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THE SHARE OF THE GLOBAL ENERGY MIX: SIGNS OF CONVERGENCE?

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ABSTRACT

This paper investigates the convergence behaviour regarding the share of global energy mix, as measured by primary energy consumption. Recent studies that employ stationary tests of panel data suggest that such data support the convergence hypothesis; however, some drawbacks exist, as these studies rely on methods that do not necessarily imply a sufficient condition for convergence. This paper adopts the concept of relative convergence as proposed by Phillips and Sul (2007), which employs a time-varying, idiosyncratic component. We choose to focus on various sources' global primary energy consumption and investigate the long- run dynamic behaviour by source. The key finding of this paper is that two distinct clubs of convergence of energy can be determined: renewable and non-renewable energy clubs of convergence.

Keywords: Energy Mix, Renewable Energy, Non-renewable Energy, Relative Convergence, Clubs of Convergence.

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1. Introduction

In the 21st century, we are faced with the challenge of transitioning from fossil fuel-based energy to renewables. Grubler (2012) emphasizes that the need for such a transition is apparent given that the current energy system is unsustainable from economic, environmental, and social perspectives. However, such transitions require a significant change in technology, regulatory tariffs and prices, as well as users' energy-consumption behaviours (Sovacool 2016). While global energy consumption continues to increase, the share of energy in economic growth has declined in developed countries, and has been increasing in countries outside of the Organisation for Economic Co-Operation and Development (OECD), such as China and India (Csereklyei and Stern 2015). This global increase in energy consumption is likely to continue, exacerbating concerns regarding climate change and the environment.

The nexus between energy consumption and growth has drawn significant interest; several hypotheses have emerged in literature to address this issue: the growth hypothesis, which posits that energy consumption causes growth; the conservation hypothesis, in which economic growth causes energy consumption; the feedback hypothesis, in which a bidirectional causality exists between energy consumption and economic growth; and the neutral hypothesis, in which no such causation exists (Ghoshray et al. 2018). While the results from extant studies are mixed, the argument can be applied that the energy sector and its patterns of energy use change with economic growth (Meng et al. 2013). For example, technological advancements in many advanced economies—such as expanding and encouraging the consumption of renewable energy—have resulted in improved energy efficiency (Mishra and Smyth 2014). If evidence exists of an increase in renewable to total energy consumption over time, coupled with economic growth and signs of curtailing carbon dioxide (CO_2) emissions, then this suggests policies to that continue with this energy mix. Alternatively, decreasing different sources' disparities in energy consumption proves that such policies have been successful. While such transitions in the energy mix can be protracted, it is of empirical interest to determine whether any signs of convergence indeed exist. Sovacool (2016) notes that transition rates are not constant over time, and that divergence can occur, as opposed to convergence.

In this context, it is important to understand the time path of energy consumption and its underlying dynamics. This paper uses Phillips and Sul's (2007)—hereafter, 'PS'—'convergence club' method to investigate whether energy consumption from different sources has converged into a single source, and hence, can be considered 'standardised'. Alternatively, we discern whether different groups exist that can be classified as 'renewable' and 'non-renewable', leading to different 'clubs'. Convergence to a non-renewable club would imply that substitutability exists between different fossil fuels due to specific external shocks leading to a steady mix of non-renewables. For example, few people in the United States questioned the extent to which their lifestyles depended on oil until an oil price shock occurred in 1973; the subsequent oil crisis changed their perspective. Consequently, policy makers aimed to manage such risk by diversifying oil suppliers or enhancing the substitutions among different oil types. This led to an increased diversification of energy from other sources, such as natural gas and coal, as nuclear power and natural gas could be substituted for crude oil in electricity generation, and crude oil could then be diverted to transportation services (Ruhl et al. 2012). Similarly, a convergence club for renewables would imply a standardised mix exists for renewable energy sources based on their production costs.

There is a growing belief that the volume of fossil fuels—such as oil, which can be commercially exploited at prices to which the global economy has become accustomed—is limited, and will soon decline. As a result, oil may soon shift from a demand-led to a supply-constrained market (Owen et al. 2010). Currently, the demand for energy to meet our requirements depends upon the rapid, immediate diversification of various forms of energy. Therefore, possible supply constraints will lead to the need for a transition to alternative energy sources where appropriate, as well as behavioural changes and adaptation.

Hence, this paper aims to study the convergence of primary energy consumption using a broader, more general framework as proposed by PS. This framework allows for the following possibilities: (i) overall convergence, (ii) clubs of convergence and/or divergence, and (iii) no convergence. We use the PS method to discover evidence that two clubs—one comprised of fossil fuels (non-renewables), and the other of non-fossil fuels (renewables)—have emerged since the 1960s. These two clubs are distinct and exhibit no signs of convergence, which implies that until now, fossil fuels have converged, as the combination of coal, natural gas and oil have revealed no signs of divergence in terms of their energy usage. The discovery of a separate club for renewables indicates that the energy mix in the non-fossil fuel category is converging. However, the two clubs collectively diverge, demonstrating that thus far, the energy mix between renewables and non-renewables will not converge.

This diversification and gradual specialisation of energy is a result of the comparative efficiency among each of the types of commercial fuel in terms of its production and conversion to usable energy, and of its contribution to GDP growth (Ruhl et al. 2012). After World War II, oil was the major provider of energy until supplies were disrupted in the 1970s (Hartshorn 1993); this led to a drive for diversification with other fuels' gaining of popularity, such as natural gas and nuclear energy. Recently, the industry has shifted towards harnessing energy from renewable sources, such as wind or solar, which has led to an energy mix comprised of oil, natural gas, nuclear, wind and solar, among others. This process of a change in the energy mix would result from the fact that fuels can now be traded across nearly all international borders, technologies are becoming increasingly shared internationally, and consumption baskets determining energy's end-use are becoming standardised across formerly different countries (Ruhl et al. 2012). This paper analyses the dynamic patterns of primary energy consumption, and is organised as follows: Section 2 provides some history of past studies and methodological issues. Section 3 then discusses this paper's econometric methodology, which describes the novel approach based on PS' research. Section 4 describes the data and the empirical results, while Section 5 concludes.

2. Past Studies and Methodological Issues

Many studies have addressed the convergence of energy consumption in its various forms, including renewable and non-renewable energy sources. Literature has also employed various energy consumption measures, including total energy consumption and energy prices. Both strands apply the concept of stochastic convergence; this is tested using the unit root and/or stationary time-series tests of the relative time-series—or data expressed as ratios of the cross-sectional sample mean of all series in the sample—to assess the presence of the convergence hypothesis. This paper augments this strand of literature by employing the convergence club approach as an alternative that allows us to focus on the dynamic patterns of primary energy consumption.

Recent studies have primarily focused on total or final energy consumption, or a particular source of energy consumption across economies, or countries or states within a country in particular. This precludes any analysis concerning various dynamic energy-consumption behaviours, including those pertaining to either renewable or non-renewable sources, which have been inconsistent across various sources of energy. In this context, de Oliveira Matias and Devezas (2007) argue that primary energy consumption in the last two centuries has differed among renewable and non-renewable energy sources. According to de Oliveira Matias and Devezas (2007), fossil fuel energy sources dominate, and their consumption levels are significantly higher than those of renewable sources. This might be due to economic fluctuations and the decline of domestic energy sources. For example, the European Union is more likely to rely more on energy imports in different business cycles, and crude oil and natural gas in particular. According to a report from the European Commission (2014), EU energy markets had to consider the industry's long-term prospects in terms of replacing decreasing domestic production with imports from EU trading partners. This implies that growth targets might affect the type of energy sources economies might choose to switch to, or the energy mix consistent with economic needs. This creates a substitution behaviour, in which each energy sector dominates the market at the expense of the others due to the increase and decrease in market shares for each energy sector (Bodger et al. 1989). Therefore, this paper attempts to apply the convergence concept to investigate the nature of the time path in primary energy consumption. This also includes identifying the energy mix, a task that requires an appropriate econometric methodology. We argue that the approaches based on stochastic convergence may not be suitable for such a task.

