OECD Energy Intensity: Measures, Trends, and Convergence

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ABSTRACT

This paper focuses on several different measures of OECD countries' energy intensity levels, plots their trends, applies a number of techniques to determine whether those intensities are converging, explores the importance of that convergence, and estimates the future steady-state or long-run distribution of energy intensity for the OECD. The paper finds that OECD energy intensity typically is declining, and a number of parametric and nonparametric methods indicate a strong degree of convergence. However, convergence is conditioned on country specific factors since differences in individual energy-GDP ratios persist. These findings suggest limits to the general decline in developed country energy intensity.

Keywords: energy intensity; convergence; intra-distribution dynamics; energy quality index; OECD countries.

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1. Introduction and literature review

Energy intensity is an important subject for energy studies. Assumptions about energy intensity and how it changes often form the backbone of projections of energy use and carbon dioxide emissions. Also, improvements (either lowering energy intensity or increasing energy efficiency) are the main “no regret” strategies to lower anthropogenic carbon emissions and thus combat climate change. A number of factors influence a country’s aggregate level of energy intensity: (1) economic structure (the share of energy-intensive industries in total economic output); (2) sectoral composition of energy use (i.e., the relative shares of different end-uses like industry, buildings, and transport); (3) fuel mix; and (4) efficiency in the conversion and end-use of energy.

This paper (i) considers three different measures of energy consumption and two different measures of GDP to examine OECD countries’ energy intensity levels (i.e., the ratio of energy consumption to economic output) and intensity trends, (ii) applies several measures (primarily developed in the economic growth literature) to determine whether those intensities are converging (i.e., whether cross-country differences are declining), (iii) briefly explores the broader significance of any convergence that is determined, and (iii) estimates the future steady-state or long-run distribution of energy intensity for the OECD. The paper finds that energy intensity typically is declining in the OECD. Also, a number of parametric and nonparametric methods indicate a strong degree of convergence in energy-GDP ratios for OECD countries. However, convergence is conditioned on country specific factors since differences in individual energy-GDP ratios exist and are predicted to persist even if convergence continues. These findings suggest limits to the general decline in developed country energy intensity.

Among the first to examine convergence in energy intensity were Mielnik and Goldemberg (2000); they visually inspected the intensity paths of 41 countries over 1971 to

1992, and showed that their 18 developed countries were on a decreasing trajectory, whereas their 23 developing countries were following an increasing trajectory. Sun (2002) demonstrated that the mean deviation of energy intensity for OECD countries has declined over 1971-1998, but did not otherwise examine convergence.

More recent work finding convergence in energy intensity has employed advanced (both parametric and nonparametric) techniques borrowed from the economic growth convergence literature. Ezcurra (2007) investigated energy intensity convergence of 98 countries over 1971-2001 using nonparametric methods, and found limited convergence that appeared to have slowed/stopped since the 1980s. Liddle (2010) updated that study, and uncovered continued convergence; however, further investigation of geographical differences revealed that, while the OECD and Eurasian countries have shown considerable, continued convergence, Latin American and Caribbean, Middle East and North African, and Sub-Saharan African countries have exhibited no convergence to divergence in energy intensity. In an even narrower geographic focus, Markandaya et al. (2006) estimated an economic growth-type convergence equation, and found that from 1992 to 2002 the energy intensity of several transition countries of Eastern Europe converged toward the levels of the European Union (EU) average. Meanwhile, Le Pen and Sevi (2010) tested for so-called stochastic convergence in a group of 97 countries by applying a pair-wise method, and rejected global convergence, but found some evidence of regional-based convergence (in the Middle East and OECD).

A few studies have examined energy intensity sectorally. Miketa and Mulder (2005) analyzed energy-productivity convergence (the inverse of energy intensity) across 56 developed and developing countries in 10 manufacturing sectors, and found that cross-country differences tended to decline—particularly in less energy-intensive sectors. Liddle (2009) looked at electricity intensity in OECD countries at various levels of sectoral aggregation, and discovered that commercial electricity intensity is converging toward a bell-shaped distribution while industry electricity intensity is converging toward a bimodal one. Mulder and De Groot (2007), also considering the OECD, but with a greater degree of sectoral disaggregation, found that, for most of the 14 economic sectors they considered (primarily at the two-digit ISIC level), lagging countries tended to catch up with technological leaders in energy productivity. Table 1 summarizes those previous studies.

