# AN EMPIRICAL STUDY ON THE EXISTENCE OF CONVERGENCE FOR ENERGY PER CAPITA

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**ABSTRACT:** *This paper focuses on energy which is a source of many serious environmental problems and examines the existence of convergence of energy per capita amongst countries in order to shed light on whether energy per capita has been growing and whether the trend is likely to change in the future. It was found that there was no evidence of convergence of energy per capita with any of the cases in the past for the world and Non-OECD countries while we found convergence of energy per capita for OECD countries. Concerning future prediction, there was no evidence of a compressed ergodic distribution of energy per capita for the world and Non-OECD countries, while a compressed distribution around the OECD average was seen for OECD countries.*

**Keywords:** *Convergence, Energy Per Capita, Inequality, World, OECD countries, Non OECE countries*

**JEL Classification:** Q40, Q56

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## 1. INTRODUCTION

Environmental problems are no longer regional issues contained to local areas but global issues. Global warming, thinning of the ozone layer, extinctions of certain species, over extraction of oil and natural gas and water pollution are all problems that cannot be solved by one country. Hardin (1968) had introduced an influential article, 'The Tragedy of Commons' where he explains that without any limitation to the access of natural resources and the environment, there is the possibility of 'free riding' and over exploitation of them. Currently there are some countries which consume far more natural resources or pollute far more than others, but the environmental damage this causes and the depletion of these resources will affect others as well. According to the World Bank (2003), 15 percent of the world's population living in high-income countries, emit 50 percent of the total carbon dioxide (CO2), using 50 percent of the world's energy. Hedenus and Azar (2005) who study the trend in global resource inequalities find that the gap in consumption of commercial energy is increasing in absolute terms between the top and bottom 20 percent consumers. There is even a sixth of the world population that lacks access to modern energy and so a provision of sustainable energy and universal access is a focus for the United Nations and World Bank (United Nations, 2014; World Bank, 2013). The Paris Agreement, the outcome of the United Nations

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Framework Convention on Climate Change (COP21), recognises these different starting points so all parties will put forward their best efforts to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances (United Nations, 2015). Addressing environmental issues through environmental policies and regulations on specific indicators of environmental quality such as CO2 is a challenge. If per capita emissions were found to diverge over time, this would affect the debate in achieving an agreement on climate change policies. In this way, understanding the distribution of per capita pollution may have important implications in designing environmental policies such as climate change policies, which leads to the need to study the existence of convergence or divergence of environmental indicators.

There are several studies that have undertaken this question on whether convergence can be observed with environmental quality indicators focusing on different pollutants. List (1999) uses SO2 and NOx data for regions in the US between 1929 and 1994 and finds convergence for both emissions. Bulte *et al.* (2007) also examines SO2 and NOx data to understand the role institutional context has on environmental convergence among US regions. They find that regulations, especially federal ones, have an impact on environmental convergence. Aldy (2007) examines production CO2 per capita and consumption CO2 per capita amongst the US states. He found that while production CO2 per capita diverged, consumption CO2 per capita converged due to the effect of increasing interstates' electricity trade over time. Brock and Taylor (2004, 2010) analyse CO2 convergence among OECD countries, developing the Solow growth model (Solow, 1956) and including technological progress in abatement and pollution. They perform a cross-sectional analysis and find convergence for CO2 emission. Empirical research by Strazicich and List (2003) also examine CO2 among industrial countries and find that CO2 emissions have converged. Stegman (2005) focuses on CO2 per capita convergence for the world and OECD countries. As a result of taking into account intra-distribution dynamics, she finds that CO2 per capita does not converge over the period between 1950 and 1999. Nguyen Van (2005) examines CO2 per capita for both the world and industrial countries, and takes intra-distribution dynamics into account as well as the traditional average behaviour approach. The results indicated divergence for the world and convergence for industrial countries. Aldy (2006) also includes the intra-distribution dynamics approach and investigates whether CO2 per capita converges over time for both the world and OECD countries. He further employs the Markov chain transition approach to forecast future distribution which predicts environmental convergence among OECD countries while environmental divergence among the world. Other than SO2, NOx and CO2 which are used in the above studies, Alvarez *et al.* (2005) examine NO2, CO and MVOC among European countries for short time periods, developing a neoclassical growth model augmented to incorporate the dynamics of a stock of pollutant. The results reveal environmental convergence for most of the air pollutants.

This paper applies commercial energy as a proxy for pollution. The consumption of energy does not only lead to the depletion of natural resources such as oil and natural gas[2], but

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[2] Energy consumption is closely related to population growth problems and depletion of nonrenewable resources through accelerating industrialization. This has been treated as a serious issue by many organizations such as the Club of Rome (Meadows et al., 1972).

commercial energy is a chief source of a number of pollutants. It is also suited to observe past trends and future predictions of overall environmental trends and has been used in the past to examine environmental issues (e.g. Suri and Chapman, 1998; Medlock and Soligo, 2001). For example, energy is related to many pollutants such as SO2 that causes acid rain and CO2 which effects global warming. However, data gathering for each individual pollutant caused by energy use such as CO and suspended particulate matter (SPM) to be used in a panel data which requires long time periods and plenty of cross sections could prove to be difficult. It is also important to note that a decline in individual pollutants does not necessarily imply a decline in the overall pollution burden related to the production, distribution and consumption of energy. In most instances, it is only when energy consumption itself is reduced can it be considered that the environmental burden it represents has been addressed in a sustainable manner. This represents another reason to use total commercial energy itself (Suri and Chapman, 1998).

For these reasons, an important contribution of this paper is that by studying the convergence of energy, we gain a broad understanding of the existence of convergence over a number of main pollutants. The second contribution of this paper is that not only does it study the world and OCED countries such as in the studies by Aldy (2006), Stegman (2005) and Nyugen Van (2005), it also analyses Non-OECD countries. It aims to look at not only the possibility of a north and south convergence but whether there is a south and south convergence. Finally, by using a number of methods to study the representative behaviour and intra-distribution dynamics of energy per capita, this paper will observe the existence of energy convergence from many different angles and forecast future energy per capita distribution.

The remainder of this paper proceeds as follows: Section 2 provides a brief background concerning the growth rate of energy per capita at a country level. Section 3 explains the data description and the empirical methods that were used. Section 4 presents the results from the empirical studies and Section 5 provides concluding comments and discusses policy implications.