The concept of stochastic convergence due to Carlino and Mills (1996) is the trend stationarity of time- series difference between two series. Two series converge relatively over time when the time series share the same stochastic or deterministic trend elements in the long run, such that the ratio of the two series eventually converges to unity (Kong et al. 2019). Further, Barassi et al. (2008) comment on the inaccuracy arising from including a particular trend, which could result in a trend-stationary series being labelled as converging even if it were actually diverging from the international average. Moreover, the available testing procedures in literature are restrictive, and could lead to the erroneous conclusion that the presence of a stochastic convergence omits the possibility of clubs of convergence, when multiple time paths or long-term levels exist to which subsets of series converge.

Club convergence concept has been predominantly discussed in the context of income convergence and CO_2 emissions. In the case of income, early contributions include Chatterji's (1992) work, in which 'clubs' involve separate clubs for convergence and divergence. However, Chatterji's (1992) approach is conceptual[2], as it implicitly assumes that members of the convergent club are homogeneous, in the sense that they all converge to the same steady state or long-term level. Similarly, stochastic convergence can also be interpreted with a combination of stationary and nonstationary elements, in which stochastically convergent series form a convergence group and non-convergent series form a divergent group. This conceptualisation of convergence clubs is also restricted by assumptions regarding the nature of the long run. Quah (1997) refers to two clubs: those of rich and poor economies. Testing for the presence of these clubs under Quah's (1997) discourse relies on an informal inspection of the data's distribution, which may lead to an erroneous identification of these clubs. Moreover, restricting the number of clubs to two rules out the presence of other clubs that would otherwise be identified. Thus, a more general framework would be appropriate to test for an 'overall' convergence and clubs of convergence that allow for the possibility of the existence of both divergence groups as well as convergence clubs with multiple long-term levels. Regarding CO_2 emissions, studies have examined whether emissions converge to long-term levels consistent with environmental agreements and targets (Aldy 2006; Barassi et al. 2008, 2011; Westerlund and Basher 2008). While these do not explicitly reference clubs of convergence, one can implicitly infer that two clubs can exist based on the empirical literature on stochastic

[2] This is indeed true if we consider the context within which Chatterji's (1992) 'convergence clubs' concept developed. Namely, the approach is consistent with income convergence literature, which assumes the presence of one long-term level to which all economies would converge.

convergence: a club of convergence, or when the unit-root hypothesis is rejected; and another of divergence, or when the unit-root hypothesis is not rejected.

Findings are generally mixed regarding convergence in energy consumption literature. While early studies consistently reject the convergence hypothesis, recent studies tend to differ, but most concur regarding the convergence of energy consumption. For example, Payne et al. (2017) find evidence to support stochastic convergence, but this evidence is solely based on fossil fuel data. This may suggest the presence of a common trend that drives the dynamics of energy consumption of the same nature, such as non-renewables. However, this contrasts Mohammadi and Ram's (2017) conclusions, which indicate the presence of divergence across US states' energy consumption. Meng et al. (2013) argue that the convergence hypothesis is rejected given erroneous conclusions in unit-root testing due to the presence of structural breaks (Perron 1989). Once the breaks are accounted for in a panel-data framework, Meng et al. (2013) demonstrate that energy use in OECD countries is stationary and favours convergence. However, their study involves per capita energy use, which includes final energy consumption and does not distinguish between the sources of energy—such as renewable versus non-renewable—with no information about the dynamic behaviour of primary energy consumption and the energy mix. The studies that report convergence in energy consumption either implicitly assume that the convergence hypothesis holds (Jakob et al. 2012), or employ panel data stationarity or LM-type tests to find evidence of convergence. For instance, works by Hao et al. (2015), Mishra and Smyth (2014), Lee and Lee (2009), among others, discover that energy consumption follows a stationary process; these authors subsequently conclude that the convergence hypothesis holds. Similar to Meng et al. (2013), these studies: (i) employ data that do not necessarily reflect primary energy consumption by source, and (ii) indicate that the stochastic convergence concept is biased in favour of the convergence hypothesis. These two common features limit existing literature and create a research gap that we aim to address.

The PS framework allows for various possibilities concerning the convergence hypotheses; in the context of this framework, we first test the overall convergence hypothesis. While the overall hypotheses assess whether all series in the data converge to a common long run trend, the overall convergence hypothesis in particular is highly relevant. This offers an alternative to stochastic convergence, as the latter does not directly test for the presence of a common long run time path to which all data series converge. Second, if overall convergence is rejected, the framework allows for clubs of both convergence and divergence, unlike existing tests. The number of clubs identified using this approach is limited only by data availability. Further, the PS procedure proposes an idiosyncratic element that is allowed to evolve over time and capture heterogeneity across individuals using a time-varying, factor-loading coefficient. The test implemented in this approach does not rely on any particular assumption concerning trend stationarity or stochastic non-stationarity of the variable of interest and the common factors across individuals in the panel; this makes it an attractive approach and prevents any issues with high persistence and unit roots when dealing with convergence in a dynamic panel framework.

While fossil energy resources are generally limited, it has been intensely debated as to whether these resources are gradually being depleted. The status of global energy is contentious, as it has been polarised between advocates of peak oil, who believe production will soon decline; and oil companies, which posit that enough oil exists to last for decades. In any case, the world in the long run may very well struggle to provide affordable oil and technological advancements, such as horizontal drilling and hydraulic fracturing. Moreover, costly and less productive methods, such as deep-sea drilling, may need to be used. As Schollnberger (2006) discussed, the global pattern of primary energy consumption will profoundly change during the 21st century, which will create a new energy mix. The advantage is that the energy mix over the years is becoming more complex and changing at varying rates. This study's results will aid in our understanding of the trajectory of this energy mix in recent decades.

3. Econometric Methodology

This paper employs two convergence concepts: stochastic and relative convergence. We aim to primarily test whether clubs of convergence exist, leading to insights on the energy mix for global primary energy consumption. However, stochastic convergence also provides a useful confirmatory test to assess the robustness of any conclusions regarding clubs of convergence.

3.1. Stochastic Convergence Testing Strategy

Researchers of environmental economics and CO_2 emissions convergence have widely used stochastic convergence (Strazicich and List 2003; Barassi et al. 2008, 2011; Westerlund and Basher 2008). This concept is considered in testing the convergence hypothesis with unit root (and/or stationarity) tests; the convergence hypothesis is rejected if the tests fail to reject the unit root hypothesis, or indeed reject the stationarity hypothesis. However, Barassi et al. (2008, 2011) note that merely applying unit root tests in relative to average forms of the process is insufficient, and may lead to erroneous conclusions of convergence when the process is actually divergent. Consequently, Barassi et al. (2008, 2011) propose a necessary condition that must hold for the stationarity hypothesis to be interpreted as stochastic convergence. Specifically, we consider the following model, which expresses each relative consumption series as function of a trend *t*:

$$y_{jt} = \beta_{j0} + \beta_{j1} t + \varepsilon_{jt} \quad (1)$$

where y_{jt} is the share of the *j*th energy source over time *t*. The intercept β_{j0} is the *j*th initial deviation from the long-term level, and ε_{jt} is the *j*th energy consumption innovation, with zero mean and a finite variance. The necessary condition mandates that the intercept and trend slope, or β_{j0} and β_{j1} respectively, have opposite signs for the stationarity hypothesis to be interpreted as stochastic convergence for a given series *j*. If this condition does not hold, then the presence of stationarity does not necessarily imply convergence. Thus, we check the validity of the necessary condition as proposed by Barassi et al. (2008) prior to performing unit root tests.

For this purpose, we adopt a testing strategy similar to that proposed by Barassi et al. (2008, 2011), which consists of the following stages:

Stage 1: We check whether the necessary condition is satisfied by estimating Equation (1) using Ordinary Least Squares (OLS). We also apply *t*-tests for heteroscedasticity and an autocorrelation-corrected (HAC) regression as suggested by Vogelsang (1998) on each relative consumption series. Thus, we obtain the estimated coefficients' signs to assess the necessary condition's validity.

