiotidis and Sharma (2013)	1870-2006	Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Colombia, Cuba, Denmark, Ecuador, Finland, France, Germany,	Nonlinear Panel unit root test.	The authors strongly argue convergence of CO <sub>2</sub> emissions for a sample period of over

		Hong Kong, India, Indonesia, Italy, Japan, Mexico, Netherlands, New Zealand, Norway, Peru, Philippines, Portugal, Spain, Sweden, Switzerland, Taiwan, Thailand, UK, USA and Venezuela.		hundred years.
Barassi, Cole and Elliot (2008)	1950-2002	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the UK and USA.	Panel unit root test.	The study concludes a non-convergence of CO <sub>2</sub> emissions taking into account the methodological inaccuracies in the previous studies.
Aldy (2006)	1960-2000	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, UK and USA.	Augmented Dickey-Fuller- Generalized least square unit root test.	The study confirms the evidence of converging CO <sub>2</sub> emissions for the 23 OECD countries. However, on the global scale of 88 countries, the emissions appear to diverge.
Lee and Chang (2008)	1960-2000	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK and USA.	Panel seemingly unrelated regressions augmented Dickey-Fuller (SURADF) unit-root tests.	The study reports that 14 out of 21 OECD countries exhibit divergence. The authors argue these results to be more robust over the results of the conventional panel unit root tests.
Barassi et al. (2011)	1870-2004	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Italy, Japan, Netherlands, Norway, Portugal, Spain, Switzerland, Sweden, UK and USA.	Unit root test, Local Whittle estimator and its variants.	The result suggests that 13 out of 18 developed country sample exhibit impending signs of convergence.
Yavuz and Yilanci (2013)	1960-2005	Canada, France, Greece, Italy, Japan, UK and USA.	Threshold Autoregressive (TAR)	The study split the data into two regimes using TAR. The results

			panel unit root test.	show the evidence of convergence in the first regime and divergence in the second regime.
Bulte et al (2017)	1929 to 1999	USA	Minimum LM Unit Root Tests for Stochastic Convergence	Found stronger evidence of converging emission (nitrogen oxides and sulphur oxides) rates during the federal pollution control years (1970–1999) than during the local control years (1929–1969).
List (1999)	1929-1994	USA	Unit Root Tests	The unit root test suggests some convergence in the environmental quality (Sulfur dioxide & Nitrogen Oxides).
<b><i>(b) Studies using Nonparametric Approaches</i></b>				
Van Nguyen (2005)	1966-1996	100 industrial countries.	Conditional distribution estimation and cross-sectional panel regression.	The study concludes very limited evidence of CO <sub>2</sub> convergence.
Ezcurra (2007)	1960-1999	140 countries.	Stochastic kernel and ergodic distribution.	The study documents some evidence of reductions in disparities of CO <sub>2</sub> emissions around the world. However, the authors further state that such convergences may not persist indefinitely.

Ezcurra (2007)	1960-1999	87 countries.	Stochastic kernel and ergodic distribution.	The author claims some evidence of CO <sub>2</sub> convergence. In addition, the author also holds per capita income, climatic conditions and trade openness to be essential determinants of CO <sub>2</sub> emissions.
Criado and Grether (2011)	1960-2002	166 countries.	Stochastic kernel and ergodic distribution.	The study concludes that the countries with higher PCE tend to exhibit more divergences. Further, the study also argues that before the oil price shocks of 1970's the spatial distribution of CO <sub>2</sub> emissions exhibit a flattening, right-skewed and non-stationary pattern. The pattern becomes more stable after 1970.
Herrerias (2007)	1920-2007	Austria, Belgium, Bulgaria, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Romania, Spain, Sweden, UK.	Distribution dynamics and asymptotic half-life convergence approach.	Results support the convergence hypothesis among the 25 EU countries. It was observed that there were differences between sub periods.

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While keeping the mixed evidence on the country level studies cited in this section so far, specifically in the subject study we are analysing CO<sub>2</sub> emissions at state-level in the USA. The rationale for doing so is manifested in the earlier discussed importance of USA to the global economy and CO<sub>2</sub> emissions as well as the implications of potential state-level heterogeneity for the climate policy in the USA. Perhaps, the dynamics of CO<sub>2</sub> emissions at state-levels are important to help in the formulation of environmental policy. On this aspect, Auffhammer and Steinhauser (2007) reported that the state-level analysis (disaggregate series and accounting for spatial effects) improved their forecast also helpful in the formulation of environmental policy. As the states with decreasing per capita emissions and a “greener” median voter are more likely to push toward voluntary cutbacks in emissions. Hence, it is vital to consider the convergence of CO<sub>2</sub> emissions at state levels. Nonetheless, we are not only analysing the dynamics of CO<sub>2</sub> emissions and convergence among states of the USA at the national level but also considering the element of club convergence (convergence in the various groups).

**3. Methodology**

To achieve our objective and to gain a deeper understanding of the convergence, in this study we employed a very novel and rich set of empirical approaches. Our empirical framework entails a number of steps. At first step, we will use Pesaran’s (2007) test and Pair-wise approach to test for the Convergence which gives in general what are the rejection frequencies and thus provides evidence of convergence. In the second step, we will adopt the approach of Chi et al (2004) and Donggyu Sul in order to understand estimate the Half-Life to CO<sub>2</sub> emissions convergence using the Panel Dataset. This is one of the contribution of this paper as no previous study on this subject has explored the convergence by employing this approach. In the third step, at the aggregate level, we will use the KPSS test with Fourier transformation as proposed by Becker et al. (2006). The notion is to find out the evidence of a country level convergence as the first two steps are based on panel models. At this juncture we use KPSS test with Fourier transformation on data  $y = \ln(\text{CO}_{2i}/\text{avgCO}_{2i.z})$  i.e., CO<sub>2</sub> of one state (in consideration) is divided by the average value of CO<sub>2</sub> from all states and then we take log value of that ratio for our testing. In the next step, we adopted Club convergence approach Phillips and Sul (2007) and identified

1 club members. The basic reason to do this is that some states may not be converging on average but they  
 2 may be converging within a group (i.e., in their clubs). Lastly, after we have identified the club members  
 3 of different clubs we again followed the estimation process discussed in the third step, for each identified  
 4 clubs in order to deeper understand about the convergence.