## 2. BACKGROUND

This section will provide a brief background on the growth rate of energy per capita relative to the world average at a country level. Table 1 compares the top 20 countries with the highest increase in its ratio of its energy per capita for that year to the average (relative energy per capita) of the world with the 20 countries with the lowest increase in relative energy per capita between 1971 and 2001. It takes into account the difference and ratio in relative energy per capita between 1971 and 2001 for each country and uses the log mean method to examine the increase rate of relative energy per capita. The majority of the countries with low increase in relative energy per capita were the less developed countries such as Korea Democratic Republic (North Korea), Congo Republic and Zambia, the highly developed countries such as Luxembourg, Denmark, the US and the former East European countries such as Romania, Czech Republic and Poland. The countries with the highest increase in relative energy per capita were oil producing nations such as Saudi Arabia and the United Arab Emirates and the Newly Industrializing Economies (NIES) in East Asia and Europe such as Singapore, Korea Republic (South Korea), Portugal and Greece. The steep economic developments of the NIES are likely to have influenced the increase in relative energy per capita. This observation shows that there is a low increase in relative energy per capita amongst the highly developed countries but a high increase amongst the developed countries with relatively lower income per capita. Amongst developing countries, countries with high economic growth or oil producing countries show high increases in relative energy per capita, while less developed countries have low increases. From these observations, there is the possibility of a convergence in relative energy per capita amongst developed countries and a divergence within the developing countries. Based on these results, in the next section, we examine whether convergence can be found with energy per capita for the world, OECD and non-OECD countries.

Table 1: *The Highest Growth Countries and the Lowest Growth Countries of Relative Energy per Capita between 1971 and 2001*

| Rank | Country | H.Growth | Rank | Country | L. Growth |
|---|---|---|---|---|---|
| 1 | Qatar | 0.791 | 1 | Luxembourg | -1.196 |
| 2 | Singapore | 0.607 | 2 | Mozambique | -0.858 |
| 3 | Brunei | 0.567 | 3 | Czech republic | -0.749 |
| 4 | Saudi Arabia | 0.514 | 4 | Gabon | -0.703 |
| 5 | United Arab Emirates | 0.481 | 5 | Romania | -0.665 |
| 6 | Korea, Rep. | 0.447 | 6 | Korea, Dem. Rep. | -0.665 |
| 7 | Iceland | 0.441 | 7 | Poland | -0.595 |
| 8 | Trinidad and Tobago | 0.354 | 8 | Denmark | -0.585 |
| 9 | Libya | 0.341 | 9 | United States | -0.544 |
| 10 | Cyprus | 0.322 | 10 | Congo, Rep. | -0.531 |
| 11 | Malaysia | 0.280 | 11 | Zimbabwe | -0.517 |
| 12 | Portugal | 0.279 | 12 | Zambia | -0.514 |
| 13 | Spain | 0.254 | 13 | Albania | -0.476 |
| 14 | Greece | 0.250 | 14 | Peru | -0.473 |
| 15 | Hong Kong, China | 0.250 | 15 | United Kingdom | -0.446 |
| 16 | Iran, Islamic Rep. | 0.214 | 16 | Germany | -0.416 |
| 17 | Thailand | 0.170 | 17 | Kuwait | -0.382 |
| 18 | Malta | 0.152 | 18 | Kenya | -0.357 |
| 19 | New Zealand | 0.146 | 19 | Bulgaria | -0.349 |
| 20 | Algeria | 0.144 | 20 | Slovak Republic | -0.349 |

## 3. METHODOLOGY AND DATA

This paper conducts four types of analysis to assess the cross-sectional convergence of energy per capita over time for the world, Non-OECD countries and OECD countries. It first estimates a variety of deviations to measure the variability of energy per capita for the world, Non-OECD countries and OECD countries. The deviations examined are the standard deviation (*SD*), the average absolute deviation (*AD*) and the median absolute deviation (*MD*). The standard deviation is used with a normally distributed data set, since it represents the variability of the data around the centre and in the tails of the distribution. However, if the data does not exhibit a normal distribution, then the average absolute deviation or the median absolute deviation is used. Compared to the average absolute deviation, the median absolute deviation is less affected by observations which exhibit distribution in the tails of the distribution (Stegman 2005).[3]

Since these measures considered the variability in the tails of a distribution of the data set, this paper will next estimate the interquartile range (IQR) which attempts to measure variability in the centre of distribution of the data. The *IQR75-25* is the value of the 75th percentile minus the value of the 25th percentile. With the IQR being sensitive to the percentile points, this paper also estimates *IQR80-20* and *IQR90-10* which are represented by the value of the 80th percentile minus the value of 20th percentile and the value of the 90th percentile minus the value of 10th percentile respectively.

Next, this paper estimated the kernel densities[4] of per capita energy in order to illustrate the energy trends since the deviations and IQRs described above, may not capture intra-distribution dynamics. A country's per capita energy is expressed as the natural logarithm of energy per capita relative to the sampled group average for each year (*e*). The Espanechikov kernel and Silverman's (1986) bandwidth choice rule to estimate the densities have been used. The Silverman bandwidth choice rule is often employed in density estimation. This produces a kernel density estimator function of

$$D(e) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{e_i - e}{h}\right) \quad , \tag{1}$$

where $K = \dfrac{3(1-0.2e^2)}{4\sqrt{5}}$ if $|e| < \sqrt{5}$, and 0 otherwise,

$$h = \frac{0.9\left(\min\left(s, \frac{Q}{1.349}\right)\right)}{\sqrt{5}}$$ , and

*N* represents the number of countries, *s* is standard deviation of the sample, and *Q* represents the *IQR75-25* for the sample. The Espanechikov kernel was used since it is

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[3] The definition of each deviation is shown in Appendix A.

[4] Kernel density estimation is a non-parametric way in statistics to estimate the probability density function of a random variable.

the most efficient kernel function to minimize the mean integrated square error (Aldy, 2007).

The methods used above are related to nonparametric approaches. Next we will examine the convergence of energy per capita using the parametric approach often used in growth empirical literature called the $\beta$-convergence analysis. This technique was developed by Baumol (1986).

$$Eg_i = \alpha + \beta E_{0i} + \varepsilon_i, \tag{2}$$

where $Eg_i$ represents the average annual growth rate of natural logarithm of energy per capita for each country i over the sample period between 1971-2001. $\alpha$ is a constant term, and $\beta$ is the parameter that tests the existence of convergence. $E_{0i}$ represents the natural logarithm of the initial level of energy per capita in country i. $\varepsilon_i$ is the contemporaneous error term which is assumed independent and identically distributed (i.i.d.) with zero mean and finite variance. As used in economic growth studies, a negative sign of $\beta$ will represent a convergence in energy per capita. $\beta = -(1-\exp^{-\lambda\tau})$ where $\tau$ represents the length of the period of the study and $\lambda$ is the convergence speed. $\lambda$ can be estimated and its variance computed by applying the delta method once the estimate of $\beta$ is available.

The above methods were used to examine the historical convergence of energy per capita. Next, this paper examines future energy per capita distribution. In order to forecast future distribution, the paper performs a Markov chain transition matrix analysis, which is a nonparametric method used in economic growth literature to evaluate income distribution. The transition matrix framework was applied to evaluate the distribution of per capita income in a study by Quah (1993). Following the work by Quah (1993), Aldy (2006, 2007) examines CO2 per capita for the US regions and the world/OECD. As used in these studies, the transition matrix framework is used to effectively map this year's distribution ($Z_t$) of each country's energy per capita relative to the sampled countries' average into next year's distribution ($Z_{t+1}$):

$$Z_{t+1} = M * Z_t \tag{3}$$

Though the mapping operator M can be assumed to follow any process, this paper assumes a first-order Markov process with time invariant transition probabilities as in the studies by Aldy (2006, 2007), Quah (1993) and Kremer et al. (2001). By repeating this expression T times it produces

$$Z_{t+T} = M^T * Z_t. \tag{4}$$

If $Z_{t+T} = Z_{t+T-1}$, the larger T becomes, this represents the long-run steady state (ergodic) distribution of relative energy per capita.