Stage 2: We apply unit root tests using single equation and panel data tests. For our single equation methods, we apply a battery of six unit root tests as proposed by Elliott et al. (1996) and Ng and Perron (2001). The Generalised Least Squares Dickey-Fuller (DF-GLS) and the Point Optimal (PT) tests are derived from work by Elliott et al. (1996), while the M-type tests (MZ_{α}, MZ_{t}, MSB and MP_{T}) are from Ng and Perron's (2001) research.

We also apply a battery of panel unit root tests covering a first-generation (Hadri 2000) LM test and an Im- Pesaran- Shin (IPS) test (Im et al. 2003) and second-generation panel unit root tests, including those proposed by Phillips and Sul (2003), Bai and Ng (2004, 2010) and Moon and Perron (2004). We also apply the Recursive Mean Adjustment (RMA) test proposed by Sul (2009), which is precise and powerful for our panel data, such as when $T > N$.

3.2. Relative Convergence—The PS Approach

The PS procedure provides a novel approach that relaxes the assumption regarding the time-series stationarity and defines the concepts of convergence and clubs of convergence. This procedure endogenously identifies clubs of convergence in a simple, convenient time-series framework to test for convergence. It also includes the possibility of mobility and catching up. Moreover, this procedure allows for a clustering of the time-series depending on the individual transition path relative to common trends; this may assist in identifying steady states describing the levels of income at which the time-series on similar time paths converge. Further, PS propose an idiosyncratic element that is allowed to evolve over time and capture individual heterogeneity using a time-varying, factor-loading coefficient. The test implemented in this approach does not rely on any particular assumption concerning trend stationarity or stochastic non-stationarity of the variable of interest and the common factors among individuals in the panel. This makes this approach highly attractive and solves the issue of unit roots and co-integration when addressing convergence in a time-series framework.

Following PS' notation, we can define the econometric model used to test for convergence and clubs of convergence as:

$$X_{it} = \delta_{it}\mu_t \tag{2}$$

where X_{it} is the dependent variable—or specifically, the global share of primary energy consumption—observed across $i = 1,2, \dots, N$ individuals over period $t = 1,2, \dots, T$. Model (2) includes two terms: δ_{it} and μ_t. The former term is an idiosyncratic element, in the sense that it captures both time- and individual-specific effects. It also measures the distance between X_{it} and the common factor μ_t, which represents the common stochastic trend in the panel. In other words, the coefficient δ_{it} measures the share of the common factor μ_t that each individual in the panel data experiences. In the context of this paper, we define a stochastic trend as the common factor term; both elements are time-varying.

The idiosyncratic element is defined as:

$$\delta_{it} = \delta_i + \sigma_i \zeta_{it} L(t)^{-1} t^{-\alpha} \quad (3)$$

where δ_i is fixed, or $\zeta_{it} \sim iid(0,1)$ across individuals $i = 1,2, \dots, N$ and dependent over time t; and $L(t)$ is a slowly varying function of time, in which $L(t) \to \infty$ as $t \to \infty$.

Based on this formulation, the null hypothesis of convergence is accepted if $\delta_{it} \to \delta_i$ or $H_0(\delta_i = \delta \ and \ \alpha \geq 0 \ )$ for all $\alpha \geq 0$ against the alternative of no convergence, or specifically, $H_A(\delta_i \neq \delta \ \forall \ i; \ and \ \alpha < 0 \ )$.

Moreover, X_{it} and μ_t do not need to be restricted to be trend stationary, as Equation (2) does not require either variable to be specified as stationary or non-stationary. The model is linearised to form a $logt$ regression, which can be used to directly test for the convergence and clubs of convergence hypotheses; this regression is expressed as:

$$log(H_1/H_t) - 2logL(t) = \hat{a} + \hat{b}logt + \hat{u}_t \quad (4)$$

where $t = \lfloor rT \rfloor, \lfloor rT \rfloor, \dots, T$, with $r > 0$, $L(t) = \log(t+1)$, $\hat{b} = 2\hat{a}$ and $\hat{a}$ is the estimate from (4). The term H_1/H_t is the cross sectional variance ratio, with the variance defined as:

$$H_t = \frac{1}{N}\sum_{i=1}^{N}(h_{it} - 1)^2 \quad (5)$$

and

$$h_{it} = X_{it}\Big/\left[\frac{1}{N}\sum_{i=1}^{N} X_{it}\right] = \delta_{it}\Big/\left[\frac{1}{N}\sum_{i=1}^{N}\delta_{it}\right] \quad (6)$$

where h_{it} measures and captures the divergent behaviour of individuals from the common stochastic trend or the long-run growth path μ_t, in addition to displaying the relative transition path for individuals in our panel data.

The regression begins at $t = \lfloor rT \rfloor$, which is the integer part of rT for some fraction $r > 0$; PS recommend that $r = 0.3$. After running the regression, we cannot reject the null hypothesis if the autocorrelation and heteroskedasticity of the robust, one-tailed $t_{\hat{b}}$ statistic exceeds the critical value: at a 5% level of significance, non-rejection of the null hypothesis occurs if $t_{\hat{b}} \geq 1.65$. Rejecting the null hypothesis implies that no *overall* convergence exists, but does not imply that there is no convergence at all. In fact, this may imply that relative convergence may exist, which can be tested using a procedure by PS, which alternatively tests for clusters of convergence.

Clustering individual series into subgroups requires evidence of the presence of clubs of convergence as the sample size substantially increases ($T \rightarrow \infty$). Further, PS propose a simple procedure to identify the clubs of convergence when the overall convergence hypothesis is statistically rejected[3]. In summary, the procedure includes defining a core subgroup G_K that contains at least K members, where $K = 2, \dots, N$. This subgroup is detected using an ordering procedure based on the last time-series observation, or the last $\lfloor rT \rfloor$ observations. Next, a size of k subgroups can be constructed, or $G_K = \{1,2, \dots, k\}$ for $= \{2, \dots, N\}$. This is followed by the $logt$ regression test within each of these subgroups, using data from G_K. The process chooses k^* to maximise t_k over all values for which $t_k > c$ for $k = \{2, \dots, N\}$ and c is the critical value.

4. Data and Empirical Results

Data were obtained from the BP Statistical Review of World Energy (published June 2017)[4]. The data measures the primary consumption of non-renewable energy, such as coal, natural gas and oil; as well as alternative energy sources that include renewables, such as hydro and nuclear power, among others. The data is measured annually from 1965 to 2016, and the unit of measurement is in millions of tonnes oil equivalent (Mtoe).

Figure 1 illustrates the time dynamics of the primary consumption of the six energy sources under consideration. Generally, all variables exhibit positive trends over the sample, with a considerable difference in terms of magnitudes with the greater consumption of non-renewable than renewable energy. The figure also indicates a slow increase in the consumption of all energy sources, with a slight increase in coal consumption and a decreasing tendency to consume nuclear energy. The consumption gap has increased, from 1,519 Mtoe recorded in 1965 to 3,826 Mtoe recorded in 2016, as displayed in Figure 2. However, this gap remains significantly wide, as reported in Table 1, Panel A. This table reports the equality tests between

[3] Phillips and Sul (2007) provide a detailed discussion on the algorithm used to identify the clusters of convergence.
[4] Data can be obtained directly from: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html.

the maximum and minimum, maximum and median and minimum and median global energy consumption as well as the shares of consumption. Subsequently, the null hypothesis of equality for both series is rejected, with a statistically significant gap. Moreover, according to Table 1, Panel B, the share of global energy consumption experienced different growth rates across the six energy sources. The data indicates that oil shares fell by 0.8% from 2010 to 2016, while gas shares increased during the same period by 0.2% after decreasing by 0.2% from 2000 to 2009. In contrast, coal shares exhibit positive growth from 1965 to 2016, by 6.6%—the highest among fossil fuels—with a noticeable increase of 1.2% from 2010 to 2016.