### 5 **3. 1 Methods**

6 Becker et al. (2006)' Fourier stationarity test

7 This section briefly presents the Becker et al. (2006)' KPSS methodology (more information can be  
 8 found in Chang et al., 2013). Becker et al. (2006) start from the Kwiatkowski et al. (1992) stationarity  
 9 test and propose a test that allows for a deterministic seasonality term in the regression, using a Fourier  
 10 function. As stated above, the Fourier function can account for unknown forms and/or a number of  
 11 smooth breaks. Different from the well-known Lee and Strazicich (2003) test, pre-specification of the  
 12 number and form of structural breaks are not prerequisites of this test, as these are controlled by the test  
 13 through a selected frequency component of a Fourier function. Let us consider the following data  
 14 generating process (DGP):

$$15 \quad y_t = a_0 + \beta t + \gamma_1 \sin(2\pi kt/T) + \gamma_2 \cos(2\pi kt/T) + x_t + \xi_t, \quad (1)$$

16 where the  $x_t$  process is described as:

$$17 \quad x_t = x_{t-1} + \zeta_t, \quad (2)$$

18 where  $\xi_t$  are stationary errors and  $\zeta_t$  are independent and identically distributed (i.i.d) with  
 19 variance  $\sigma_\zeta^2$ .

20 Under the null hypothesis ( $H_0 : \sigma_\zeta^2 = 0$ ), the process described by equations (1) and (2) is  
 21 stationary. The rationale for selecting  $[\sin(2\pi kt/T), \cos(2\pi kt/T)]$  as the Fourier expression  
 22 (where  $k$  is the frequency and  $T$  is the sample size) is motivated by its ability to approximate  
 23 absolutely integrable functions to any desired degree of accuracy, where  $\gamma = [\gamma_1, \gamma_2]'$  measures  
 24 the amplitude and displacement of the frequency component, and represents the frequency  
 25 selected for the approximation.



1 If  $H_0: \gamma_1 = \gamma_2 = 0$ , is rejected, the series must have a nonlinear component. In this regard,  
2 Testing for the presence of non-linear terms, Becker et al. (2006) propose a F(k) test. However,  
3 the distribution of F(k) does not have to be non-standard because of the presence of the nuisance  
4 parameter. In this paper, we estimate the critical values for all series used by first generating  
5 10,000 random series under the null of linearity, and thereafter, using the optimum frequency  
6 of all actual series to calculate the F-statistic for all of the 10,000 pseudo series. Lastly, the  
7 critical values from the sorted vector of the pseudo-F-statistic are obtained. Using this property  
8 of equation (2), Becker et al. (2004) develop a test wherein first, one needs to obtain the  
9 residuals from the following equations:

$$10 \quad y_t = a_0 + \gamma_1 \sin(2\pi kt/T) + \gamma_2 \cos(2\pi kt/T) + \zeta_t \quad (3)$$

11 and

$$12 \quad y_t = a_0 + \beta t + \gamma_1 \sin(2\pi kt/T) + \gamma_2 \cos(2\pi kt/T) + \zeta_t. \quad (4)$$

13 where equation (3) tests the null of level stationarity, whereas equation (4) tests the null of trend  
14 stationarity. The test statistic is given by:

$$15 \quad \tau_{KPSS} = \frac{1}{T^2} \frac{\sum_{t=1}^T \tilde{S}_t(k)^2}{\tilde{\sigma}^2}, \quad (5)$$

16 where  $\tilde{S}_t(k) = \sum_{j=1}^l \tilde{\zeta}_j$  and  $\tilde{\zeta}_j$  are the OLS residuals from regressions (3) and (4), respectively.

17 Here, Becker et al. (2006) suggest, similar to the KPSS framework and following the PP-type  
18 approach, that a nonparametric estimate of  $\sigma^2$  can be obtained by choosing a truncation lag  
19 parameter  $l$  and a set of weights  $\varpi_j, j = 1, 2, \dots, l$ .

$$20 \quad \sigma^2 = \tilde{\eta}_0 + 2 \sum_{j=1}^l \varpi_j \tilde{\eta}_j \quad (6)$$

21 where  $\tilde{\eta}_j$  is the  $j^{\text{th}}$  sample autocovariance of the residuals  $\zeta_t$  from equations (3) and (4),  
22 respectively.

23 In this paper, we follow Carrion-i-Silvestre and Sansó (2006) for the choice of the kernel.  
24 On this aspect, for comparing different procedures to establish a boundary rule, Carrion-i-

1 Silvestre and Sansó (2006) demonstrate that the proposal of Sul et al. (2005) is the best one in  
2 terms of size and power. Further, as in Becker et al. (2006), we obtain the frequencies in  
3 equations (3) and (4) via the minimization of the sum of squared residuals (SSR). Becker et al.  
4 (2006) demonstrate that the loss of power is associated with a large number of frequencies and  
5 therefore suggest the use of no more than one or two frequencies. Consequently, we first  
6 determine the maximum frequency equal to 5. That is, we estimate the sum of squared residuals  
7 for each frequency.