Following the studies by Aldy (2007) on environmental convergence and Quah (1993) and Kremer *et al.* (2001) on income convergence, the sampled countries (i.e. 108 countries in the world, 78 Non-OECD countries, and 30 OECD countries) are grouped according to the five categories of relative energy per capita. The five categories are: less than one-half of the observed group's average; between one-half and three-quarters of the observed group's average; between three-quarters of the observed group's average and the observed group's average; between the observed group's average and double the observed group's average; and greater than double the observed group's average. Then the one year transitions between categories are calculated to produce the transition matrices. In order to estimate the future distribution for the data set, the mapping operator is applied to the distribution in the last year of the data set. This approach illustrates the changes to the data over time with limited constraint, since the only changes to the structure of the data is in the construction of the five categories and the first-order Markov assumption. However, there are some limitations to this approach. Since this approach uses data of past distribution to forecast future distribution, significant events in the past such as changes to regulations or technological development may not be well depicted (Aldy, 2006, 2007). The other limitations is that though this approach can illustrate the characteristics of future distribution, further analysis is necessary to understand the reason for the changes in the distribution of energy per capita. As performed by Aldy (2006, 2007) we further analyse by comparing the ergodic distribution derived from transition probabilities based on various periods. On top of the one year Markov transition matrix we also performed a five year Markov transition matrix, since as explained by Kremer *et al.* (2001), transitions periods longer than one year reduces the impact on the estimated transition matrix for frequent fluctuation that occur near the border of the different groups at the beginning of the period. This means that it represents a closer picture of long-run dynamics than when annual data is used.

Concerning the data information, energy per capita used is commercial energy use from the World Development Indicators (World Bank, 2005). The data on energy per capita is collected from 108 countries. The countries are listed in Appendix B.

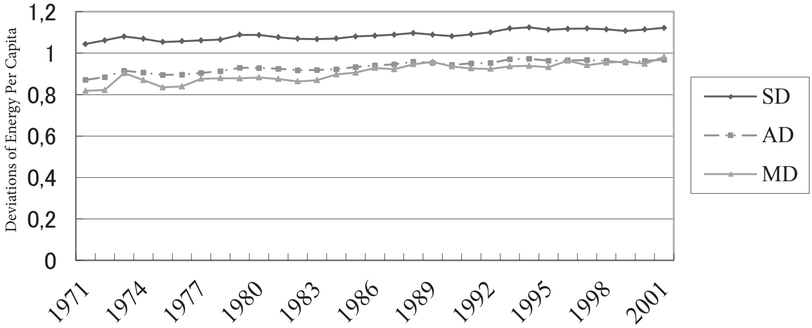
## 4. RESULTS

### *Historical Results*

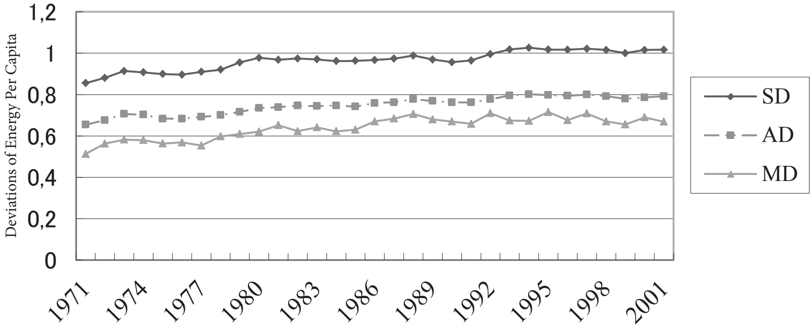
First, we examine the historical results of energy per capita. Figure 1 (a) contains estimates of each of the deviations over the period between 1971 and 2001 for the world. Figure 1 (a) shows that all of the measures slightly increase over the sampled period. These results suggest that the variability of the energy per capita data series slightly increases or there is insignificant change at the world level. We further divide the world into Non-OECD countries and OECD countries. Figure 1 (b) illustrates the results of Non-OECD countries. We find that all of the measures regarding deviations slightly increase over the sampled periods, and has a higher increase than seen in the world results. Overall, the results of Non-OECD countries indicate that the variability of the energy per capita data series, slightly increases or have insignificant changes. The results for the OECD countries showed a different trend. Figure 1 (c) shows that all of the measures decreased over the time period between 1971 and 2001. The results present that the variability of the energy per capita data series decreases over the sample time period for the OECD countries, which implies that energy per capita for OECD converges.

Figure 1: *Deviations of Energy Per Capita.*
(a) World (b) Non-OECD countries (c) OECD countries

