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RESEARCH ARTICLE

Revisiting energy intensity convergence: new evidence from OECD countries

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Abstract
In this study, we examine the energy intensity convergence in OECD countries within the context of recent developments in unit root analysis by paying attention to modeling structural shifts. We collect the total primary energy consumption/GDP data of 27 OECD countries during the period 1980–2014. The findings indicate that controlling for shifts plays a crucial role, and different approximations in modeling breaks lead to changes in inferences. In conclusion, we present some policy proposals.

Keywords Energy intensity · Convergence · Structural breaks · Unit root tests

Introduction

It is well accepted that energy is one of the basic factors of production for a modern economy as it is essential for all economic activities. In the last decades, energy demand has grown rapidly depending on increases in economic activities and industrialization. With regard to the British Petroleum (British Petroleum 2017) and World Bank (2017) data, world primary energy consumption increased by 19% over the period 2005–2014 while the share of fossil energy sources, such as oil, coal, and natural gas; in total, primary energy consumption was 80.8% in 2014. The world therefore leans on fossil energy sources as most of energy is generated using fossil sources. This great increase in energy consumption and the high share of fossil energy sources in energy consumption lead to three main concerns all over the world, namely, sustainability of energy sources, energy security, and environmental problems, such as air pollution, global warming, and climate change.

One can claim that these concerns presented above are caused by the increase in the use of fossil energy sources. At this point, it can be argued that there are two options to decrease the usage of fossil energy sources. One of them is increasing the usage of renewable energy sources in the economic activities. The utilization of more clean energy is crucial in terms of sustainability of energy sources, but more importantly, it is indispensable for environmental problems. The second option is to use energy more efficiently. The usage of energy more efficiently means producing the same amount of output by using less energy or producing more output by employing the same amount of energy. If energy is used more efficiently, economies do not have to sacrifice economic growth and can also reduce environmental problems stemming from fossil energy sources (Liddle 2010). From another point of view, more efficient energy usage means an increase in energy productivity and a decrease in energy intensity, because, energy intensity is calculated as units of energy consumption per unit of GDP.

Over the last two decades, the issue of energy intensity has become one of the most considerable debates among energy economics researchers. Especially in recent years,

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there has been a decrease in energy intensity in both developed and developing countries (Herrerias 2012). The economic structure (the share of energy-intensive industries in total GDP), the sectoral composition of energy use (relative shares of industry, buildings, and transport), the mix of fuel, and efficiency in the conversion and end-use of energy are considered to be the main factors that cause energy intensity to fall (Liddle 2010). Then, a question becomes meaningful: do differences in energy intensity across countries decline over time? In other words, do energy intensities of economies converge to each other over time? The findings on this topic may provide some crucial implications for both policy makers and researchers. Because, if convergence does not dominate for countries with higher levels of energy intensity, credibility of national governments and their international commitments in terms of climate change may weaken, and hence, national governments may have to prioritize energy-saving measures (Markandya et al. 2006; Le Pen and Sevi 2010; Herrerias 2012). Since energy is one of the most considerable factors of production for a modern economy, economic growth can be damaged in these countries.

Although the concept of convergence has mainly discussed in economic growth literature since primarily with Barro and Sala-i Martin (1991, 1992, 1995), some recent studies have also started to pay attention to this issue in energy economics and have tested energy intensity convergence. Table 1 presents the studies examining energy intensity convergence in the energy economics literature. As can be seen from the table, the previous empirical works on energy intensity convergence do not exhibit a clear-cut evidence. These studies can be distinguished into three parts according to their methodological approaches. First group of the studies have examined energy intensity convergence within the scope of β-convergence and/or σ-convergence by cross-section or panel data techniques. The former tests whether the dispersion of levels of energy intensity reduces through time. The latter that is more commonly used tests whether there exists a negative influence of initial energy intensity rates on energy intensity growth. Most of these works have examined this issue by utilizing the β-convergence approach. However, the cross-sectional (or panel) regression model test of β-convergence has been criticized particularly because of several drawbacks. For example, Bernard and Durlauf (1995) argue that it can only test the hypothesis that whether all countries in the sample are converging or not. Quah (1993) shows that inferences from cross-sectional analyses are misleading because such a formulation is inappropriate for analyzing dynamic behavior of the data. Moreover, Evans (1996) demonstrates that cross-country regressions have highly implausible assumptions which can never be satisfied by the real data.[1]

Therefore, more recent studies proposed alternative methodological concepts for testing whether energy intensity converges or diverges among countries and constituted the second group. They have extended the cross-sectional testing approach by considering (i) nonparametric techniques (Ezcurra 2007), (ii) distribution dynamics (Herrerias 2012), and (iii) nonlinear time-varying factor modeling (Apergis and Christou 2016).