Table 1

2. Measures of energy intensity

A common measure of energy intensity is drawn from the International Energy Agency's (IEA) total primary energy supply (TPES) divided by GDP, which is in units of tons of oil equivalent (toe) per thousand year-2000 purchasing price parity (PPP) US dollars (USD), converted to natural logs (e.g., used by Mielnik and Goldemberg 2000; and Liddle 2010). TPES accounts for all the energy consumed within a country (including energy imports and excluding exports); in addition, it adjusts for the energy consumed in producing electricity, and as such, is different from delivered energy (also called net energy or total final consumption). Thus, TPES measures the total amount of energy used by a country in that country's economic activity (as well as being the measure the IEA collects). Converting GDP using PPP, rather than using foreign exchange rates, does have important implications for developing country data, but is less important for cross-country analyses of OECD countries. Yet, since a meaningful amount of energy use can be considered final goods consumption (e.g., that used for personal transport or in the home), it is appropriate to adjust GDP for purchasing power or levels of consumption.

Figure 1-a-c shows the energy intensity of OECD countries calculated by both TPES per GDP converted with exchange rates 1-(a) and TPES per GDP converted with PPP 1-(b) at 2010 and 1980. The form of GDP used does change the level of energy intensity (smaller

with PPP) and the rankings of countries. The latter change occurs in a mostly predictable way—countries with lower prices/wages (e.g., Czech Republic, Hungary, Poland, Turkey) have larger GDPs when adjusted for PPP, and thus, have lower relative intensities. However, the percentage change in intensity over that period (Figure 1-c) does not change. Also robust to the calculation of GDP is the finding that the dispersion (i.e., standard deviation divided by the average) of energy intensity among OECD countries has declined; however, the extent of this decline is tempered when GDP is based on exchange rates (a 32% decline vs. a 42% fall with PPP).

Figures 1-a-c

Total final consumption (TFC), which is an aggregate of end-use energy (i.e., that consumed in the transport, industry, and building sectors), was analyzed by Le Pen and Sevi (2010) as well as by researchers performing sectoral-level studies (e.g., Mulder and De Groot 2007; Liddle 2009). Because of the energy losses incurred in generating electricity and the increased use of electricity as a final energy supply, TFC is less than TPES (i.e., energy intensity will be lower), but TFC plots roughly parallel to TPES. Indeed, the ratio of TFC to TPES has been declining in OECD countries (to an average of 0.72); but that decline reflects the growing importance of electricity in final energy consumption rather than growing inefficiency in generating electricity.

Indeed, from 1974 to 2007 the average IEA efficiency of fossil fuel electricity plants increased from 35% to 40%. However, by far the greatest improvement in electricity and heat production has occurred in plants fired by natural gas—in part because of the introduction of combined-cycle gas turbines (CCGT), which can have efficiencies of 60%. Thus, the countries that have enjoyed the greatest improvements in conversion efficiency are the ones that have moved toward CCGT technology.

This importance of electricity (as well as other fuel choices like natural gas and oil over coal and biomass or fuel wood) leads to a third measure of energy consumption—one based on quality weighted final energy use. Some forms of energy can produce more work than others: a unit of electricity is of higher quality than a unit oil, which itself is of higher quality than a unit of coal. Also, arguably reflecting these differences in productivity, electricity tends to be the most expensive energy source, followed by oil, and coal tends to be among the least expensive sources. Berndt (1978) describes this situation as: "the different prices of energy forms per Btu illustrate the fact that end-users of energy are concerned not only with the Btu heat content of the various energy types, but also with other attributes." Or according to Stern (1993), "quality weighted final energy use … is likely to be a superior measure of the energy input to economic activity as it will reflect better the productivity of the uses to which energy is put."