8 More precisely, in the first step, we estimate equation (3) for each integer  $k=1, \dots, 5$ ,  
9 following the recommendations of Enders and Lee (2012a), who state that a single frequency  
10 can capture a wide variety of breaks. A grid-search is performed to find the best frequency, as  
11 there is no *a priori* knowledge concerning the shape of the breaks in the data. In the second  
12 step, we resort to the stationarity test proposed by Becker et al. (2006), using the obtained best  
13 frequency in the first step.

14

### 15 **3. 2. Data**

16 *The USA CO<sub>2</sub> emissions data on the state level for all the states for the period of 1976-2014 was*  
17 *employed. The choice of time horizon is based on the availability of a balanced panel dataset. The*  
18 *annual data was obtained from the U.S. Energy Information Administration (EIA). The selected*  
19 *timeframe is induced by the availability of data.*

### 20 **4. Analysing and Finding**

21 The starting point of our analysis is to conduct the Pesaran's pair-wise test for CO<sub>2</sub> emissions. To do  
22 this, we selected a maximum of 11 lags and show AIC and SBC criteria at 5% and 10% level of  
23 significance. Our results are reported based on tests that consider: (i) intercept only; and (ii) intercept  
24 and linear trend. These results are presented in Panel A of Table 2.

25

**Table 2: Pairwise Approach to Test Convergence.**

<b>Panel A: Below results obtained using Pesaran (2007) Pair-Wise test.</b>								
Maximum Lag-Order was:	11				Maximum Lag-Order was:	11		
Average Lag-Order by AIC:	3.629				Average Lag-Order by AIC:	4.781		
Average Lag-Order by SBC:	1.621				Average Lag-Order by SBC:	1.945		
Case II: An Intercept Only				Case III: An Intercept and a Linear Trend				
	AIC	SBC	AIC	SBC	AIC	SBC	AIC	SBC
ADF	0.288**	0.267**	0.348***	0.347***	0.366**	0.353**	0.457***	0.430***
ADF-GLS	0.146**	0.156**	0.229***	0.246***	0.189**	0.227**	0.262***	0.304***
ADF-WS	0.157**	0.158**	0.214***	0.231***	0.197**	0.206**	0.282***	0.313***
KPSS	0.746**		0.808***		0.541**		0.688***	
<b>Panel B: Results based on approach followed by Choi et al. (2006)</b>								
	No bias corrections	Nickell bias corrected	Time aggregation Bias corrected	Nickell and Time Aggregation bias corrected				
	$\hat{\rho}$	$\hat{\rho}$	$\hat{\rho}$	$\hat{\rho}_{GNTAU}$	$H_{0.025}$	$H_{0.5}$	$H_{0.975}$	
Alabama	0.892	0.947	0.815	0.883	4.676	5.584	6.892	
Alaska	0.892	0.964	0.833	0.906	5.766	7.033	8.958	
Arizona	0.888	0.943	0.806	0.877	4.451	5.274	6.436	
Arkansas	0.892	0.95	0.815	0.887	4.798	5.754	7.142	
California	0.897	0.947	0.812	0.883	4.716	5.584	6.811	
Colorado	0.887	0.947	0.812	0.88	4.524	5.425	6.731	
Connecticut	0.888	0.954	0.821	0.89	4.913	5.934	7.443	
Delaware	0.899	0.906	0.76	0.827	3.11	3.651	4.391	
Florida	0.879	0.936	0.8	0.87	4.191	4.997	6.147	
Georgia	0.886	0.923	0.786	0.852	3.713	4.315	5.125	
Hawaii	0.886	0.95	0.815	0.887	4.794	5.754	7.152	
Idaho	0.894	0.947	0.815	0.883	4.662	5.584	6.922	
Illinois	0.895	0.964	0.83	0.903	5.533	6.781	8.699	
Indiana	0.892	0.95	0.818	0.89	4.948	5.934	7.368	
Iowa	0.885	0.919	0.78	0.845	3.521	4.127	4.958	
Kansas	0.889	0.947	0.812	0.883	4.683	5.584	6.877	
Kentucky	0.899	0.933	0.795	0.864	4.057	4.747	5.69	
Louisiana	0.891	0.961	0.83	0.9	5.398	6.547	8.27	
Maine	0.896	0.957	0.824	0.896	5.197	6.329	8.04	
Maryland	0.893	0.954	0.821	0.893	5.026	6.125	7.785	
Massachusetts	0.896	0.964	0.833	0.906	5.689	7.033	9.142	
Michigan	0.892	0.954	0.821	0.893	5.038	6.125	7.759	
Minnesota	0.891	0.957	0.827	0.896	5.197	6.329	8.04	
Mississippi	0.888	0.954	0.818	0.89	4.938	5.934	7.39	
Missouri	0.897	0.968	0.836	0.909	5.861	7.303	9.615	
Montana	0.885	0.933	0.797	0.864	4.006	4.747	5.788	
Nebraska	0.887	0.94	0.803	0.87	4.217	4.997	6.096	