Third group of the studies analyzed energy intensity convergence using stochastic convergence technique in a time series context. In this approach, unit root tests are typically used to answer the question of whether the difference between two series such as energy consumption/GDP ($\mathrm{EI}_{i,t}$) for one country and the sample average $\left(\overline{\mathrm{EI}_t}\right)$ possess a unit root. If the result of unit root testing procedure of $y_t = \ln\left(\mathrm{EI}_{i,t}/\overline{\mathrm{EI}_t}\right)$ shows that log difference in two series has a stationary process, this would be regarded as an evidence for convergence (see Carlino and Mills 1993; Bernard and Durlauf 1995). Up to date, to our knowledge, there is only one study (Le Pen and Sevi 2010) which examines energy intensity convergence through the stochastic convergence approach. Le Pen and Sevi (2010) use the pair-wise convergence approach of Pesaran (2007) and some panel unit root tests for a group of 97 countries. They also test the convergence hypothesis by taking into account one structural break in the unit root testing procedure of Zivot and Andrews (1992, hereafter Z&A) but find marginal contribution to the results.

Our study goes one step further and analyses the stochastic convergence in energy intensity by utilizing time series unit root testing approaches which provide more implications for policy makers. We employ the stochastic convergence approach proposed by Carlino and Mills (1993) in the economic growth literature to analyze the energy intensity convergence in 27 OECD countries over the period 1980–2014. The econometric methodology reveals that considering the structural shifts in the analyses significantly affects the results (Perron 1989). Moreover, recent empirical works indicate that modeling structural breaks in different forms may also lead to change in the findings (Zivot and Andrews 1992 (Z&A); Narayan and Popp 2010 (N&P) and Enders and Lee 2012 (E&L)). Accordingly, the purpose

[1] The inferences of standard methods are valid under these conditions: the economies must have identical first-order autoregressive dynamic structures and all explanatory variables control for all permanent cross-country differences.

Table 1 Literature summary

Author(s)	Sample	Method	Findings
Markandya et al. (2006)	12 transition of Eastern Europe countries	β-convergence	Convergence
Ezcurra (2007)	98 countries	Nonparametric approach	Convergence
Le Pen and Sevi (2010)	97 countries	Stochastic convergence	Mixed findings
Liddle (2010)	111 countries 134 countries	β-, σ- and γ-convergence	Convergence
Herrerias (2012)	83 countries	Weighted distribution dynamics approach	Convergence
Mulder & Groot (2012)	18 OECD countries and 50 sectors	β-convergence	Convergence after 1995
Adhikari & Chen (2014)	35 countries	β and σ-convergence	Mixed findings
Apergis and Christou (2016)	31 countries	Nonlinear time-varying factor models	Mixed findings
Burnett and Madariaga (2017)	USA	Panel GMM	Convergence
Karimu et al. (2017)	14 Swedish industry sectors	β-convergence	Convergence

of this study is to present a comprehensive viewpoint to energy intensity convergence by providing different modeling of structural shifts for the OECD countries data. We first start with the standard unit root test of Dickey and Fuller (1981, hereafter ADF) which does not control for structural breaks in the data. Then, in order to take structural breaks into account, we employ three different unit root tests which use different approximations to model structural breaks. While the unit root tests produced by Z&A and N&P consider sharp breaks, the unit root test propounded by E&L deals with gradual breaks. Advantages of unit root tests with sharp breaks against unit root tests without breaks have long been discussed in econometrics literature. As a considerable contribution to the energy economics literature, this paper also employs E&L unit root test with gradual breaks to test convergence. Superiority of this test against traditional unit root tests with sharp breaks is discussed in the Methodology section. This paper therefore tries to present new findings about energy intensity convergence in OECD countries.

The rest of the paper is organized as follows: Data and methodology section introduces data and methodology. Findings are reported in Findings section. Discussion and conclusion section concludes the paper with a summary of main findings and some implications.

Data and methodology

As was denoted above, to yield energy intensity data, total primary energy consumption (Quad Btu) is divided by GDP at market prices (constant 2010 trillion USD). While energy consumption data are obtained from US Energy Information Administration (EIA 2017), GDP data are extracted from World Bank (2017). The data set belongs to 27 OECD countries (Australia, Austria, Belgium, Canada, Chile, Denmark, Finland, France, Greece, Iceland, Ireland, Israel, Italy, Japan, South Korea, Luxembourg Mexico, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the UK, and the USA) for the period 1980–2014.