Overall, renewable energy consumption shares exhibit better performance than fossil fuels. Aside from other renewable energy sources, the performance of consumption shares of hydro and nuclear energy decreased by 1.7% and 2.1% from 2000 to 2009, respectively, and 0.2% and 2% from 2010 to 2016, respectively. Overall, the share of fossil fuel consumption has not decreased as much as renewable energy in recent years, although renewable energy consumption shares have more rapidly increased over the full sample.

[Figures 1 and 2 about here]

[Table 1 about here]

However, Figures 1 and 2 do not convey much about the dynamics of the shares of consumption for each energy source. Thus, we must transform the data to express it in terms of shares instead of levels. These shares are defined as

$$X_{it} = (Y_{it}/Total_t) \times 100 \quad (7)$$

where Y_{it} is the ith variable of interest from 1965 to 2016, such as oil, coal, gas, nuclear or hydro energy, among others; and $Total$ is the total consumption observed over the same period. Figure 3 illustrates the gap in global energy consumption shares. Although this gap has slightly diminished between energy shares on the top and bottom of the distribution, Figure 3 demonstrates that the gap in global primary energy consumption shares remains visually wider from 1965 to 2016. The equality tests reported in Table 1, Panel A, also suggest the relative gap remains statistically significant for the same period.

Table 1, Panel B, reports the global energy consumption growth rates for all six energy sources over different periods of time between 1965 and 2016. The data reveals that oil consumption shares decreased by 0.8% from 2010 to 2016. During the same period, gas consumption shares increased by 0.2% after decreasing by 0.2% from 2000 to 2009. However, coal consumption shares experienced positive growth of 6.6% from 1965 to 2016—the highest among fossil fuels—with a noticeable increase of 1.2% from 2010 to 2016. Overall, renewable energy consumption shares exhibit better performance than fossil fuels from 1965 to 2016. However, shares of hydro and nuclear energy consumption have recently decreased by 1.7% and 2.1% from 2000 to 2009, and 0.2% and 2% from 2010 to 2016, respectively.

[Figure 3 about here]

The dynamics of consumption shares can also be illustrated using the relative transition curves as approximated using Equation (6) and illustrated in Figure 4. All relative transition curves displayed in Figure 4 are smoothed using the Hodrick-Prescott filter, with a smoothing parameter equal to 100[5]. The relative transition curves displayed in Figure 4 illustrate the

[5] A value of 100 was chosen since the data are annual.

tendencies in global consumption for all six energy types. Generally, all types of global energy consumption fluctuate over time in a divergent pattern, with a clear deviation away from the overall steady state as represented by the horizontal line at a value of one, in that $h_{it} \rightarrow 1$ is not satisfied (Figure 4). We also notice that this line splits the shares of consumption series into two groups: a group with very high consumption shares, including all traditional energy sources that fluctuate over time above the steady state level; and a group with low consumption shares, including all renewable energy sources fluctuating below the steady state level. This discussion leads us to formally test for convergence using the concepts of stochastic convergence and relative convergence as proposed by PS.

[Figure 4 about here]

4.1. Stochastic Convergence Results

Following the discussion in Section 3, we first check whether the necessary condition is satisfied. Table 2 reports the OLS estimates with HAC standard errors from Equation (1). The estimation output reveals that the necessary condition is satisfied for all consumption share series except for the gas consumption share, which has already surpassed the average. Figure 5 depicts the locations of consumption shares of all energy sources versus a cross-sectional average of total consumption. The observed pattern demonstrates that fossil fuels are all above the average, while renewable energy is below the average. In other words, fossil fuels are diverging from the norm.

[Table 2 about here]

[Figure 5 about here]

As reported in Table 3, the single-equation unit-root test results suggest a lack of stochastic convergence. All the test results are consistent in rejecting stationarity or failing to reject the unit root hypotheses, which implies the non-convergence of consumption shares. The exception is hydro consumption shares, which are convergent according to four of the six tests implemented[6].

[Table 3 about here]

However, the panel unit-root tests strongly suggest the presence of the unit root hypothesis. The reported tests involve two sets of panel data. First, the tests are implemented on all energy sources, which we denote as Panel Data 6. Second, following the Table 2 results, the necessary condition is not satisfied for gas consumption shares; therefore, we omit this from the original data set and re-run panel unit root tests on the resulting data set, denoted as Panel Data 5. Consequently, we use both first- and second-generation panel unit-root tests to conclude divergence exists in all cases.

4.2. Relative and Clubs of Convergence

As the previous section's panel unit-root tests rejected the convergence hypothesis, we extend the analysis by examining the possibility of relative convergence as proposed by the PS approach. Table 4 reports the PS procedure's results using trimming rates of r = 0.3, 0.25 and 0.2. The additional trimming rates confirm the trimming rate of choice, or r = 0.3. The statistic -44.76 reported in the overall test is well below the 5% level of significance from the one-tailed critical value (-1.65), which implies that the overall convergence hypothesis is rejected. In other

[6] Cautionary Note: Single-equation unit-root test results must be interpreted with caution, as the tests might suffer from low power and size distortions when the sample size is relatively small, which is the case with our data.

words, no convergence exists in all energy shares series. However, we can apply the PS procedure to identify two distinct convergence clubs. The first contains only fossil fuel-based energy, while the second contains non-fossil-based renewable energy. Figure 6 illustrates these clubs and reveals the significant disparities across clubs over the sample span despite the slight increase in renewable energy shares noted in the mid-1980s, which coincides with a decrease in fossil fuel shares. The two clubs' dynamics remained relatively constant for subsequent periods, with steadily higher fossil fuel shares. The conclusions remain the same when using trimming rates of 0.25 and 0.20.

[Table 4 and Figure 6 about here]

5. Conclusions and Policy Implications

One can only observe the data to conclude that no clear conclusion exists regarding the global energy mix. Further, one may discern that the impacts are clear in some dimensions, while historical data is less conclusive in others. The United States' Energy Information Administration (EIA—Today in Energy, 2013) has projected that global energy consumption will continue to grow, and that the fastest-growing energy sources are renewable energy and nuclear power, which have increased at a rate of 2.5% per year. Our analysis provides some clear characteristics of the data revealing the formation of two clubs: fossil fuels on the one hand, and nuclear and renewable energy on the other. The first club will continue to prevail in the near future, and presently demonstrates no signs of convergence with the second and more marginal club, comprised of renewables and nuclear energy.

The first club comprised of fossil fuels comes as no surprise. According to EIA estimates, oil demand is set to increase, with half of global oil demand emanating from China. This is likely to continue, as oil demand from the transportation sector is growing at robust rates in China and India. More recently, coal—which is locally available and relatively inexpensive in China—has gained a dramatic market share, driven by rapid economic and energy demand growth in China and other emerging economies. While coal has been the fastest-growing energy source in recent years, this growth has been unevenly distributed; specifically, it has been largely driven by China, while demand from OECD countries has been sluggish. As coal is critical in China and India, coal demand is likely to grow in the future. Further, different fuels have emerged in China's energy mix due to the size of its economy; the nation's natural gas sector and its related challenges cannot be observed in isolation from the global gas market, and gas consumption has increased four-fold since 2000 (OECD-IEA 2012).

The second club is comprised of nuclear and hydro energy, as well as other renewables. More recently, the use of renewable fuels has increased, and energy security and diversifying the energy mix are major policy drivers for renewables. The results reveal that the energy mix in this category has converged to a steady state, implying the substitutability and reallocation of energy sources over time. As renewables' growth generally contributes to energy diversification, the use of renewables can also reduce fuel imports and insulate the economy from fossil fuel price increases and fluctuations, to some extent. This may increase energy security, although the concentrated growth of variable renewables can make it more difficult to balance power systems. The renewable energy sector has demonstrated its capacity to deliver reduced costs, provided that appropriate policy frameworks are in place and enacted.