Berndt (1978) proposed a Divisia index in which the consumption of the individual fuel types is weighted by their expenditure shares, i.e., the differences in prices reflect the differences in energy quality or productivity. Stern (1993) used this approach in his analysis of energy and economic growth in the US, but to my knowledge quality weighted energy has not been considered in examining energy intensity convergence. Borrowing from Berndt (1978) and Stern (1993), I use the following formula to calculate quality weighted final energy use, Eq_t:

$$\ln Eq_t - \ln Eq_{t-1} = \sum_{i=1}^{n}\left(\left(\frac{P_{it}E_{it}}{2\sum_{i=1}^{n}P_{it}E_{it}} + \frac{P_{it-1}E_{it-1}}{2\sum_{i=1}^{n}P_{it-1}E_{it-1}}\right)x(\ln E_{it} - \ln E_{it-1})\right) \qquad (1)$$

Where P are the prices of the fuels i, and E are the quantities consumed (in koe) for each fuel in final energy use. The (n = 5) fuel types are electricity, oil, natural gas, coal, and combustible renewables and waste. Like Stern (1993), I assume the price of combustible renewables and waste is equal to 60% of the coal price. It is important to note that the weighted index relies on local (but real) prices; thus, energy price differences across countries (because of, for example, taxes) are less important.[1]

3. Energy intensity trends

As an illustration of the relative paths of the three energy consumption measures, Figure 2 displays the energy intensity traces for the OECD as a whole (employing each of the three consumption measures). Because IEA price data is not available until 1978, the energy quality index measure runs from 1978-2007 (the other two measures span 1971-2007). The three measures of energy intensity all decline over the study period and are roughly parallel to one another. Again, because of the growing importance of electricity consumption in the OECD, and because electricity generation incurs energy losses, electricity is typically more expensive than other energy forms, and TFC provides the least intense measure (or the most negative since logs are taken), followed by energy quality and then TPES.

Figure 2

For each of the 23 OECD countries for which all three measures of energy consumption could be calculated (i.e., the price data was available to construct the energy quality index), the energy intensity plots are highly similar, mostly parallel to one another, and primarily declining throughout the study period (individual country traces are shown in an appendix). Thus, because of that similarity, the finding of convergence does not hinge on any particular measure of energy consumption/intensity.

In considering those individual country plots, they appear mostly similar; however, there are a few differences. For example, for Czech Republic, Poland, and Turkey, beginning around 1991, the energy quality index and TFC diverge—energy intensity based on energy quality becomes much flatter—in part, because of a large (relative and absolute) price

[1] As mentioned by an anonymous reviewer, energy/electricity prices reflect prevailing technologies and regulatory practices; however, the price weighting is preferred because (i) there is no other obvious differential weighting of energy quality and (ii) for each country, over time, the price weighting consistently produces the desired quality ranking, i.e., electricity greater than oil, which is greater than natural gas, which is greater than coal.

increase of electricity in those countries. However, fully understanding the different patterns within countries or among countries would require substantially more detailed data (which would not be available for some countries) and is beyond the scope of the present, macro-level analysis.

4. Measures of convergence

The paper examines IEA data from 28 OECD countries over the period 1960 to 2006.[2] A first measure of convergence, called beta-convergence, seeks to determine whether a catch-up process is taking place. That is, do countries with lower initial levels of a specific country factor (or higher in the case of energy-GDP ratios) exhibit the fastest rates of change. Beta-convergence is tested by regressing average growth rates on the initial level. A negative and statistically significant coefficient is interpreted as evidence of beta-convergence.

A next measure of convergence, called sigma-convergence, focuses on the change in the spread of the distribution. Beta-convergence is a necessary, but not sufficient, condition for sigma-convergence. Sigma-convergence is considered important since past poor performers could catch and overtake once strong performers to an extent that the spread of the distribution increases. Furthermore, sigma-convergence measures how effective a catch-up process is at bringing countries closer together—past poor performers could be gaining on the leaders, but at a very slow rate.