Nevada	0.902	0.926	0.786	0.852	3.687	4.315	5.172
New Hampshire	0.896	0.964	0.833	0.906	5.641	7.033	9.263
New Jersey	0.887	0.954	0.818	0.89	4.911	5.934	7.446
New Mexico	0.888	0.954	0.821	0.893	5.081	6.125	7.663
New York	0.891	0.954	0.821	0.893	5.072	6.125	7.684
North Carolina	0.892	0.943	0.806	0.877	4.372	5.274	6.599
North Dakota	0.884	0.867	0.715	0.777	2.366	2.751	3.262
Ohio	0.883	0.95	0.815	0.883	4.762	5.584	6.721
Oklahoma	0.886	0.954	0.818	0.89	4.933	5.934	7.4
Oregon	0.891	0.954	0.821	0.89	4.932	5.934	7.401
Pennsylvania	0.886	0.95	0.815	0.887	4.825	5.754	7.086
Rhode Island	0.897	0.964	0.83	0.903	5.535	6.781	8.694
South Carolina	0.892	0.957	0.824	0.896	5.216	6.329	7.997
South Dakota	0.889	0.95	0.815	0.887	4.802	5.754	7.134
Tennessee	0.906	0.957	0.824	0.896	5.191	6.329	8.053
Texas	0.894	0.906	0.763	0.83	3.225	3.723	4.379
Utah	0.885	0.947	0.812	0.88	4.518	5.425	6.745
Vermont	0.896	0.964	0.833	0.906	5.685	7.033	9.153
Virginia	0.884	0.943	0.809	0.877	4.403	5.274	6.534
Washington	0.883	0.943	0.806	0.877	4.535	5.274	6.275
West Virginia	0.888	0.957	0.824	0.896	5.245	6.329	7.933
Wisconsin	0.891	0.947	0.815	0.883	4.665	5.584	6.914
Wyoming	0.893	0.968	0.836	0.909	5.928	7.303	9.447

1 Note: In panel A- (1) Each test is conducted at the 5% significance level. (2) In this code, the critical values are  
2 NOT depending on T and lag-order p. (3) Bandwidth for KPSS test is  $\text{round}((T^{1/3}) \times 0.75)$  (4) \*\*[Fraction of  
3 Rejections, based on 5% nominal level tests] (5) \*\*\*[Fraction of Rejections, based on 10% nominal level tests].  
4 In panel B – Results reported in this panel are based on the Choi et al (2006) who employed this approach to test  
5 PPP convergence originally.

6  
7 Source: Authors' computation. Note: the reason for omitting entries in SBC criteria and KPSS test is that Pesaran test does not  
8 report them in their computation  
9

10 The results of the ADF test shows that the fraction of the rejection of the null hypothesis of unit root is  
11 very small. It takes the value of 0.289(0.367) for the intercept (intercept and trend) using the AIC criteria.  
12 There is a noticeable decline in the fractions of rejection when ADF-GLS and ADF-WS tests are  
13 considered. Overall, the small proportion of the rejection of the null hypothesis points to the fact that  
14 PCE, at the state level, is divergent. The high values of fraction of rejection for KPSS test that were  
15 estimated to be 0.746(0.541) for the intercept (intercept + trend), further reinforce the evidence of  
16 divergence in the sample. Studies whose results are similar to ours include Lee and Chang (2008),  
17 Herrerias (2013), and El-Montasser et al. (2015). Further to the above, we calculated the speed of  
18 convergence using the Choi et al. (2016) half-life convergence and these are presented in Panel B of

1 Table 2. This gives information on the time required to eliminate half of the initial gap between actual  
2 emissions levels and the steady-state. The advantage of this test is that it overcomes the biases induced  
3 by inappropriate cross-sectional aggregation of heterogeneous coefficients, small-sample estimation  
4 bias of dynamic lag coefficients, and bias induced by time aggregation (See Choi et al 2006 for details).  
5 The results of the half-life estimation for the CO<sub>2</sub> convergence indicates that the duration from 2.75  
6 years (North Dakota) to 7.3 years (Missouri) is required to reduce the level of emission to halve in order  
7 to achieve a steady state. The average half-life of convergence was 5.70 with a 95% confidence interval  
8 of 5.4 – 5.9 years. This to some extents support earlier results of divergence among PCE at the state  
9 level. The closet study to our results is Westerlund and Basher (2008) who obtained half-life  
10 convergence to range between 3.1 and 6.1 years for both developing and developed countries.  
11 The next stage of our empirical strategy is to examine KPSS that accounts for Fourier functions. This  
12 test is examined for both constant and constant with the trend. Table 3 has these results in two panels  
13 namely Panel A and B for constant and trend models respectively.

14 **Table 3: KPSS test with Fourier function results for entire sample**

<b>Panel A: The results for Constant with Fourier drift stationarity</b>									
	Optimum frequency	Optimum ssr.	Optimum F-stat.	95%	99%	Optimum band	Fourier stat.	95%	99%
Alabama	1	0.0395	22.5079***	3.404	5.465	1	0.101	0.183	0.290
Alaska	1	0.289	18.8008***	3.374	5.355	1	0.225**	0.179	0.326
Arizona	1	0.1478	56.4488***	3.324	5.480	1	0.075	0.182	0.271
Arkansas	1	0.1376	3.3274	3.482	4.996	1	0.096	0.182	0.273
California	1	0.2285	37.5809***	3.173	6.322	3	0.231	0.489	0.669
Colorado	1	0.0202	73.0987***	3.504	5.752	1	0.202**	0.171	0.256
Connecticut	1	0.1447	13.0899***	3.471	5.267	1	0.151	0.165	0.260
Delaware	1	0.4679	40.653***	3.694	6.213	1	0.064	0.179	0.293
Florida	1	0.1151	12.868***	3.419	5.651	4	0.842***	0.511	0.827
Georgia	1	0.0618	40.8632***	3.314	5.661	1	0.024	0.174	0.248
Hawaii	1	0.1664	7.7179***	3.458	5.969	1	0.033	0.169	0.255
Idaho	2	0.2799	8.9681***	3.659	5.595	1	0.438***	0.182	0.283
Illinois	1	0.0846	48.6627***	3.484	5.147	1	0.206**	0.180	0.310
Indiana	2	0.0119	4.1993**	3.293	5.114	1	0.286**	0.185	0.305
Iowa	1	0.1959	17.7594***	3.535	5.473	4	0.269	0.484	0.721
Kansas	1	0.0384	35.4435***	3.575	5.334	2	0.096	0.434	0.700
Kentucky	1	0.0818	26.6459***	3.483	5.927	1	0.104	0.172	0.248
Louisiana	2	0.0768	14.1319***	3.293	5.174	3	0.407	0.472	0.737
Maine	1	0.1979	2.6399	3.019	5.430	1	0.122	0.173	0.255
Maryland	1	0.1373	23.0785***	3.560	5.953	2	0.087	0.410	0.674