Over the years, supply-side technologies have also influenced energy policy. A transition may be possible in which individuals' energy-consumption behaviours could be changed by demand-side measures. For example, countries' nuclear capacity grew rapidly in the 1970s and

1980s as they sought to reduce their dependence on fossil fuels, and especially after the oil crisis in the 1970s. However, growth stagnated in the 1990s, with the exception of Japan and Korea, due to increased safety concerns following incidents at Three Mile Island in 1979 and Chernobyl in 1986. While there has been a renewed interest in nuclear energy since the year 2000, a 2011 tsunami inflicted disaster on Japan's Fukushima Daiichi nuclear power plant. Its impact on nations' growth of their nuclear-generating capacity will only become fully clear in the coming years.

Currently, fossil fuels remain the world's leading energy source. We have found evidence of an advance towards a long-term convergence process among the shares of oil, coal and natural gas in the global fuel mix. If this long-term convergence process were to continue, it would indeed lead us to a world not dominated by a single commercial fuel. While other energy sources other than fossil fuels have shown signs of convergence in their shares of consumption—such as nuclear and renewable energy—they are still distinct from the club formed by fossil fuels.

References

Aldy, J. (2006). Per capita carbon dioxide emissions: Convergence or divergence? *Environmental and Resource Economics*, 33, 533–555.

Bai, J., and Ng, S. (2004). A PANIC attack on unit roots and cointegration. *Econometrica*, 72 (4), 1127–1177.

Bai, J., and Ng, S. (2010). Panel unit root tests with cross section dependence: A further investigation. *Econometric Theory*, 26 (4), 1088–1114.

Barassi, M. R., Cole, M. A., and Elliot, R. J. R. (2008). Stochastic divergence or convergence or per capita carbon dioxide emissions: Re-examining the evidence. *Environmental and Resource Economics*, 40, 121–137.

Barassi, M. R., Cole, M. A., and Elliot, R. J. R. (2011). The stochastic convergence of CO_2 emissions: A long memory approach. *Environmental and Resource Economics*, 49, 367–385.

Bodger, P. S., Hayes, D. J., and Bains, J. T. (1989). The dynamics of primary energy substitution. *Technological Forecasting and Social Change*, 36 (4), 425–439.

Carlino, G., and Mills, L. (1996). Testing neoclassical convergence in regional incomes and earnings. *Regional Science and Urban Economics*, 26 (6), 565–590.

Chatterji, M. (1992). Convergence clubs and endogenous growth. *Oxford Review of Economic Policy*, 8 (4), 43–56.

Csereklyei, Z., and Stern, D. I. (2015). Global energy use: Decoupling or convergence? *Energy Economics*, 51, 633–641.

de Oliveira Matias, J. C., and Devezas, T. C. (2007). Consumption dynamics of primary-energy sources: The century of alternative energies. *Applied Energy*, 84 (7-8), 763–770.

Elliott, G., Rothenberg, T., and Stock, J. (1996). Efficient tests for an autoregressive unit root. *Econometrica*, 64 (4), 813–836.

European Commission. (2014). Communication from the commission to the European parliament and the council. Available online at http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0330&from=EN [accessed 07/02/2018].

Ghoshray, A., Mendoza, Y., Monfort, M., and Ordoñez, J. (2018). Re-assessing causality between energy consumption and economic growth. *PLoS ONE*, 13 (11), e0205671.

Grubler, A. (2012). Energy transitions research: Insights and cautionary tales. *Energy Policy*, 50, 8–16.

Hao, Y., Wang, S., and Zhang, Z. Y. (2015). Examine the convergence in per capita energy consumption in China with breakpoints. *Energy Procedia*, 75, 2617–2625.

Hadri, K. (2000). Testing for stationarity in heterogeneous panel data. *Econometrics Journal*, 3, 148–161.

Hartshorn, J. E. (1993). *Oil Trade: Politics and Prospects*. Cambridge: Cambridge University Press.

Im, K. S., Pesaran, M. H., and Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of Econometrics*, 115, 53–74.

Jakob, M., Haller, M., and Marschinski, R. (2012). Will history repeat itself? Economic convergence and convergence in energy use patterns. *Energy Economics*, 34 (1), 95–104.

Kong, J., Phillips, P. C. B., and Sul, D. (2019). Weak σ-convergence: Theory and applications. *Journal of Econometrics*, 209 (2), 185–207.

Lee, C. C., and Lee, J. D. (2009). Energy prices, multiple structural breaks and efficient market hypothesis. *Applied Energy*, 86 (4), 466–479.

Meng, M., Payne, J. E., and Lee, J. (2013). Convergence in per capita energy use among OECD countries. *Energy Economics*, 36 (C), 536–545.

Mishra, V., and Smyth, R. (2014). Convergence in energy consumption per capita among ASEAN countries. *Energy Policy*, 73, 180–185.

Mohammadi, H., and Ram, R. (2017). Convergence in energy consumption per capita across the US states, 1970–2013: An exploration through selected parametric and non-parametric methods. *Energy Economics*, 62, 404–410.

Moon, H. R., and Perron, B. (2004). Testing for a unit root in panels with dynamic factors. *Journal of Econometrics*, 122, 81–126.

Ng, S., and Perron, P. (2001). Lag length selection and the construction of unit root tests with good size and power. *Econometrica*, 69, 1519–1554.

Organisation for Economic Co-operation and Development—OECD and International Energy Agency—IEA. (2012). *Gas Pricing and Regulation: China's Challenges and IEA Experience*. International Energy Agency, Paris, France. Available online at: https://webstore.iea.org/partner-country-series-gas-pricing-chinas-challenges-and-iea-experience [Accessed 10/09/2019].

Owen, N., Inderwildi, O. R., and King, D. A. (2010). The status of conventional world oil reserves: Hype or cause for concern? *Energy Policy*, 38 (8), 4743–4749.

Payne, E. E., Vizek, M., and Lee, J. (2017). Stochastic convergence in per capita fossil fuel consumption in US states. *Energy Economics*, 62 (C), 382–395.

Perron, P. (1989). The great crash, the oil price shock, and the unit root hypothesis. *Econometrica*, 57 (6), 1361–1401.

Pesaran, M. H. (2004). General diagnostic tests for cross-section dependence in panels. *IZA Discussion Paper No. 1240*.

Phillips, P. C. B., and Sul, D. (2003). Dynamic panel estimation and homogeneity testing under cross section dependence. *Econometrics Journal*, 6 (1), 217–259.

Phillips, P. C. B., and Sul, D. (2007). Transition modelling and econometric convergence tests. *Econometrica*, 75 (6), 1771–1855.

Quah, D. (1997). Empirics for growth and distribution: Stratification, polarization and convergence clubs. *Journal of Economic Growth*, 2 (1), 27–59.

Ruhl, C., Appleby, P., Fennema, J., Naumov, A., and Schaffer, M. (2012) Economic development and the demand for energy: A historical perspective on the next 20 years. *Energy Policy*, 50, 109–116.

Schollnberger, W. E. (2006). Who shapes the future mix of primary energy? What might it be? *Oil Gas European Magazine*, 32 (1), 8–20.

Sovacool, B. K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science*, 13, 202–215.

Sul, D. (2009). Panel unit root tests under cross section dependence with recursive mean adjustment. *Economics Letters*, 105, 123–126.

Strazicich, M. C., and List, J. A. (2003). Are CO_2 emission levels converging among industrial countries? *Environmental and Resource Economics*, 24 (3), 263–271.

Today in Energy. (2013). U.S. Energy Information Administration. U.S. Department of Energy, July 25, 2013. Washington DC, USA. Available online at: https://www.eia.gov/todayinenergy/detail.php?id=12251 [Accessed 10/09/2019]

Vogelsang, T. J. (1998). Trend function hypothesis testing in the presence of serial correlation. *Econometrica*, 66 (1), 123–148.

Westerlund, J., and Basher, S. A. (2008). Testing for convergence in carbon dioxide emissions using a century of panel data. *Environmental and Resource Economics*, 40, 109–120.