Two measures of sigma-convergence are evaluated. First, to determine whether the shape of the distribution has changed over time, I look at kernel density estimates of the distribution—a smoothed version of a histogram. I use the Epanechnikov kernel (although the results are not appreciably different if a Gaussian kernel is used) and, as is typical in the convergence literature, the data-based bandwidth estimation from Silverman (1986).[3] It is important to look at the shape of the distribution since a sigma-converging distribution could

[2] The energy data begins in 1971 for Czech Republic, Korea, Mexico, and Slovak Republic and in 1965 for Hungary.

[3] However, the results are not materially dependent on the bandwidth selection.

have a single mode or could be multi-modal—what the growth literature calls "convergence clubs." Second, I track the inter-temporal change (i.e., data normalized to the initial year) in the coefficient of variation (CV—i.e., the standard deviation divided by the average) of the cross country energy intensity distribution. If this measure is falling over time, then that result is interpreted as evidence of convergence.

The last measure of convergence focuses on the intra-distribution mobility (sometimes called gamma-convergence); that measure is of interest since true convergence—i.e., that countries tend toward each other—would preclude continuous crisscrossing, where countries move from the upper to the lower bounds of the distribution and back again. To examine the intra-distribution mobility, i.e., whether the individual countries with the highest energy intensity and those with the lowest energy intensity remain the same, I use an index of rank concordance that ranges from zero to unity. The closer the index value is to zero the greater the extent of mobility within the distribution. This index, from Boyle and McCarthy (1997) and used in Liddle (2010), is calculated as:

$$\gamma = \frac{Variance\left(AR(I)_{it} + AR(I)_{i0}\right)}{Variance\left(2 * AR(I)_{i0}\right)} \qquad (2)$$

where $AR(I)_{it}$ is the actual rank of country i's energy intensity in year t; and $AR(I)_{i0}$ is the actual rank of country i's energy intensity in the initial year 0. Some studies in the literature have used stochastic kernels to generate contour plots of the distribution to analyze intra-distribution mobility (e.g., Ezcurra 2007). But these resulting three-dimensional figures can be difficult to interpret. The gamma-convergence index used here has the advantage of being a single number traced over time in two dimensions, analogous to the CV sigma-convergence measure. Table 2 summarizes the convergence measures considered here.

Table 2

An additional measure of convergence not evaluated here is stochastic convergence—whether or not shocks to the level of a variable relative to the sample average of that variable are temporary. Stochastic convergence is usually examined via panel unit root tests. This measure of convergence has rarely been analyzed in regards to energy intensity (Le Pen and Sevi 2010 is the only such study of which I am aware).[4]

4.1 Absolute vs. conditioned convergence

A lack of gamma-convergence coupled with a substantial sigma-convergence could be interpreted as indicating that country differences in energy intensity remain, but that those differences have reduced considerably. That above phenomena (substantial sigma-convergence but little gamma-convergence) are described in the economic growth convergence literature as conditional convergence, i.e., energy intensity converges to country-specific steady states that are conditioned on country-specific characteristics.

The methods described in the previous sub-section are used to determine *absolute* convergence. *Conditional* convergence, on the other hand, seeks to determine whether convergence exists after controlling (or conditioning) for certain country-specific characteristics. The type of conditional convergence that can be directly observed is beta-convergence, which is analyzed via multi-variate regression (e.g., Markandaya et al. 2006; Mulder and De Groot 2007). Yet, beta-convergence (or catch-up rates) is among the least interesting forms and is only a necessary but not sufficient condition for sigma-convergence. Thus, later in this paper, we compare the trends and convergence of some factors—i.e., possible drivers of energy intensity convergence—to ascertain whether such factors could be influencing OECD energy intensity convergence.

5. Results and discussion

Table 3 shows the results of two beta-convergence regressions: the top panel considers the 23 countries for which 1960 is the initial level observation and their growth over 1960-2006; the bottom panel takes 1971 as the first observation and includes all 28

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[4] There are, however, a number of stochastic convergence studies concerned with per capita carbon emissions, many of which have appeared in the journal *Environmental and Resource Economics*.

countries and their growth rates over 1971-2006. Beta-convergence is evidenced in both regressions since each beta coefficient is both negative and statistically significant. Thus, the countries with the highest energy intensity tended to reduce that intensity at the highest rates, and countries with the lowest energy intensity tended to have lower rates of change.