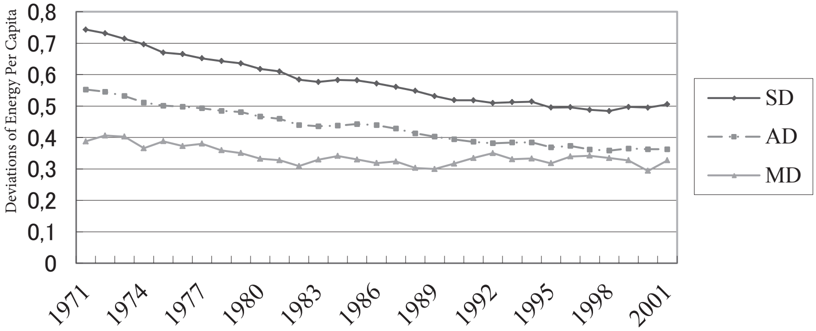
(a) World



(b) Non-OECD Countries



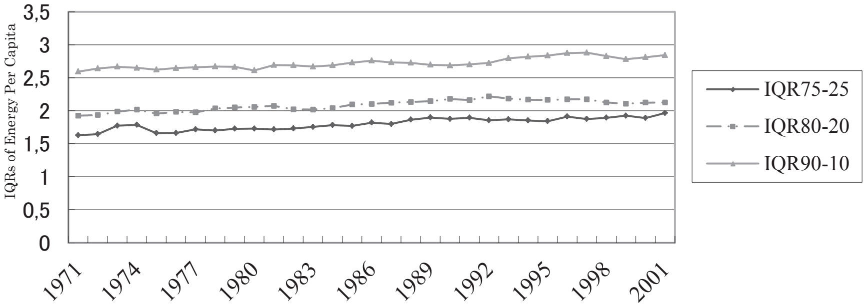
(c) OECD Countries



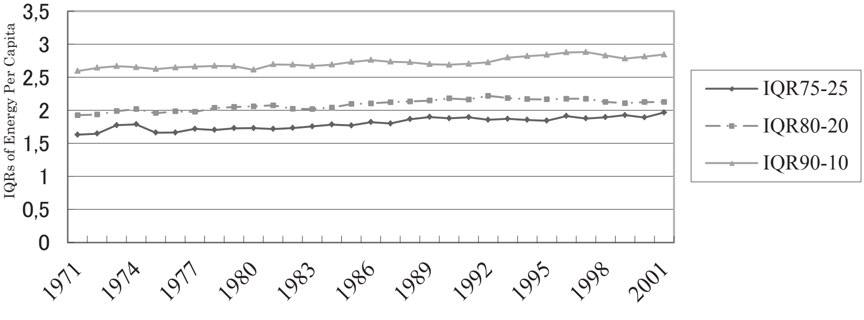
According to the analysis using the IQR, which focuses on the variability in the centre of the distribution of the data, Figure 2 (a) which represents the results of the world, shows that there is only a slight increase with all the IQR measures during the sample period. This means that there is very little evidence of convergence with energy per capita. Furthermore, the results of the IQR from observations towards the centre of the data showed a slightly stronger divergence of energy per capita. This implies that at a world level, the countries which are towards the centre of the data have a tendency to diverge concerning energy per capita. Concerning the results of the Non-OECD countries, Figure 2 (b) indicates that there was a slight increase which was slightly larger than the results at the world level. The increase was strongest with *IQR90-10* and there was a tendency to diverge the further the observations of the IQR were from the centre of the data. We were able to find from these results that Non-OECD countries that are located toward the tails of the data are more inclined to diverge concerning energy per capita. On the other hand, the results of the OECD countries shown in Figure 2 (c) illustrate a decrease with all of the IQR measures indicating evidence of convergence. The decrease is especially strong with *IQR90-10* which indicates that the OECD countries toward the tail of the data have a smaller difference in energy per capita. We found that these results of the IQR were consistent to the results of the deviation analysis and that energy per capita slightly diverges for the world and Non-OECD countries, but showed convergence for OECD countries.

Figure 2: *IQRs of Energy Per Capita.*
(a) World (b) Non-OECD Countries (c) OECD Countries

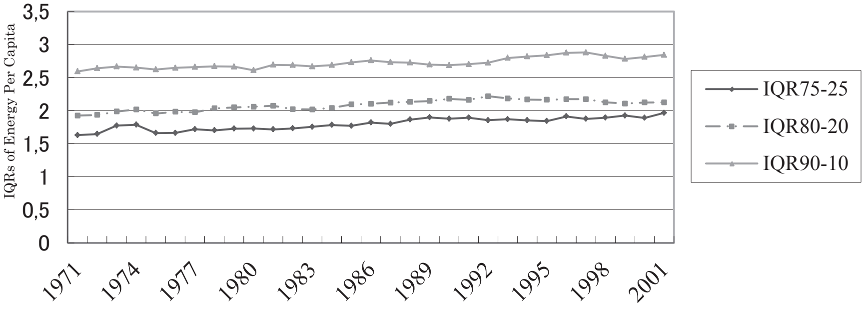
(a) World



(b) Non-OECD Countries



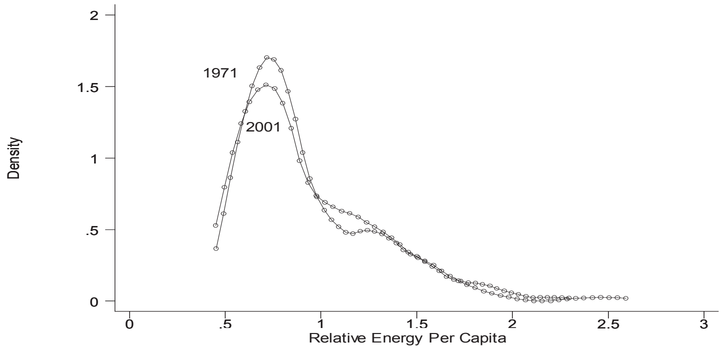
(c) OECD Countries



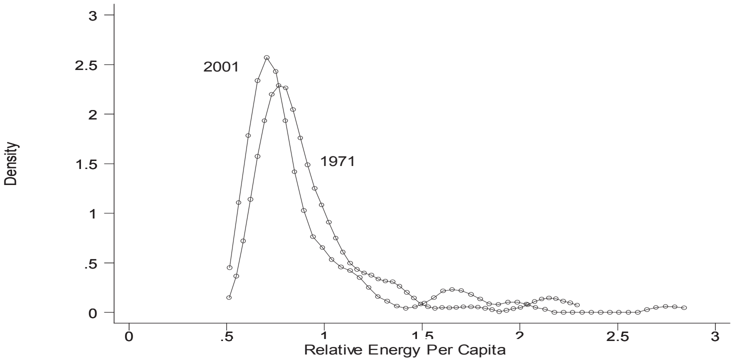
As described in Section 3, these deviations and IQRs do not characterize the cross-sectional distribution over time. Figure 3 illustrate comparison of the kernel densities between the beginning of the sample period (1971) and the end of the sample period (2001). Figure 3 (a) shows that for the distribution of world, relative energy per capita at 2001 is not meaningfully different from that of 1971 since the density of relative energy per capita around both mean (i.e. 1) and tails at 2001 are not different than those of 1971. As for the Non-OECD countries, Figure 3 (b) shows divergence of the relative energy per capita since the density of relative energy per capita around the mean at 2001 is lower than that of 1971 and the tails at 2001 are slightly thicker than those of 1971. With regards to the OECD countries, however, Figure 3 (c) shows that the relative energy per capita converge, since the density of relative energy per capita around the mean at 2001 is higher than that at 1971 and the tails at 2001 are thinner and shorter than those at 1971. These results support the results of the above deviations and IQRs analysis for OECD countries.

Figure 3: *Comparison of Kernel Density Distribution of First Year with Last Year.* (a) World (b) Non-OECD Countries (c) OECD Countries