Graphs

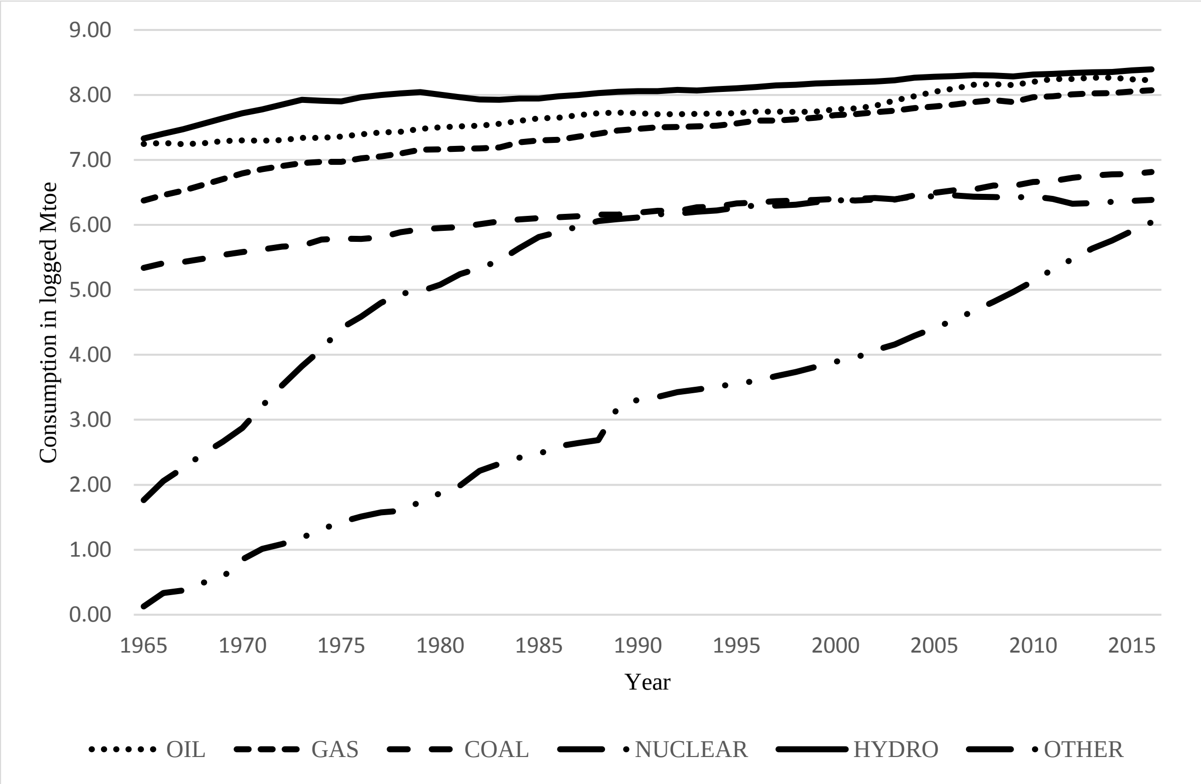

Figure 1: Energy consumption (1965–2016)

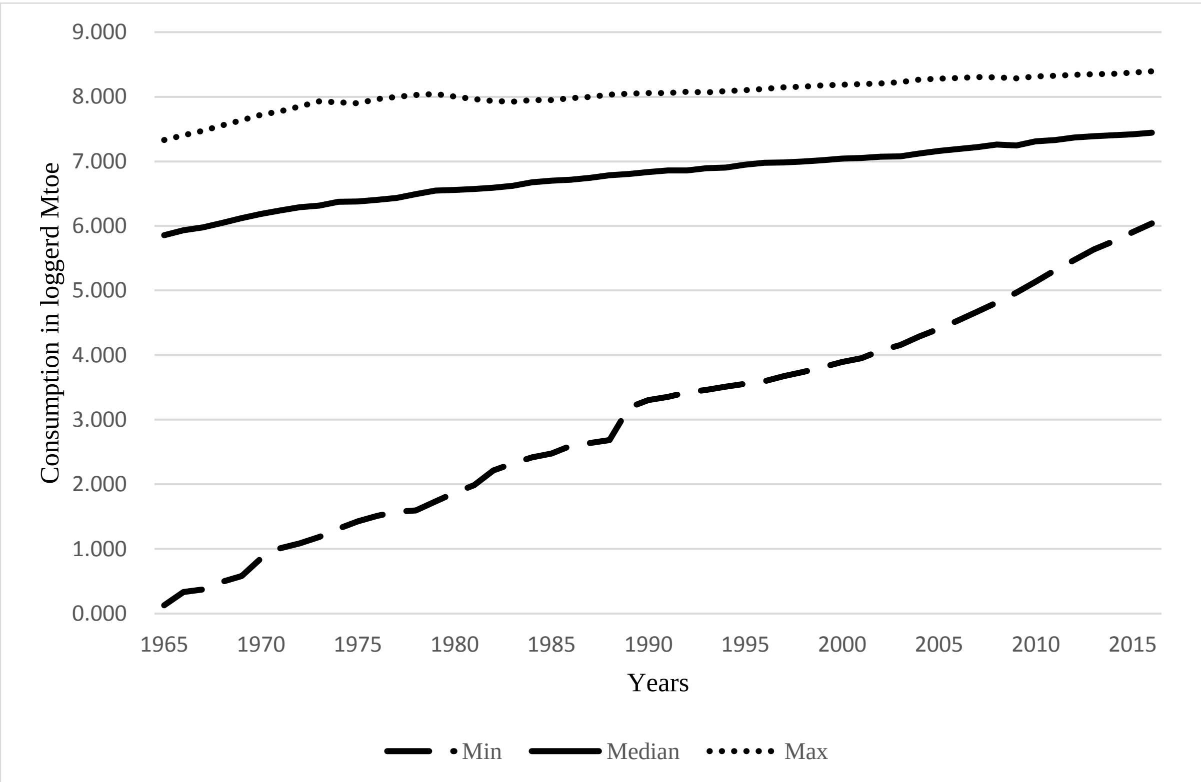

Figure 2: Gaps in consumption (1965–2016)