Massachusetts	1	0.1919	18.2066***	3.689	5.364	4	0.182	0.451	0.656
Michigan	1	0.0588	9.8012***	3.413	5.051	2	0.139	0.431	0.659
Minnesota	1	0.045	13.7664***	3.324	5.180	1	0.1239	0.182	0.319
Mississippi	1	0.0496	40.8844***	3.265	5.438	1	0.4061**	0.169	0.228
Missouri	1	0.0325	54.337***	3.164	4.855	1	0.0196	0.183	0.270
Montana	1	0.354	12.4944***	3.283	6.402	1	0.056	0.170	0.307
Nebraska	1	0.1246	20.7568***	3.289	5.083	1	0.0529	0.184	0.273
Nevada	1	0.934	23.2356***	3.309	5.589	1	0.1486	0.175	0.297
New Hampshire	1	0.1288	14.8744***	3.582	5.355	2	0.0984	0.434	0.623
New Jersey	1	0.0436	41.1981***	3.622	5.648	1	0.2028**	0.175	0.246
New Mexico	1	0.1045	23.61***	3.628	6.037	1	0.2267**	0.184	0.268
New York	1	0.2925	12.0951***	3.266	5.077	3	0.2835	0.466	0.727
North Carolina	2	0.1203	11.3595***	3.255	5.596	3	0.2917	0.490	0.735
North Dakota	1	1.1367	14.6192***	3.437	5.795	3	1.2936***	0.454	0.655
Ohio	1	0.0716	35.317***	3.544	6.265	1	0.2128**	0.169	0.289
Oklahoma	2	0.0639	0.5146	3.308	5.512	1	0.1614	0.174	0.248
Oregon	2	0.0502	9.7562***	3.210	5.383	1	0.0427	0.171	0.260
Pennsylvania	1	0.0949	21.4255***	3.499	5.091	1	0.1682	0.172	0.280
Rhode Island	1	0.3046	6.722***	3.419	5.946	1	0.0637	0.182	0.302
South Carolina	1	0.0216	42.3941***	3.212	4.980	1	0.1607	0.184	0.266
South Dakota	1	0.0934	9.7278***	3.225	5.266	1	0.0471	0.191	0.275
Tennessee	1	0.1292	6.3823***	3.423	5.101	1	0.1489	0.177	0.249
Texas	1	0.2053	17.9654***	3.319	5.108	3	0.393	0.480	0.756
Utah	1	0.0899	17.0162***	3.220	4.819	1	0.0184	0.182	0.270
Vermont	2	0.1437	2.6929	3.464	5.014	3	0.374	0.436	0.721
Virginia	1	0.0625	2.7048	3.424	5.046	1	0.1469	0.182	0.283
Washington	1	0.1361	20.7089***	3.429	5.717	1	0.165	0.195	0.300
West Virginia	2	0.0513	7.0059***	3.562	6.266	1	0.4194***	0.182	0.256
Wisconsin	1	0.0231	9.0016***	3.428	4.873	1	0.1349	0.162	0.321
Wyoming	1	0.2189	21.5697***	3.373	5.094	2	0.1451	0.4138	0.603