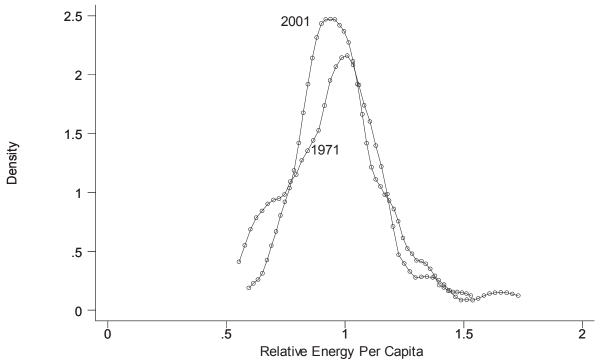
(a) World



(b) Non-OECD Countries



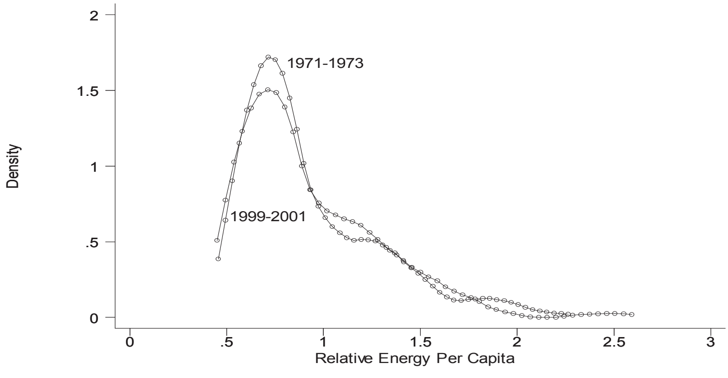
(c) OECD Countries



We next compare the kernel density distribution from observing the first several years of the sample period and the last several years. This will increase the number of observations and obtain a more robust result than comparing the first year of the sample period to the last year of the sample period. So we compared the kernel density distribution analysis for the period from 1971 to 1973 to the period from 1999 to 2001[5]. As shown in Figure 4 (a) which illustrates the result of the world analysis, there is little difference between the kernel density distributions for the period 1971 to 1973 to the distribution of the period 1999 to 2001. The result is consistent to the result found when comparing the distribution of the first and last year of the sample period and we can conclude that there is no evidence of convergence for relative energy per capita at the world level. These results are also in line with the previous results of the deviations, and IQRs. The results for Non-OECD countries are illustrated in Figure 4 (b). It shows that the result of the comparison between the kernel density distribution for the period of 1971 to 1973 and the period 1999 and 2001 was that the kernel density distribution was thicker in the centre for the period of 1971 to 1973. This result was consistent to the result of the comparison of the kernel density distribution for the first and last year of the sample period which is an indication that there is a divergence in relative energy per capita with Non-OECD countries. The results of the kernel density distribution for Non-OECD are consistent with the previous results of the deviations and IQRs. As indicated in Figure 4 (c), we find different results with the comparison of the kernel density distribution of the OECD countries. In this case, the kernel density distribution was thinner in the centre and thicker in the tails for the period of 1971 to 1973, indicating a convergence. This OECD result for the kernel density distribution also supports the previous results of the deviations and IQRs.

Figure 4: *Comparison of Kernel Density Distribution of First 3 Years with Last 3 Years.* (a) World (b) Non-OECD Countries (c) OECD Countries

(a) World



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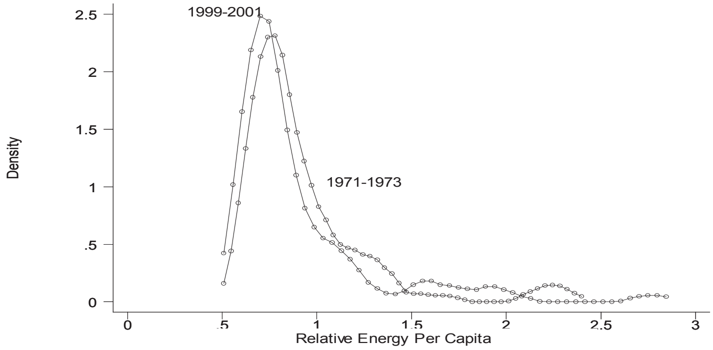
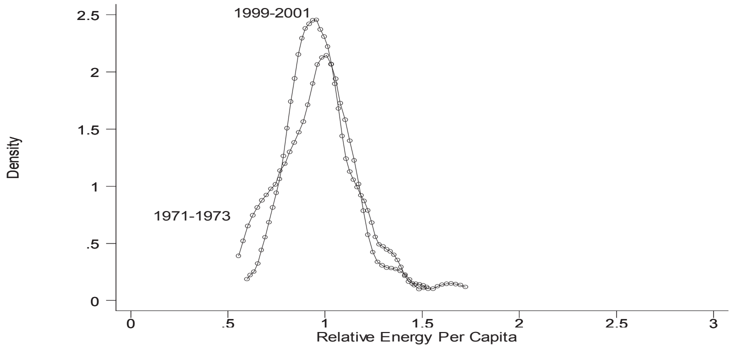
[5] Comparison between the kernel density distribution of 1971 to 1980 and 1992 to 2001 and the comparison between 1971 to 1975 and 1997 to 2001 was also conducted for the world, Non-OECD countries and OECD countries and all showed similar results. These are available from the author upon request.

(b) Non-OECD Countries



(c) OECD Countries



These results of the kernel density distribution are also supported by the $\beta$ convergence analysis. According to Figure 5 (a) and (b), which represent the case for the world and Non-OECD countries respectively, the plots do not show any consistent relationship between the initial level of energy per capita and the average growth rate of energy per capita. We will examine this further in Table 2. The results of the cross-sectional econometric analysis for the world and Non-OECD, show significant heteroscedasticity when performing the Breusch-Pagan/Cook-Weisberg test. Hence, we use the OLS with robust standard error which is based on the Huber/White/sandwich estimator of variance. As a result, in both the world and Non-OECD countries, we find no significant evidence of convergence[6]. On the other hand, according to Figure 5 (c), convergence seems to occur for OECD countries.

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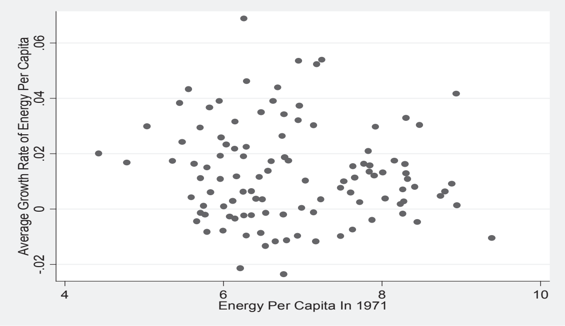
[6] We perform the estimations of standard errors by using the bootstrap and the jackknife method. The results concerning statistical significance of initial level of energy per capita are the same as those from robust standard error which is based on Huber/White/sandwich estimator of variance.