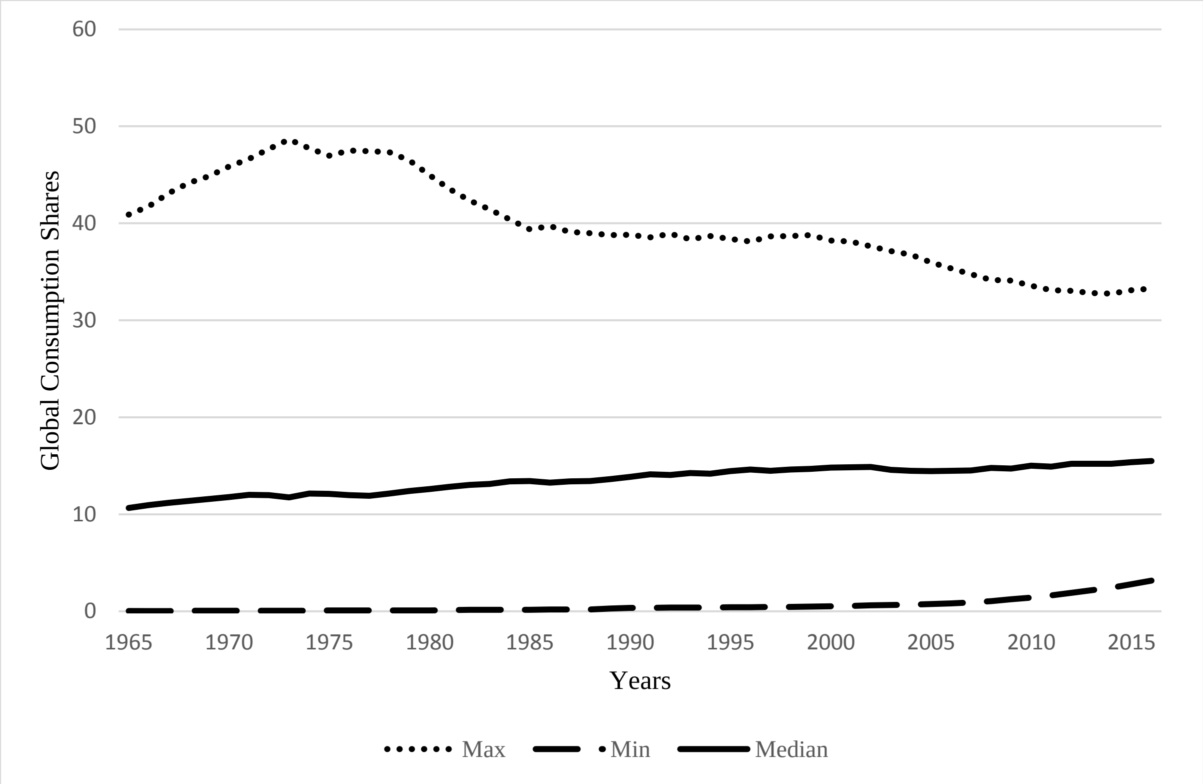

Figure 3: **Gaps in global consumption shares (1965–2016)**

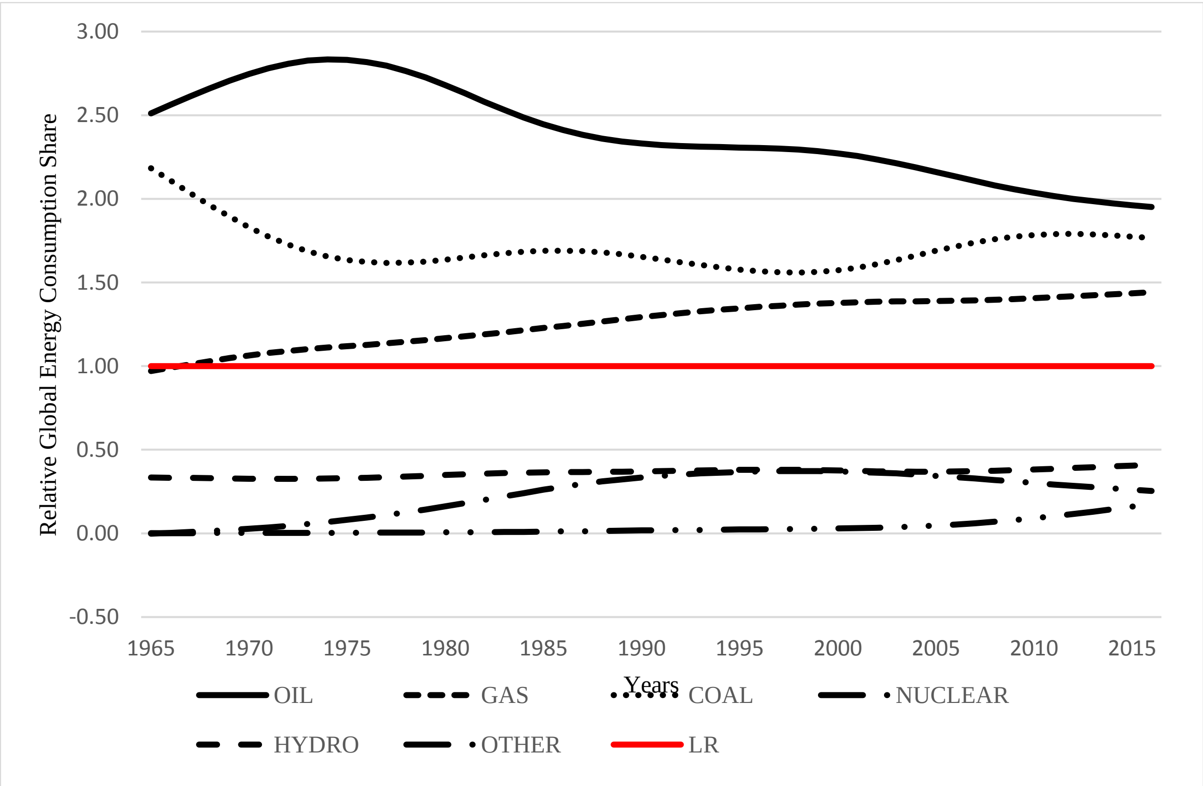

Figure 4: Relative transition curves of energy shares

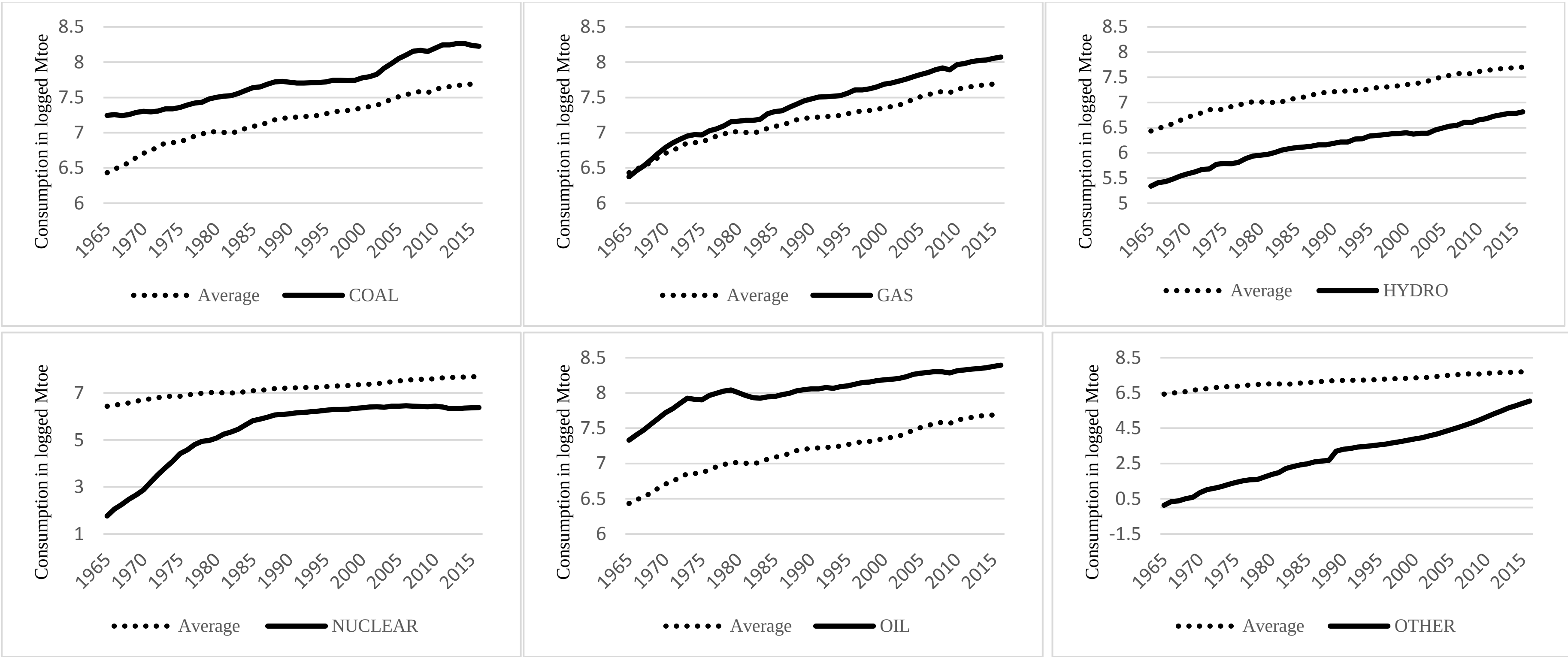

Figure 5: Consumption shares relative to data average

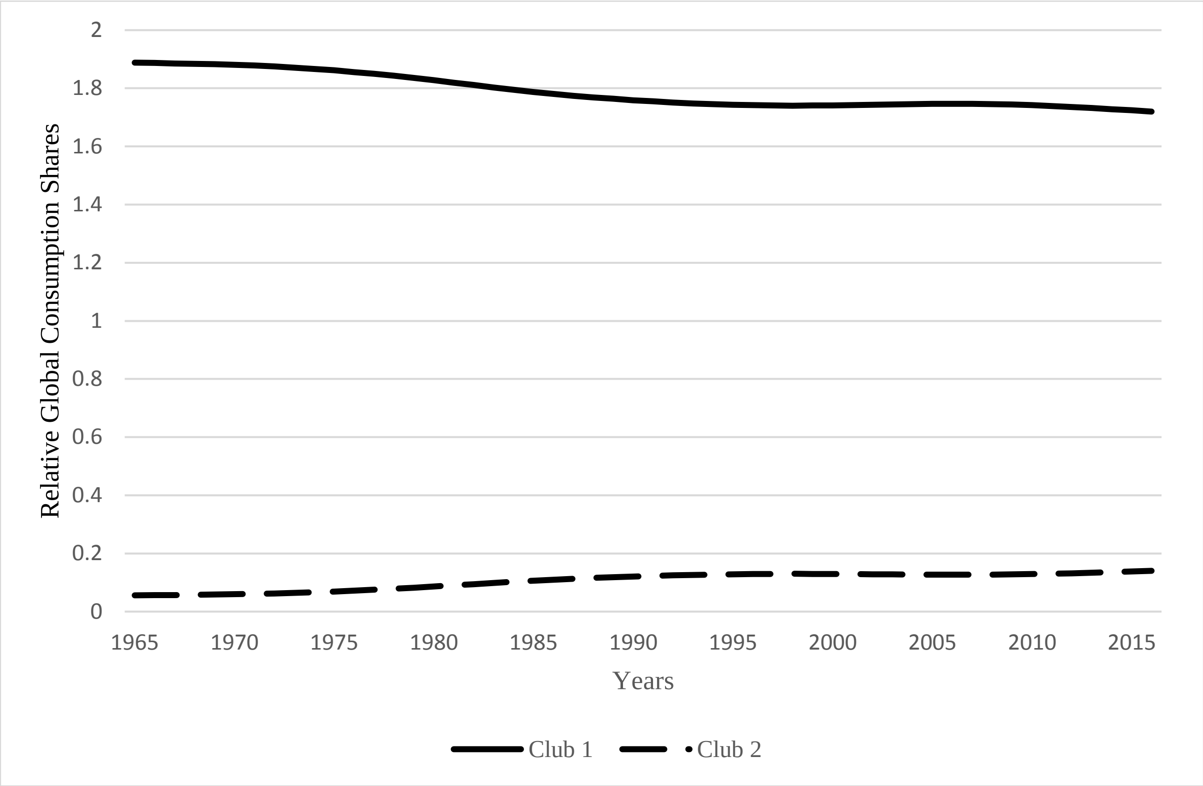

Figure 6: Relative transition curves—Estimated clubs

Tables

Table 1: *Key Statistics*

Panel A: Gap Equality Tests			
	Max-Min	Max-Med	Med-Min
Consumption	21.61***	18.35***	15.82***
Consumption Shares	59.02***	51.21***	45.99***

Panel B: Energy Consumption Shares—Growth Rates						
Period	**Oil**	**Gas**	**Coal**	**Nuclear**	**Hydro**	**Other**
1965–1969	-2.7%	1.8%	0.4%	37.9%	0.8%	148.7%
1970–1979	-2.1%	0.7%	1.6%	50.3%	-0.4%	66.7%
1980–1989	0.3%	1.2%	0.7%	15.4%	-2.1%	50.7%
1990–1999	-1.3%	0.6%	1.4%	2.1%	-0.2%	12.7%
2000–2009	1.9%	-0.2%	0.3%	-2.1%	-1.7%	21.6%
2010–2016	-0.8%	0.2%	1.2%	-2.0%	-0.2%	15.1%
1965–2016	-5.2%	5.8%	6.6%	202.3%	-4.4%	3,858.4%

*** refers to a 1% level of significance.

Table 2: *OLS Regression of Consumption Shares—Equation (1)*

Energy Source	Constant	Trend
Coal	0.566*** [0.054]	-0.001 [0.002]
Gas	0.040 ** [0.018]	0.007*** [0.001]
Hydro	-1.116*** [0.017]	0.003***[0.001]
Nuclear	-3.228*** [0.428]	0.056*** [0.014]
Oil	1.049*** [0.034]	-0.007*** [0.001]
Other	-6.336*** [0.041]	0.087*** [0.002]

T = 52. Values in [.] are HAC standard errors. *, ** and *** refer to rejection of the null hypothesis at 10%, 5% and 1% levels of significance.

Table 3: *Stochastic Convergence Tests*

Series	MZ_{α}	MZ_{t}	$DF-GLS$	MSB	P_{T}	MP_{T}
			Panel A			
			Single Equation Unit Root Tests			
Oil	-1.725	-0.918	-1.462	0.532	70.478	51.949
Gas	-2.768	-1.021	-1.397	0.369	36.148	28.304
Coal	-0.967	-0.62	-1.351	0.641	109.054	77.89
Nuclear	0.733	0.637	0.53	0.869	168.067	167.762
Hydro	-8.443**	-2.013**	-2.231**	0.238*	10.753	10.931
Other	4.308	2.714	2.4	0.63	140.632	135.213
			Critical Values			
			Ng and Perron (2001)			
1%	**-13.8**	**-2.58**	**-2.58**	**0.174**	**1.78**	**1.78**
5%	**-8.1**	**-1.98**	**-1.98**	**0.233**	**3.17**	**3.17**
10%	**-5.7**	**-1.62**	**-1.62**	**0.275**	**4.45**	**4.45**

		Panel B			
		Panel Unit Root Tests			