Stochastic convergence models have become a standard tool in analyzing whether different time series of any variable are converging to the benchmark or average. In a unit root framework, to test convergence to average, this paper follows Carlino and Mills (1993) methodology and defines stochastic convergence as the stationarity of the log difference in the two series. To test the null hypothesis of unit root against the alternative hypothesis of stationarity, we first start with the ADF test and estimate the following model:

$$\Delta y_t = Z_t^{'}\delta + \alpha y_{t-1}\sum_{j=1}^{p}\beta_j \Delta y_{t-j} + \varepsilon_t \tag{1}$$

where y_t denotes the natural logarithm of relative energy intensity for country i to the average energy intensity of the OECD countries at time t, $\left(y_t = 1n\left(EI_{i,t}/\overline{EI}_t\right)\right)$, the deterministic term Z_t is described by [1, t], Δ stands for the difference operator, and ε_t is the i.i.d error term.

The standard ADF test assumes there is no structural break in the data. However, economic time series probably include breaks due to some events, such as political reforms, wars, etc., and ignoring the presence of such breaks leads to a bias that reduces the power of the unit root test (Perron, 1989). In order to overcome this problem, Z&A propose one-break ADF test which allows a break in the ADF test by defining Z_t as $[1, t, DU_{1t}, DT_{1t}]$ where $DU_{it} = 0$ for $t < T_B$ and 1 otherwise, $DT_{1t} = 0$ for $t < T_B$ and $t - T_B$ otherwise, and T_B denotes the break date. For testing unit root in the presence of two breaks, N&P extend the Z&A approach by redefining the deterministic term Z_t as $[1, t, DU_{1t}, DU_{2t}, DT_{1t}, DT_{2t}]$ where $DU_{it} = 0$ for $t < T_{Bi}$ and 1otherwise, $DT_{it} = 0$ for $t < T_{Bi}$and $t - T_{Bi}$ otherwise, and T_{Bi} $(i = 1, 2)$ shows the break dates.

More recently, E&L take a different approach and modify the standard ADF test by using a Fourier function in the deterministic term. The traditional unit root tests can capture the instantaneous changes in the data by using dummy variables. However, it is quite difficult to know the actual number and the date of the breaks in the macroeconomic variables. Moreover, the breakpoints may behave in the gradual form rather than abrupt structural breaks. Fourier type unit root tests do not need predetermination of the number, location, and the functional form of the structural breaks. Thus, in the presence of multiple smooth breaks, E&L approach seems to be more appropriate than other testing frameworks. The Fourier expansion for Z_t is described as$1, t, \sin\left(\frac{2\pi kt}{T}\right), \cos\left(\frac{2\pi kt}{T}\right)$ where k represents an integer frequency.

Findings

Table 2 depicts the results of stochastic convergence. Since the null hypothesis of a unit root indicates divergence, the rejection of the null hypothesis of a unit root means convergence.

As is seen, the null hypothesis of a unit root can be rejected for Australia, Ireland, Norway, and Portugal with regard to the no shift ADF test. Put differently, findings of

Table 2 Results of stochastic convergence

Country	No shift	One sharp shift		Two sharp shift			Gradual shift
	ADF	Z&A	TB	N&P	TB1	TB2	E&L
Australia	−4.00**	−6.10***	2003	−7.21***	2003	2006	−3.78*
Austria	−2.81	−4.27	1999	−5.65**	1990	2006	−4.57**
Belgium	−0.39	−5.95***	2007	−8.17***	1994	2007	−6.39***
Canada	−1.15	−3.16	2006	−6.90***	1996	2006	−5.22***
Chile	−2.55	−3.56	1997	−6.35***	1994	2005	−3.91
Denmark	−3.12	−4.84*	1997	−6.66***	1987	1996	−3.03
Finland	−2.09	−4.33	1989	−5.47**	1989	2007	−3.06
France	−2.40	−4.10	2007	−6.39***	1986	2007	−4.03
Greece	−1.62	−3.28	1990	−4.22	1992	1996	−4.54**
Iceland	−2.35	−4.80	2006	−6.11***	1996	2006	−3.30
Ireland	−4.61***	−6.40***	2001	−5.88**	1993	2002	−4.73***
Israel	−2.76	−5.13**	2001	−6.24***	1989	2006	−3.11
Italy	−1.59	−2.87	2001	−5.85**	1992	2002	−3.15
Japan	−2.42	−3.57	2007	−7.04***	1991	2006	−4.90**
South Korea	−2.48	−4.99*	1999	−5.12*	1998	2006	−2.19
Luxembourg	−2.92	−4.20	2001	−7.13***	1988	2002	−4.11**
Mexico	−2.97	−7.04***	1988	−8.50***	1988	2007	−4.19**
Netherlands	−1.99	−3.59	1995	−4.97*	1990	1996	−2.73
New Zealand	−2.72	−3.41	1986	−5.71**	1988	2003	−3.41
Norway	−3.43*	−5.18**	1994	−6.30***	1990	1994	−4.41**
Portugal	−3.43*	−8.34***	1991	−10.17***	1990	2006	−2.28
Spain	−2.57	−3.23	2011	−7.01***	1991	2006	−5.06***
Sweden	−2.75	−4.12	1997	−6.52***	1996	2006	−4.67**
Switzerland	−2.90	−4.97*	1997	−7.45***	1987	1997	−3.84*
Turkey	−1.98	−4.12	1999	−5.12*	1988	2000	−3.28
UK	−2.82	−5.16**	1989	−5.81**	1986	1989	−4.68**
USA	−1.11	−3.18	2008	−5.77**	1989	2001	−2.33