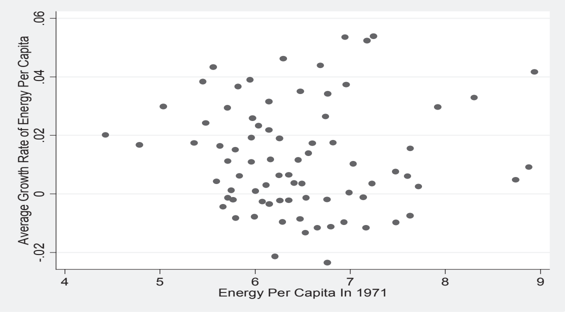
Figure 5: *Relationship between Initial Energy Per Capita and the Average Growth Rate of Energy Per Capita.*

(a) World (b) Non-OECD Countries (c) OECD Countries

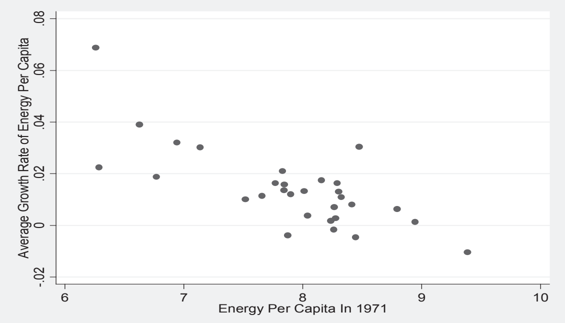
(a) World



(b) Non-OECD Countries



(c) OECD Countries



To confirm this, we performed the cross-sectional econometric analysis. Since we cannot reject the null hypothesis of constant variance, this time we use the OLS with normal standard error for OECD countries. The results in Table 2 suggest that countries with higher initial level of energy per capita have lower average growth rate of energy per capita at a significant level of one percent which implies that evidence of convergence among OECD countries has been found. The speed of the convergence which is represented by $\lambda$ was 0.0005011.

Table 2: *β Convergence Analysis of Energy Per Capita*

| | World | | Non-OECD | OECD | |
|---|---|---|---|---|---|
| | OLS with Robust S.E. | | OLS with Robust S.E. | OLS | |
| Energy per capita 1971 (β) | -0.0017074 | | -0.000084 | -0.0154144 | *** |
| | (-1.28) | | (-0.04) | (-5.88) | |
| α | 0.0246195 | ** | 0.0129504 | 0.1358455 | *** |
| | 2.58 | | 0.89 | 6.54 | |
| λ | 0.0000551 | | 2.71E-06 | 0.0005011 | *** |
| | ( 1.28) | | (0.04) | ( 5.84) | |
| Breusch-Pagan / Cook-Weisberg test | 0.82 | | 1.43 | 7.03 | *** |
| No. of Obs. | 108 | | 78 | 30 | |

Robust standard error is based on Huber/White/sandwich estimator of variance

T-statistics reported in parentheses.

*, ** and *** denote significance at 90%, 95% and 99% confidence levels, respectively.

### *Future Projections*

We have examined the results regarding historical evaluation of energy per capita. Next, we will review future distribution of energy per capita. Table 3 (a) presents the Markov chain transition matrix for relative energy per capita over 1971 to 2001 and the estimated ergodic distribution for the world. For example, it shows that a country in the lowest category where energy per capita is less than one-half of the world average has approximately 99 percent probability of remaining in that category the following year and a country in the highest category where energy per capita is more than double the world average has approximately 97 percent probability of remaining in that category the following year. The high probabilities along the diagonal suggest a high degree of persistence in countries' relative energy per capita. The long-run steady state (ergodic) distribution of relative energy per capita shows that two third of the world would be expected to be in the lowest or highest category of relative energy per capita. Around one out of four countries would have energy per capita within the two categories which are around the world average (i.e. energy per capita between 0.75 and 2 of the world average), indicating that the estimated ergodic distribution was not compressed around the average.

Table 3: *Estimates of Transition Matrix and Ergodic Distribution (Energy Per Capita Relative to the Sampled Countries' Average): 1 Year Transitions.*

(a) World (b) Non-OECD Countries (c) OECD Countries

(a) World

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Upper Endpoint | 0.5 | 0.75 | 1 | 2 | ∞ |
| 0.5 | 0.987 | 0.013 | 0.000 | 0.000 | 0.000 |
| 0.75 | 0.098 | 0.816 | 0.082 | 0.004 | 0.000 |
| 1 | 0.000 | 0.103 | 0.787 | 0.109 | 0.000 |
| 2 | 0.000 | 0.000 | 0.030 | 0.948 | 0.022 |
| ∞ | 0.000 | 0.000 | 0.000 | 0.033 | 0.967 |
| Ergodic | 0.52 | 0.07 | 0.06 | 0.20 | 0.15 |

(b) Non-OECD Countries

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Upper Endpoint | 0.5 | 0.75 | 1 | 2 | ∞ |
| 0.5 | 0.978 | 0.022 | 0.000 | 0.000 | 0.000 |
| 0.75 | 0.118 | 0.835 | 0.047 | 0.000 | 0.000 |
| 1 | 0.000 | 0.169 | 0.761 | 0.070 | 0.000 |
| 2 | 0.000 | 0.000 | 0.050 | 0.921 | 0.030 |
| ∞ | 0.000 | 0.000 | 0.000 | 0.037 | 0.963 |
| Ergodic | 0.56 | 0.15 | 0.06 | 0.13 | 0.10 |

(c) OECD Countries

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Upper Endpoint | 0.5 | 0.75 | 1 | 2 | ∞ |
| 0.5 | 0.972 | 0.028 | 0.000 | 0.000 | 0.000 |
| 0.75 | 0.000 | 0.963 | 0.037 | 0.000 | 0.000 |
| 1 | 0.000 | 0.012 | 0.948 | 0.040 | 0.000 |
| 2 | 0.000 | 0.000 | 0.040 | 0.944 | 0.015 |
| ∞ | 0.000 | 0.000 | 0.000 | 0.120 | 0.880 |
| Ergodic | 0.15 | 0.15 | 0.29 | 0.36 | 0.05 |

Table 3 (b) presents the transition matrix over 1971 to 2001 and the estimated ergodic distribution for relative energy per capita of Non-OECD countries. The high probabilities along the diagonal suggest a high degree of persistence in countries' relative energy per capita. We find the triple-diagonal condition observed in studies on income convergence which means that the transition probabilities that are not on the three main diagonals are zero. This suggests that Non-OECD countries do not experience very substantial changes in their energy per capita relative to the Non-OECD countries' average. The ergodic distribution of relative energy per capita shows that around two third of the Non-OECD countries would be expected to be in the lowest or highest category of relative energy per capita. Around one out of five of the Non-OECD countries would have energy per capita within the two categories which are around the Non-OECD countries' average (i.e. relative energy per capita between 0.75 and 2 of Non-OECD countries' average), implying that the estimated ergodic distribution was not compressed around the average.

Table 3 (c) presents the transition matrix over 1971-2001 and the estimated ergodic distribution for relative energy per capita of OECD countries. The triple-diagonal condition is found once more, suggesting that OECD countries do not show meaningful changes in their energy per capita relative to the OECD countries' average as with the Non-OECD countries. The high probabilities along the diagonal suggest an extremely high degree of persistence in countries' relative energy per capita. The estimated ergodic distribution of relative energy per capita shows that one out of five of the OECD countries would be expected to be in the lowest or highest category of relative energy per capita. Around two third of OECD countries would have energy per capita within the two categories which are around the OECD countries' average (i.e. relative energy per capita between 0.75 and 2 of OECD countries' average) which indicates that the distribution is compressed around the average.