Table 3

Figure 3 displays the estimated kernel density functions of relative energy intensity (TPES per GDP PPP) for 1971 (the first year with data for all 28 countries) and for 2006. For Figure 3, each country's energy-GDP ratio has been normalized by the OECD average for 1971 and 2006 (i.e., relative energy/GDP). These curves reveal distributions that are becoming more compressed over time since the 2006 density function is considerably narrower and more peaked than the 1971 density function. Indeed, by 2006 all but three countries have an energy-GDP ratio within 20% of the OECD average, and all countries are nearly within 25% of that average—the high and low for 2006 are 1.256 (Ireland) and 0.733 (Canada), respectively. The estimated kernel density functions for energy intensity calculated from TFC and the energy quality index have also narrowed and are effectively bell-shaped (single modal), too.

Figure 3

Figure 4 shows the traces of each of two (sigma and gamma) convergence measures for the 23 countries sample over 1960-2006.[5] The figure indicates substantial, continued sigma-convergence—or narrowing of the energy intensity distribution—as the CV of the sample has dropped to 35% of its initial value. Similarly, when energy intensity is calculated from TFC or the energy quality index, the CV dropped to 44% and 55% (respectively) of its 1978 value.

[5] The two traces are essentially the same if the shorter, 1971-2006, 28 country sample is used.

Figure 4

Indeed, the dual findings of sigma-convergence and a continued, approximately linear decline of dispersion of energy intensity does not depend on various potential measures of energy intensity. From about the early 1990s onward, all six CV-based traces (i.e., constructed from the three numerators of TPES, TFC, and quality weighted energy consumption and the two denominators of GDP at foreign exchange rates and GDP at PPP) move more or less parallel to one another. Figure 5 displays those traces over 1980-2007 for a sample of 23 OECD countries.[6] Again, the ultimate decline (in dispersion) is greater when GDP is adjusted for PPP (than when it is adjusted at foreign exchange rates only)—perhaps not surprising since the PPP adjustment is motivated by the desire to improve cross-country comparisons (i.e., increase similarities). Also, the decline (in the CV) is less when the energy quality weighted measure is used (there are little differences between the TPES and TFC traces), probably reflecting the importance of slow moving, country specific factors (like technology and natural resource endowment) that help to determine individual countries' energy fuel mix (e.g., electricity vs. coal).

Figure 5

Figure 4 also displays relatively little intra-distribution mobility (i.e., gamma-convergence), however, since the only slightly lower y-axis values reveal little change from the 1960 rankings of energy intensity. Indeed, comparing the groupings of countries in quartiles over the study period reveals that most country movement is between adjacent quartiles (results not shown). From 1971 to the present only four countries were big movers, i.e., moved two quartiles or more. Both Ireland and the United Kingdom began in the second most energy intensive quartile and ended in the least energy intensive one; whereas, Korea

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[6] The sample contains fewer countries because of the limited availability of the price data needed to construct the energy quality measure.

moved from the second least energy intensive quartile to the most energy intensive one, and Mexico moved from the least energy intensive quartile to the second most intensive one.[7] There is even somewhat less intra-distribution mobility when energy intensity is calculated from TFC and effectively no such movement when energy intensity is calculated from the energy quality index.

The lack of gamma-convergence coupled with the substantial sigma-convergence, revealed above, indicates that country differences in energy intensity remain, but that those differences have reduced considerably (i.e., the existence of conditional convergence). Energy intensity differences among countries are likely to be determined by a number of slow moving factors: the extent to which mobility depends on cars, the size of natural endowments like coal and hydroelectric potential, the technical and political capacity/interest in nuclear energy, and the presence and influence of particularly energy intensive industry sectors like smelting.