**Panel B: The results for Constant and trend with Fourier trend stationarity**

	Optimum frequency	Optimum ssr.	Optimum F-stat.	95%	99%	Optimum band	Fourier stat.	95%	99%
Alabama	1	0.0348	19.0763***	3.641	6.123	1	0.040	0.053	0.065
Alaska	1	0.1674	18.8384***	3.593	5.698	1	0.040	0.053	0.067
Arizona	1	0.0702	35.8999***	3.098	5.108	1	0.046	0.056	0.069
Arkansas	1	0.0809	5.5074***	3.513	5.472	1	0.028	0.056	0.070
California	1	0.0205	97.1551***	3.340	5.397	1	0.038	0.056	0.071
Colorado	1	0.012	66.3057***	3.189	4.822	1	0.026	0.054	0.068
Connecticut	1	0.0528	9.2118***	3.187	5.848	1	0.030	0.054	0.068
Delaware	1	0.1365	12.5628***	3.667	5.671	1	0.025	0.057	0.073
Florida	1	0.0353	11.9829***	3.763	5.614	4	0.331***	0.154	0.223
Georgia	1	0.0607	12.704***	3.317	5.068	1	0.025	0.056	0.068
Hawaii	2	0.0996	8.5757***	3.612	5.237	1	0.0362	0.057	0.068
Idaho	1	0.0958	24.6821***	3.382	5.420	1	0.027	0.055	0.070
Illinois	1	0.0244	138.5393***	3.166	5.400	1	0.0422	0.056	0.071
Indiana	2	0.0108	3.0653	3.736	5.439	2	0.0786	0.133	0.194
Iowa	2	0.0321	6.4459***	3.556	5.460	4	0.1024	0.151	0.209
Kansas	1	0.0382	13.8201***	3.362	5.906	2	0.091	0.137	0.199
Kentucky	1	0.0114	5.5247***	3.428	5.324	1	0.0463	0.053	0.068
Louisiana	2	0.0546	12.3429***	3.466	6.072	3	0.133	0.158	0.234
Maine	1	0.1754	4.8093**	3.604	6.343	1	0.0465	0.056	0.070
Maryland	1	0.037	12.19***	3.132	5.016	2	0.0471	0.130	0.184
Massachusetts	2	0.0608	4.2231**	3.319	4.977	4	0.2152***	0.152	0.207
Michigan	1	0.0142	4.8213**	3.333	6.590	2	0.0445	0.136	0.196
Minnesota	1	0.0293	28.5844***	3.338	5.381	1	0.0298	0.057	0.073
Mississippi	1	0.0358	32.4346***	3.682	5.738	1	0.0535	0.056	0.074
Missouri	1	0.0325	50.5816***	3.462	5.289	1	0.0193	0.055	0.068
Montana	2	0.1511	10.043***	3.302	5.249	1	0.0921***	0.054	0.070
Nebraska	1	0.0479	5.1458**	3.412	5.617	1	0.0335	0.054	0.069
Nevada	2	0.0699	3.4032**	3.401	5.239	3	0.2377***	0.153	0.213
New Hampshire	1	0.1176	16.4198***	3.354	5.905	2	0.0505	0.139	0.202
New Jersey	1	0.0324	9.8355***	3.671	6.226	4	0.1512	0.155	0.218
New Mexico	1	0.0638	2.8883	3.370	5.084	4	0.2139***	0.145	0.202
New York	1	0.0373	40.0432***	3.350	4.774	1	0.0247	0.055	0.069
North Carolina	2	0.0331	13.884***	3.550	5.521	3	0.0733	0.152	0.211
North Dakota	1	0.0576	105.6152***	3.594	5.193	1	0.0283	0.055	0.070
Ohio	1	0.0092	122.8591***	3.131	5.921	1	0.0485	0.054	0.068
Oklahoma	1	0.0357	5.9526***	3.405	5.821	1	0.0228	0.056	0.068
Oregon	2	0.0502	8.4455***	3.427	5.052	1	0.0427	0.054	0.070
Pennsylvania	1	0.0181	38.4488***	3.096	5.613	2	0.0687	0.134	0.207
Rhode Island	2	0.2399	10.8406***	3.290	5.156	1	0.0618***	0.055	0.066
South Carolina	1	0.0178	32.7744***	3.279	5.006	1	0.0373	0.054	0.069
South Dakota	1	0.0924	9.7127***	3.066	5.187	1	0.0383	0.054	0.067
Tennessee	1	0.0426	3.097	3.422	5.300	1	0.0391	0.055	0.067
Texas	2	0.0226	15.9083***	3.398	5.295	1	0.1151***	0.055	0.070
Utah	1	0.0899	15.7802***	3.629	5.403	1	0.0184	0.055	0.072

Vermont	1	0.1147	6.8699***	3.305	5.647	1	0.0294	0.054	0.069
Virginia	1	0.0251	15.8909***	3.388	5.536	1	0.0376	0.056	0.074
Washington	1	0.0585	7.7225***	3.399	5.404	1	0.036	0.056	0.071
West Virginia	2	0.0423	6.7081***	3.363	4.778	2	0.1254	0.136	0.207
Wisconsin	1	0.0166	18.2175***	3.198	5.114	1	0.037	0.053	0.069
Wyoming	1	0.052	43.2759***	3.513	5.428	1	0.0514	0.056	0.075

1 Note: \*\* denotes rejection of the null hypothesis at 5% level of acceptance. \*\*\* denotes rejection of the null  
2 hypothesis at 1% level of acceptance.  
3 Source: Authors' computation. Note: the reason for omitting entries in SBC criteria and KPSS test is that Pesaran's test does  
4 not report them in their computation  
5

6 These results presented by employing the KPSS stationary test compliment the earlier results on the  
7 stationarity using Pesaran (2007) pair-wise approach. There was a clear indication that the null was  
8 rejected for about 70% to 80% times. Further, results based on full sample data (i.e., without club  
9 formations) with constant Fourier stationarity test provide evidence that the null hypothesis of  
10 stationarity was not rejected for states such as but not limited to Georgia, Hawaii, Montana, Nebraska,  
11 Oregon South Dakota and Utah. However, with constant and trend Fourier stationarity test it showed  
12 that for Indiana, New Mexico, Tennessee the Fourier based model is an appropriate choice, and the null  
13 hypothesis of stationarity is rejected only for Florida, Massachusetts, Montana, Nevada, New Mexico,  
14 Rhode Island, Texas indicating that only these states are not convergent. These findings implied that  
15 there are state-level heterogeneities for which it would be appropriate to consider the aspect of club  
16 convergence. Due to the fact that we have established the existences of two groups, as a result of  
17 heterogeneity among the states.