The estimated ergodic distribution is affected by the period that has been chosen to construct the transition matrix. The estimated ergodic distributions for the transition matrices for the world, Non-OECD and OECD samples for the following periods: 1971 to 2001; 1981 to 2001; and 1991 to 2001 are shown in Table 4. As for the world, the estimated ergodic distribution for transition matrices for all of the periods show a similar trend as seen in Table 4 (a). According to Table 4 (b), which show the results for Non-OECD countries, the estimated ergodic distribution for transition matrices based on more recent sample periods shows a slightly less compact distribution illustrated by a thicker tail. Table 4 (c) shows that in the case of the OECD countries, the relative energy per capita exhibits thinner tails of the estimated ergodic distribution over shorter periods. This suggests that the estimated ergodic distribution based on more recent sample periods shows a more compact distribution.

Table 4: Estimates of Ergodic Distributions based on Various Time Periods *(Energy Per Capita Relative to the Sampled Countries' Average): 1 Year Transitions.*

(a) World (b) Non-OECD Countries (c) OECD Countries

(a) World

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Time Period | 0.5 | 0.75 | 1 | 2 | ∞ |
| 1971-2001 | 0.52 | 0.07 | 0.06 | 0.20 | 0.15 |
| 1981-2001 | 0.52 | 0.07 | 0.06 | 0.21 | 0.14 |
| 1991-2001 | 0.52 | 0.07 | 0.07 | 0.20 | 0.14 |

(b) Non-OECD Countries

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Time Period | 0.5 | 0.75 | 1 | 2 | ∞ |
| 1971-2001 | 0.56 | 0.15 | 0.06 | 0.13 | 0.10 |
| 1981-2001 | 0.58 | 0.13 | 0.06 | 0.12 | 0.11 |
| 1991-2001 | 0.59 | 0.12 | 0.07 | 0.12 | 0.10 |

(c) OECD Countries

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Time Period | 0.5 | 0.75 | 1 | 2 | ∞ |
| 1971-2001 | 0.15 | 0.15 | 0.29 | 0.36 | 0.05 |
| 1981-2001 | 0.13 | 0.18 | 0.30 | 0.35 | 0.04 |
| 1991-2001 | 0.08 | 0.21 | 0.34 | 0.33 | 0.04 |

Further to the previous one year Markov transition matrix we also performed a five year Markov transition matrix based on the period from 1971 to 2001, since as explained in Section 3, the transition periods longer than one year reduce the impact on the estimated transition matrix for frequent fluctuation. According to Table 5 (a), the world results of the five year transition matrix indicate that the countries in the lowest and highest category where energy per capita is less than one-half of the world average or more than double the world average and the category by the world average (between 1 and 2) have high probabilities along the diagonal. The other category by the world average (between 0.75 and 1) did not have a high probability. This means that half of the countries in this category are not likely to remain in this category in the following five years. Transition probabilities off the main diagonals that are not zero are increasing, implying that countries experiencing more than double or less than half of relative energy per capita increases over a five year period compared to a one year. Since the allocated time for relative energy per capita to change is longer in a five year period this is a reasonable outcome. The estimated ergodic distribution of the five year transitions had similar results to the estimated ergodic distribution of the one year transitions and two third of the countries are located in the lowest and highest categories and one fourth in the two categories around the average resulting in a non compressed distribution.

Table 5: *Estimates of Transition Matrix and Ergodic Distribution (Energy Per Capita Relative to the Sampled Countries' Average): 5 Year Transitions.*

(a) World (b) Non-OECD Countries (c) OECD Countries

(a) World

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Upper Endpoint | 0.5 | 0.75 | 1 | 2 | ∞ |
| 0.5 | 0.967 | 0.032 | 0.001 | 0.000 | 0.000 |
| 0.75 | 0.209 | 0.544 | 0.214 | 0.028 | 0.005 |
| 1 | 0.014 | 0.194 | 0.525 | 0.259 | 0.007 |
| 2 | 0.000 | 0.000 | 0.072 | 0.884 | 0.043 |
| ∞ | 0.000 | 0.000 | 0.000 | 0.078 | 0.922 |
| Ergodic | 0.52 | 0.07 | 0.06 | 0.20 | 0.15 |

(b) Non-OECD Countries

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Upper Endpoint | 0.5 | 0.75 | 1 | 2 | ∞ |
| 0.5 | 0.956 | 0.044 | 0.000 | 0.000 | 0.000 |
| 0.75 | 0.290 | 0.604 | 0.104 | 0.003 | 0.000 |
| 1 | 0.025 | 0.320 | 0.434 | 0.221 | 0.000 |
| 2 | 0.004 | 0.038 | 0.106 | 0.787 | 0.065 |
| ∞ | 0.000 | 0.000 | 0.000 | 0.067 | 0.933 |
| Ergodic | 0.57 | 0.14 | 0.06 | 0.12 | 0.11 |

(c) OECD Countries

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Upper Endpoint | 0.5 | 0.75 | 1 | 2 | ∞ |
| 0.5 | 0.856 | 0.144 | 0.000 | 0.000 | 0.000 |
| 0.75 | 0.000 | 0.889 | 0.111 | 0.000 | 0.000 |
| 1 | 0.000 | 0.043 | 0.900 | 0.057 | 0.000 |
| 2 | 0.000 | 0.000 | 0.095 | 0.880 | 0.025 |
| ∞ | 0.000 | 0.000 | 0.000 | 0.283 | 0.717 |
| Ergodic | 0.14 | 0.16 | 0.30 | 0.35 | 0.05 |

Concerning the Non-OECD countries, the results of the five year transition matrix in Table 5 (b) show high probabilities in the lowest category, highest category and the one by the average (between 1 and 2). There are some transition probabilities which are not zero appearing off the three main diagonals which suggest that some of the Non-OECD countries have shown a significant change in relative energy per capita over the five year periods. This can be explained with some Non-OECD countries having stronger economic growth rates compared to OECD countries which effect the growth of energy per capita. The estimated ergodic distribution of the five year transitions show similar results to the estimated ergodic distribution of the one year and two third of the countries are included in the lowest and highest categories and one fifth can be found in the two categories around the average which illustrates a distribution which is not compressed around the average.

For OECD countries, the results of the five year Markov transition matrix in Table 5 (c) are consistent to the one year and show high probabilities along the diagonal. The transition probabilities off the three main diagonals are also similar which indicates that there are no major changes to relative energy per capita even in the five year period. The estimated ergodic distribution of the five year transitions, like the estimated ergodic distribution for the one year transitions show one fifth of the countries in the lowest and highest categories and two third in the two categories around the average. This illustrates a compressed distribution around the average which was not evident in the estimated ergodic distributions for the world and Non- OECD countries.

Since the transition period can affect the results, in order to predict future distribution, we have based the estimated ergodic distribution for the five year transition matrices on the periods from 1981 to 2001 and from 1991 to 2001 and compared them with the ergodic distribution from 1971 to 2001. According to Table 6 (a), the results for the world were similar to the estimated ergodic distribution of the one year transitions and the distribution was not compressed with two third of the countries in the lowest and highest categories and one fourth in the two categories around the average. As illustrated in Table 6 (b) and (c), for both Non-OECD countries and OECD countries, the results of the estimated ergodic distribution were similar for the five year transition as for the one year transition. In other words, it did not exhibit a compressed ergodic distribution for Non-OECD countries, but did exhibit compressed ergodic distribution for OECD countries.