5.1 Significance/importance of convergence

The continued, substantial, and single-modal convergence in energy intensity among OECD countries is interesting for several reasons. Continuing energy intensity convergence is not a world-wide phenomenon: some regions exhibit little to no convergence (Ezcurra 2007; Liddle 2010; Le Pen and Sevi 2010). Furthermore, despite the strong evidence of considerable sigma-convergence, country differences remain important among OECD countries. That country differences remain important could be interpreted as evidence of limits in both convergence and the general decline in energy intensities that nearly all OECD countries have experienced.

[7] The CV index was recalculated without various combinations of these big movers, and the finding of sigma-convergence among OECD countries was not dependent on the inclusion/exclusion of any one or two countries (results not shown).

Also, both the finding of energy intensity convergence among certain countries and the finding of lack of convergence among/between other countries are not simply a matter of international trade or economic specialization. Liddle (2010) found that "convergence clubs" exist for energy intensity, and that the converging group—the OECD, greater Europe, and Asia—is involved in considerable trade among the members, including specifically between the OECD and Asia (e.g., with China). Thus, such realities (i) imply that trade facilitates energy intensity convergence, perhaps through mechanisms like technology transfer, and (ii) contradict the idea that trade would cause energy intensity divergence by encouraging specialization. Similarly, Mulder and De Groot (2007), who studied 14 OECD countries over 1970-1997, found that specialization had a positive effect on convergence in energy productivity (the inverse of energy intensity) in the iron and steel and non-metallic minerals sectors.

Lastly, Liddle (2009), also an OECD study, found that industrial electricity intensity was converging toward a bimodal distribution—a smaller group of countries with relatively high electricity intensity and a larger group with relatively low intensity; membership in that high intensity group reflects a concentration in particularly energy intensive industry sub-sectors (and to a lesser degree such membership also reflects a greater reliance on electricity within the industry sector).[8] Yet, as shown here, aggregate-level energy intensity convergence is single-modal for the OECD. In other words, trade within/among the sub-sectors of industry—and the attendant economic specialization—likely lead to a bimodal *industry* electricity intensity distribution; but, at the aggregate level, single-modal energy intensity convergence is occurring in the OECD *despite* that specialization in industry sub-sectors—not because of it.

[8] Those high industrial electricity intensity countries are: Australia, Canada, Finland, Luxembourg, Norway, and Sweden. All are countries whose industrial structures are skewed toward iron and steel, minerals, mining, and pulp and paper.

From the discussion above one might surmise that among the factors leading to lower energy intensity is improvements in end-use efficiency. Better understanding of both the factors affecting energy use over time and the role of energy efficiency is important. However, such an analysis requires indicators based on more detailed data than are available in the IEA Statistical Balances (i.e., such data has been collected for substantially fewer countries than those analyzed here); thus, we leave a more detailed, disaggregated analysis for future research.

5.2 Future OECD energy intensity convergence

To determine the future steady-state or long-run (ergodic) distribution of energy intensity, I first calculate a transition matrix. Then I use those transition probabilities as a mapping operator that is applied to the distribution in the last year (2006) to estimate the ergodic distribution. Quah (1993) used this transition matrix framework to evaluate convergence of per capita income, and he assumed the mapping operator was a Markov chain transition matrix whose (*j,k*) entry is the probability that a country in state *j* transits to state *k* in the following period. Here, a high degree of convergence has already occurred among OECD countries; again, nearly all countries are within 20% of the OECD mean, and convergence is expected to continue in the near future. Because of those conditions, I divide the relative energy intensity data into five categories: less than 85% of the OECD average, between 85 and 95% of the average, between 95 and 105% of the average, between 105 and 115% of the average, and over 115% of the average. In addition, I consider only recent data, from 1996-2006, to calculate the one-year transitions from one category to another.

Table 4 presents the transition matrix and estimated ergodic distribution (the column and row headings indicate the upper endpoint of each category). The table can be read as follows: a country that begins a period in the less than 85 of the OECD average, has a 93% chance of remaining in that category the following period and a 7% chance of moving to the next highest category (between 85 and 95% of the average). If that country did move up to the higher category, it has a 91% chance of remaining in that higher category after the following period, a 4% chance of returning to its original category (less than 85% of the average), and a 5% chance of moving up a category again (to between 95 and 105% of the average).