Study	Test	Panel Data 6		Panel Data 5	
		Statistics	*P-values*	*Statistics*	*P-values*
Hadri (2000)	*Z-stat*	31.74***	0.00	28.62	0.00
	HAC-Z	36.19***	0.00	31.28	0.00
Im et al. (2003)	*Z-stat*	1.50	0.93	2.11	0.98
Moon and	t_a	2.72	0.99	1.97	0.98
Perron (2004)	t_b	1.14	0.87	1.27	0.90
Bai and Ng (2010)	*PMSB*	2.27	0.98	1.33	0.91
Phillips and Sul (2003)	*Z-test*	7.33	0.69	9.39	0.31
Sul (2009)	*RMA*	4.17	-1.77†	4.33	-1.79†
		Panel C			
		Cross-Sectional Dependence			
CD test statistic		-0.25	0.8	-2.87	0.004

***, ** and * refer to rejecting the null hypothesis at 1%, 5% and 10% significance levels, respectively.

Panel A (Ng and Perron 2001): The process under the null has a unit for tests MZ_{α}, MZ_{t} and $DF-GLS$. The null hypothesis states the stationarity of the process for the remaining tests. The DGP allows for both an intercept and trend in all tests.

Panel B: *Panel Data 6* refers to the full data set including all energy sources. *Panel Data 5* refers to the panel data set without gas consumption shares, as the necessary condition was not satisfied. Hadri (2000) tests the null of stationarity, while the remaining authors test the presence of a unit root under the null. † refers to critical values at 5%.

Panel C: This panel reports the results from Pesaran's (2004) cross-dependence test. The null hypothesis indicates cross-correlational independence.

Table 4: *Convergence and Clubs of Convergence Test Results*

r	0.3		0.25		0.2	
	$\hat{t}$	$\hat{\alpha}$	$\hat{t}$	$\hat{\alpha}$	$\hat{t}$	$\hat{\alpha}$
Overall Test	-44.76*	-0.12	-67.13*	-0.12	-32.94*	-0.12
Club 1	21.92	0.51	23.63	0.47	20.81	0.41
Club 2	3.63	0.25	3.49	0.23	3.63	0.25

* refers to the rejection of the null of convergence, while $\hat{t}$ denotes the estimated one-tailed t-test statistic. The critical value at a 5% significance level is $t_c = -1.65$. The coefficient $\hat{\alpha}$ indicates the speed of convergence. The sample—in all series—spans 1965 to 2016 (T = 52).
Club 1: Oil, gas and coal.
Club 2: Nuclear and hydro.
The trimming rate $r = 0.3$ is the rate recommended by Phillips and Sul (2007). The other trimming rates are reported for a robustness check.

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