Table 6: *Estimates of Ergodic Distributions based on Various Time Periods (Energy Per Capita Relative to the Sampled Countries' Average): 5 Year Transitions.*

(a) World (b) Non-OECD Countries (c) OECD Countries

(a) World

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Time Period | 0.5 | 0.75 | 1 | 2 | ∞ |
| 1971-2001 | 0.52 | 0.07 | 0.06 | 0.20 | 0.15 |
| 1981-2001 | 0.52 | 0.07 | 0.06 | 0.20 | 0.15 |
| 1991-2001 | 0.52 | 0.07 | 0.08 | 0.19 | 0.14 |

(b) Non-OECD Countries

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Time Period | 0.5 | 0.75 | 1 | 2 | ∞ |
| 1971-2001 | 0.57 | 0.14 | 0.06 | 0.12 | 0.11 |
| 1981-2001 | 0.58 | 0.13 | 0.06 | 0.12 | 0.11 |
| 1991-2001 | 0.60 | 0.11 | 0.07 | 0.12 | 0.10 |

(c) OECD Countries

| | Upper Endpoint | | | | |
|---|---|---|---|---|---|
| Time Period | 0.5 | 0.75 | 1 | 2 | ∞ |
| 1971-2001 | 0.14 | 0.16 | 0.30 | 0.35 | 0.05 |
| 1981-2001 | 0.11 | 0.19 | 0.31 | 0.35 | 0.04 |
| 1991-2001 | 0.08 | 0.21 | 0.35 | 0.33 | 0.03 |

## 5. CONCLUSIONS

With the absence of any limitation to the access to natural resources and the environment there is the possibility of 'free riding' and over exploitation of them. Currently certain countries pollute and exploit resources and other countries are affected through the environmental degradation and resource depletion of the global environment. For this reason, it is important to focus on the possibility of divergence of environmental quality indicators. In order to consider this issue, energy per capita can be used as a proxy for pollution and resource use. In order to examine this, this paper analysed both the existence of historical convergence of energy per capita and the forecast of future distribution. Concerning historical convergence, the energy per capita for each country is analysed and then the existence of energy convergence for the world, OECD and Non-OECD countries are examined. From the study of the energy per capita for each country, it was found that the highest growing countries were the NIES and oil producing countries and the countries with the lowest growth in energy per capita were the developed countries with the highest income per capita and less developed countries. If we study the world, Non-OECD, and OECD countries, it was found that for both the world and Non-OECD countries we find no evidence of convergence for energy per capita with any of the measures used here-deviations, IQRs, kernel densities distribution and $\beta$ convergence analysis. This implies that there was no evidence found of any improvement in "environmental inequality" among both the world and Non-OECD countries over the time period between 1971 and 2001. On the other hand, with OECD countries, we found that energy per capita converged with all of the measures used, which suggests movement towards "environmental equality" among OECD countries.

These results imply that it is required to take precautions concerning the absence of free access to natural resources and the environment which may cause certain countries to damage and exploit them effecting other countries and causing environmental inequality. Measures such as a polluters pay policy where optimal pollution tax or energy tax is introduced may be a possibility to address this inequality. This could be introduced as an environmental policy to countries with high level of growth in energy per capita such as BRICS and oil producing countries.

Concerning forecasting of future energy distributions, from the results of the Markov chain transition matrix, we find no evidence of a compressed ergodic distribution in energy per capita at the world level and with Non-OECD countries. On the other hand, OECD countries showed evidence of a compressed distribution around the average. This may be an indication that there are variances in environmental regulations and technological development for the world and Non-OECD countries but environmental regulation and technology is converging for OECD countries. If so, this could mean that in the future, a regional approach to improve the environment could be taken amongst OECD countries and gaining an agreement on policies such as climate change may become a possibility between OECD countries.

With policymakers continuing to discuss on ways to address climate change, the information on future distribution of environmental indicators will be beneficial. This paper studies the historical distribution of energy per capita and future predictions. Future studies using other indicators of pollution such as energy per unit of GDP would provide a broader understanding and studies within other regions such as Asia, Europe or Africa could also provide insight for policymakers.

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## Appendix A – Definition of Deviations

The following three deviations define the standard deviation (*SD*), average absolute deviation (*AD*), and median standard deviation (*MD*)

$$SD = \sqrt{\frac{\sum_{i=1}^{N}(Y_i - \bar{Y})^2}{N-1}} \tag{A1}$$

where *i* denote country, and *N* is the number of countries. *Yi* is the natural logarithm of energy per capita of country *i*. $\bar{Y}$ represents the average natural logarithm of energy per capita of the observed group.

$$AD = \frac{\sum_{i=1}^{N}(| Y_i - \bar{Y} |)}{N} \tag{A2}$$

where $| Y |$ is the absolute value of *Y*.

$$MD = median(| Y_i - \overset{*}{Y} |) \tag{A3}$$

where $\overset{*}{Y}$ represents the median of the data.

## Appendix B – Sampled Countries (Countries in **bold** are the OECD countries)

Albania; Algeria; Angola; Argentina; **Australia**; **Austria**; Bahrain; Bangladesh; **Belgium**; Benin; Bolivia; Brazil; Brunei; **Bulgaria**; Cameroon; **Canada**; Chile; China; Colombia; Congo Dem. Rep.; Congo, Rep.; Costa Rica; Cote d'Ivoire; Cuba; Cyprus; **Czech Republic**; **Denmark**; Dominican Republic; Ecuador; Egypt Arab Rep.; El Salvador; Ethiopia; **Finland**; **France**; Gabon; **Germany**; Ghana; **Greece**; Guatemala; Haiti; Honduras; Hong Kong, China; **Hungary**; **Iceland**; India; Indonesia; Iran Islamic Rep.; Iraq; **Ireland**; Israel; **Italy**; Jamaica; **Japan**; Jordan; Kenya; Korea, Dem. Rep.; **Korea Rep**.; Kuwait; Lebanon; Libya; **Luxembourg**; Malaysia; Malta; **Mexico**; Morocco; Mozambique; Myanmar; Nepal; **Netherlands**; **New Zealand**; Nicaragua; Nigeria; Norway; Pakistan; Panama; Paraguay; Peru; Philippines; **Poland**; **Portugal**; Qatar; Romania; Saudi Arabia; Senegal; Singapore; **Slovak Republic**; South Africa; **Spain**; Sri Lanka; Sudan; **Sweden**; **Switzerland**; Syrian Arab Republic; Tanzania; Thailand; Togo; Trinidad and Tobago; Tunisia; **Turkey**; United Arab Emirates; **United Kingdom**; **United States**; Uruguay; Venezuela RB; Vietnam; Yemen, Rep.; Zambia; Zimbabwe