18 **Table 4: Results Based on Club Convergence**

19 **Panel A1: Club Convergence Test**

20  
21 Full Sample: Alabama, Alaska, Arizona, Arkansas, California, Colorado, Connecticut, Delaware,  
22 District of Columbia, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky,  
23 Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana,  
24 Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North  
25 Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, Rhode Island, South Carolina, South Dakota,  
26 Tennessee, Texas, Utah, Vermont, Virginia, Washington, West Virginia, Wisconsin, Wyoming

27 Beta Coefficient: -0.8208

28 t-statistics: -18.6026

29

30 **1<sup>st</sup> club:** North Dakota and Wyoming

31 **Beta Coefficient=** 0.192



1 **t-statistics:** 3.2

2

3 **2<sup>nd</sup> Club:** Alsaka, Iowa, West Virginia

4 **Beta Coefficient** = 0.012

5 **t-statistics:** 0.133

6 **Divergent:** Iowa

7

8 **3<sup>rd</sup> Club:** Indiana, Kentucky, Louisiana, Montana and Nebraska

9 **Beta Coefficient** = 0.145

10 **t-statistics:** 1.275

11 **Divergent:** Kentucky and Montana

12

13 **4<sup>th</sup> Club:** Alabama, Arkansas, Colorado, Georgia, Illinois, Kansas, Maine, Michigan, Minnesota,  
14 Mississippi, Missouri, New Hampshire, New Mexico, Ohio, Oklahoma, South Carolina, South Dakota,  
15 Tennessee, Texas, Utah, Wisconsin.

16 **Beta Coefficient** = -2.006

17 **t-statistics:** -5.640

18 **Divergent:** South Dakota and New Mexico

19

20 **5<sup>th</sup> Club:** Arizona, California, Connecticut, Delaware, Florida, Hawaii, Idaho, Maryland,  
21 Massachusetts, Nevada, New Jersey, New York, North Carolina, Oregon, Rhode Island, Vermont,  
22 Virginia and Washington.

23 **Beta Coefficient:** = 0.143

24 **t-statistics:** 1.341

25

26 **Panel A2: Summary of Club Convergence Test**

log(t)	Club1	Club2	Club3	Club4	Club5
Coeff	0.192	0.012	0.145	-0.19	0.143
T-stat	3.2	0.133	1.275	-1.563	1.341

27

28

29 **Panel B: Clubs Merging Analysis**

30 **New Club 1** (Club 1 + other convergent clubs)

31 Club merging statistics -0.814

32 (-19.498)

33 **New Club II** (Club 2 + other convergent clubs)

34 Club merging statistics -0.795

35 (-11.754)

36 **New Club III** (Club 3 + other convergent clubs)

37 Club merging statistics -0.698

38 (-11.178)

39 **New Club IV** (Club 4 + other convergent clubs)

40 Club merging statistics -0.190

41 (-1.563)

42 **New Club V** (Club 5 + other convergent clubs)

43 Club merging statistics -0.143

44 (1.341)

45

**Panel C: Clubs Merging Analysis based on Schnurbus et al. (2016)**

log(t)	Club1+2	Club2+3	Club3+4	Club4+5
Coeff	-0.273	-0.08	-0.462	-0.698
T-stat	-6.509	-0.698	-5.253	-11.178

**Panel D: Final Club Memberships**

log(t)	Club1	Club2	Club3	Club4
Coeff	0.192	-0.08	-0.19	0.143
T-stat	3.2	-0.698	-1.563	1.341

**Panel D2: Final Club classifications**

**Club 1:** | North Dakota | Wyoming |

**Club 2:** | Alaska | Indiana | Iowa | Kentucky | Louisiana | Montana | Nebraska | West Virginia |

**Club 3:** | Alabama | Arkansas | Colorado | Georgia | Illinois | Kansas | Maine | Michigan | Minnesota | Mississippi | Missouri | New Hampshire | New Mexico | Ohio | Oklahoma | Pennsylvania | South Carolina | South Dakota | Tennessee | Texas | Utah | Wisconsin |

**Club 4:** | Arizona | California | Connecticut | Delaware | Florida | Hawaii | Idaho | Maryland | Massachusetts | Nevada | New Jersey | New York | North Carolina | Oregon | Rhode Island | Vermont | Virginia | Washington |

Source: Authors' Computations

Notes: Testing for the one-sided null hypothesis  $\hat{b} \geq 0$  against  $b < 0$ , the analysis makes use the critical value  $t_{0.05; rT-2-1=228} = -1.65156$  across all cases. Statistical significance at the 5% level is denoted by 'a', rejecting the null hypothesis of convergence. The figures in parenthesis denote t-statistics.

Results of the club-convergence are presented in Table 4. Essentially, we examined five different clubs/subgroups, which consist of 2, 3, 5, 22 and 18 countries, respectively. A formal test of convergence would give answers to inquires whether we can merge clubs to form a larger convergence, on the one hand, and also give general information on each club. It is presented in Table 4 that there is convergence in club one member states (North Dakota and Wyoming). These states are similar in terms of socio and economic fundamentals such as GDP per capita, population density, and geographical locations. Thus, it could be argued that the PCEs are high and not be too different from each other. This is due to the fact that North Dakota is an oil-producing state, while Wyoming fracking is celebrated for its large oil and mining sites. Hence, both states would converge towards steady states in the long run. The speed of convergence is estimated to be one-fifth of the average of the full sample's speed. We proceed to inquire if the rest group forms the other convergent club. The significance of the t- statistics shows that we can repeat the clustering procedures. This procedure would continue until the t-statistics for the repeated clustering is no longer significant. The second club convergence has three member countries (Alaska, Iowa and West Virginia). These states economic activities revolves around agriculture. Iowa could be regarded to have diverging tendencies due to their higher in population density, income (GDP per

1 capita). Alaska and West Virginia are among the lowest GDP level and GDP growth. The speed of  
2 convergence of this club is somehow low. This might be attributed to the fact that the club has  
3 representatives of both convergence and divergence tendencies.