***, **, and * indicate 1, 5, and 10% statistical significance, respectively. *TB* stands for break dates

ADF test indicate that energy intensities of these countries converge to the sample average. To take structural breaks into account, the paper first considers Z&A and N&P unit root tests that control breaks as a sharp process. The findings of Z&A unit root test with one sharp break indicate that the null hypothesis can be rejected for 11 countries, namely, Australia, Belgium, Denmark, Ireland, Israel, South Korea, Mexico, Norway, Portugal, Switzerland, and the UK. That is to say, energy intensities of these countries converge to the average. Besides, the outcome of N&P test with two sharp breaks signifies that only energy intensity of Greece does not converge to average since the null hypothesis of a unit root cannot be rejected for this country. In other words, N&P unit root test displays very strong evidence in favor of convergence. Finally, the findings of E&L test present evidence in favor of convergence for 14 countries in the sample, namely, Australia, Austria, Belgium, Canada, Greece, Ireland, Japan, Luxembourg, Mexico, Norway, Spain, Sweden, Switzerland, and the UK. Based on the findings of stochastic convergence, one can claim that energy intensities of Australia, Ireland, and Norway converge to average with regard to all four unit root tests.

Discussion and conclusion

This paper examines whether energy intensity converges among 27 OECD countries over the period 1980–2014. To test whether energy intensities of the countries converge to the sample average, four different unit root tests are employed. The paper first utilizes conventional ADF test which does not consider structural breaks and second performs Z&A and N&P unit root tests with structural breaks based on dummy variables. Finally, the paper exploits E&L unit root test with a gradual process based on a Fourier approximation. The findings can be summarized as below:

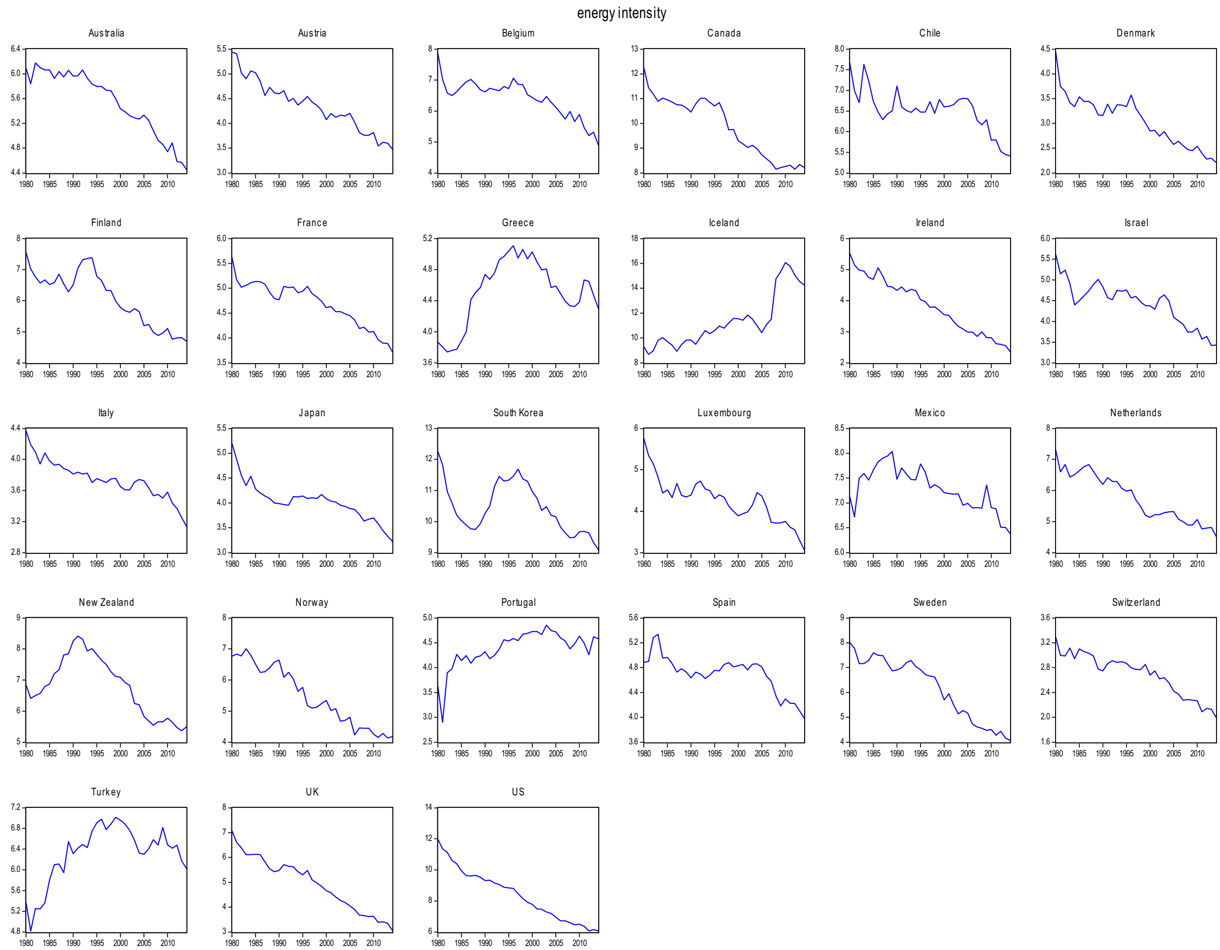
(i) ADF test implies that energy intensities of 4 countries converge to the average.
(ii) There seems to be energy intensity convergence for 11 countries with regard to Z&A test.
(iii) The findings obtained from N&P test reveal that only energy intensity of Greece does not converge to the average.
(iv) The findings of E&L test present evidence in favor of convergence for 14 countries.
(v) Based on the findings from (i) to (iv), the paper yields that considering structural breaks and modeling breaks with different approximations leads to different findings while testing stochastic convergence.

Considering Appendix that depicts energy intensity levels of the countries in the sample, the country-specific results of the E&L modeling approach, which is considered as more realistic for the economic data sets, provide some patterns for the general discussion of energy intensity convergence. First, the findings demonstrate that none of the countries with high energy intensities (such as Iceland, South Korea, the USA, Mexico, and Chile) does not converge to the OECD average, except Canada. Second, all countries with moderate energy intensity (Netherlands, Australia, Norway, the UK, and Spain) show evidence on the convergence. Third, two of the three countries with the lowest energy intensity, namely, Italy and Denmark, do not provide any evidence on convergence.

Under these findings and observations, this paper presents some policy proposals about energy usage since rapid increases in energy demand lead to some considerable concerns, namely, sustainability of energy sources, energy security, and environmental problems, as was denoted in the first section. Accordingly, some policy recommendations may be listed as follows: First, countries with high energy intensity should make some plans to preserve their credibility in international environmental agreements. For example, policy makers in these countries should set up some incentive mechanisms which can induce producers to be more innovative and guide them to develop and use more modern and eco-friendly technologies (see, e.g., Madlener and Sunak 2011; Elliott et al. 2014; Bilgili et al. 2017a). In this context, green building codes such as Leadership in Energy & Enviromental Design certificates may be useful to decrease energy intensity in buildings. Second, a great deal of works in the energy economics literature suggests proposals for increasing the relative use of renewable energy since renewable energy sources are more clean compared to fossil energy sources (see Zoundi 2017 for the empirical literature). Policy makers in these countries can therefore implement (i) demand side management strategies for renewables (EIA 2014; Bergaenztle et al. 2014; Ardakani and Ardehali 2014), (ii) some subsidies/incentives for renewables (Fischer and Newell 2008; Galinato and Yoder 2010), (iii) some subsidies/incentives to substitute oil-based fuels with biomass sources (Bilgili et al. 2017b), (iv) policies for easy access to electricity that is generated from renewable sources (Reiche and Bechberger 2004), and (v) some tax incentives for renewables as carried out by Energy Policy Act in the US (EIA 2005). Taking into account all these, it can be clearly foreseen that environmental problems will increase even further if countries with high energy intensity do not implement the above measures.

Appendix

Energy intensity levels of the countries in the sample



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