4 The third club membership includes Kentucky, Indiana, Louisiana, Montana and Nebraska. These states  
5 economic activities is a mix of both agricultural, manufacturing and industrial. It could be argued that  
6 these countries are related in terms of median income level (GDP per capita), and housing units.  
7 However, it could be deduced that Montana and Kentucky are divergent from this club. This could be  
8 due to the fact that the level of industrialization is relatively low (for instance, Kentucky is famous for  
9 its distillery industry, while Montana is widely known as cattle ranching). Thus, these diverging states  
10 could be due to low carbon emissions. Another plausible reason for this could be related to higher  
11 population in Kentucky, which is estimated to be about four folds of Montana's. Also, the population  
12 growth rate in the former is twice that of the latter (United States Census Bureau). It is worthy to note  
13 that the GDP of Kentucky is almost 5 times that of Montana's. The fourth club majorly consists of states  
14 with relatively high income, high population and population density. The economic activities of these  
15 states are majorly manufacturing and services (retail) with less emphasis on agriculture. The  
16 manufacturing activities include automobile, shipping docks, aeroplanes, fabrics, rug and carpet mills,  
17 pharmacy, to mention a few. Also, this group has several iconic companies that are listed in the Fortune  
18 1000 companies. However, of this group, it was discovered that South Dakota and New Mexico have  
19 diverging tendencies, a situation attributable to their means of economic activities (agriculture). Hence,  
20 their level of emission is considered to be low. Further scrutiny into these states shows that (i) they have  
21 relatively low income and GDP per capita; (ii) lower population and population density, and (iii) lower  
22 housing units. The rest of the states belongs to the fifth club. These states economic activities are hugely  
23 centred on services, which covers financial, fashion, sport, sport, hospitality, civil service and tourism.  
24 Also, states house the manufacturing of computers and other ICT gadgets. Of this lot, it was found that  
25 Maryland, New Jersey, Oregon and Rhode Island behave in a different manner. This might be due to  
26 their different level of economic activities. For instance, Rhode Island derives her income from Marinas  
27 and ship-building. Also, prior to the millennium, Oregon is a natural resource centred state (fishing,

1 timber and agriculture). Perhaps, there is a renewed attempt to shift the economy to the high tech sector,  
2 which started receiving attention in the early 2000s. For instance, to know whether we can merge club  
3 1 with any other clubs, we can use the log t-test with a panel that contains information of all member  
4 clubs. If it was found that the estimated convergence parameter ( $\beta$ ) is significant, which indicates  
5 convergence, we can conclude that the clubs can be merged. This iteration continues until the points  
6 where the convergence parameter is no longer statistically significant. The results presented in Table 4  
7 prima facie evidence of the rejection of the null hypothesis of convergence. This leads us to conclude.

## 8 **5. Conclusion**

9 This paper examines the convergence hypothesis for 50 states in the United States of America for the  
10 period 1976-2014. In essence, we seek to examine whether per capita carbon emission across the states  
11 moves in the same direction and converge over time or there are tendencies towards divergence. The  
12 two techniques used to test out hypothesis are Pesaran (2007) panel unit root test and Phillips and Sul's  
13 (2007) tests. The advantages of these two approaches are that they can capture the effect and/or  
14 significance of the heterogeneity that might be inherent in the dataset. Furthermore, these tests have  
15 been identified to be very flexible to cover a range of transition periods.

16 Our results support the existence of divergence at the state level of carbon emission in the USA. Using  
17 the half-life convergence method, we were able to report a point estimate of the unbiased half-life of  
18 convergence. Although, we found that there were significant differences among states on the time it  
19 takes to converge, however, the average among the states was 5.7 years with a 95% confidence interval  
20 of 5.4 – 5.9 years. The results of stationarity using the KPSS stationary test complimented and hence  
21 provided robustness to our estimates by suggesting that the null of a unit root was rejected most of the  
22 time. The notion of the club convergence which was also a significant contribution of this study was  
23 also tested. The results showed that there were four identifiable clubs. The rest of the states are put  
24 together into another single club, making a total of five clubs. The estimates and classifications of the  
25 club convergence and corresponding clubs are particularly important in terms of harmonisation and  
26 formulations of climate policies at state and federal levels.

1 The half-life estimates are also important in terms of policy formulation on CO<sub>2</sub> emissions and  
2 coordinated actions by the states to influence the convergence and homogeneity of policy in the Post-  
3 convergence epoch. Evidence of divergence from the USA would make it difficult for other developed  
4 or developing countries to agree to emissions reduction obligations. These diverging tendencies require  
5 special consideration from policymakers. There is a need for policymakers in the US to be aggressive  
6 in terms of setting policies that would seek to achieve convergence, while simultaneously reducing PCE.  
7 If this can be achieved, other developed countries will follow suit and encourage developing countries  
8 to also reduce their emission level. Also, the attainment of convergence will enhance the accuracy of  
9 future projection of the emission rate.

10 The results of the club-convergence test have demonstrated the importance of streamlining emission  
11 abatement policies to emission convergence paths that is unique to the clusters of states. Hence, the  
12 state-specific structure must be considered when designing and implementing policies that seek to  
13 mitigate emissions, so that some states would not be adversely affected due to the influence and actions  
14 of other states. Concomitantly, a common federal level policy for all the states under investigation may  
15 not be very efficient due to the heterogeneity among them. Undauntedly, there is a need to cut down on  
16 unsustainable energy use and carbon emissions at a global level which also requires technology transfer  
17 and domestic innovations. In this regards, the actions and policies at the national or federal levels require  
18 to be matched with states and international levels. On the states levels, the aspect of convergence and  
19 club convergence covered in this treatise has profound implications which can be a good guide to  
20 navigate the federal policy and match it with global efforts to tackle the environmental challenges.

21 The transparency and quality of direct GHG emissions have not been significantly improved over time  
22 and it had been acknowledged in forums that energy-intensive organisations in the USA decreased the  
23 transparency, it is proposed the future research shall incept this aspect.

24

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