As is typical for transition matrices in the economic growth literature (e.g., Quah 1993), the probabilities on the main diagonal are very high, and the off-diagonal, corner probabilities are zero; hence, there is limited period-to-period movement between categories, and countries do not hurdle (move more than one) category when they do move. The estimated ergodic distribution (the last row in Table 4) indicates further convergence: one-third (or 0.34) of the countries will be within 5% of the mean; and nearly three-quarters (0.12 + 0.34 + 0.27) will be within 15% of the mean. Yet, in the long-run steady-state distribution, one-quarter of the countries will be still outside 15% of the mean—again, conditional, rather than absolute, convergence. Furthermore, that long-run distribution implies limits to or a slowing of convergence.

Table 4

6. Conclusions

OECD countries exhibit a high degree of continued (i.e., over the entire period 1960-2006) decline in their energy intensity differences—a finding that is robust to several different ways of calculating/measuring energy intensity. Further, if current trends hold, those differences/that dispersion will continue to decline. Both the decline in energy intensity (where that is occurring) and its convergence (i.e., lowering of dispersion/differences) are not simply a function of similar economic structures; improvements in the efficiency of both energy *end-use* and electricity conversion are likely to be part of the story.

Despite this decline in energy intensity differences/dispersion (i.e., sigma-convergence) among OECD countries, significant and important individual country differences in energy intensity levels remain: there was little intra-distributional mobility (i.e., relative rankings were steady), and in the estimated long-run, steady-state distribution, over one-quarter of countries will be still outside 15% of the OECD mean. That importance of country-specific conditions or history echoes Mulder and De Groot (2007), who found that individual country effects explained most to nearly all the variance in catch-up in rates of change (i.e., beta-convergence) among OECD countries in the sectors they examined; hence, they concluded that convergence in sectoral energy productivity is conditional rather than absolute. That history should matter—in either current levels of energy intensity or the likelihood of ultimate convergence to a similar level—is not surprising. After all, many of the factors that contribute to energy intensity are slow moving ones like capital stocks (e.g., nuclear reactors or electricity grids) or country endowments (e.g., potential for hydro- or geothermal- electricity).

The persistent country differences, combined with the estimated long-run distribution discussed above, suggest limits to OECD energy intensity convergence given "business as usual" behavior. Ultimately, overcoming persistent country differences in energy intensity likely will require the introduction of a significant policy regime—like a carbon tax or rigorous emissions cap and trade scheme. However, those country differences may present important obstacles to those types of global policies.

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Table 1. Summary of energy/electricity intensity convergence studies.

Study	Data (panel size; level of aggregation)	Intensity measure studied	Evaluation method considered[a]	Findings
Mielnik & Goldemberg (2000)	41 developed & developing countries x 1971-1992; national aggregates	TPES per GDP PPP	Visual inspection of traces	Developed countries have decreasing trajectory; developing countries have increasing trajectory
Sun (2002)	27 OECD countries x 1971-1998; national aggregates	TPES per GDP PPP	Mean deviation	Mean deviation has declined
Miketa & Mulder (2005)	56 developed & developing countries x 1971-1995; ISIC level 2	TFC per VA	Beta (absolute & conditional)	Cross-country differences have declined—particularly in less energy-intensive sectors
Markandaya et al. (2006)	27 transition/Eastern European & EU countries x 1992-2002	TFC per GDP PPP	Beta (absolute & conditional), Sigma (CV)	Transition countries (Eastern Europe) converged toward EU average
Ezcurra (2007)	98 countries x 1971-2001; national aggregates	TFP per GDP PPP	Sigma (density functions, CV), Gamma (stochastic kernel)	Convergence slowed/stopped since 1980s
Mulder & De Groot (2007)	14 OECD countries x 1970-1997; ISIC level 2	TFC per VA PPP	Beta (absolute & conditional), Sigma (CV)	Lagging countries caught up with energy productivity leaders
Liddle (2009)	22 OECD countries x 1960-2006; ISIC level 1	Electricity consumption per VA PPP	Sigma (histograms, CV), Gamma (rank concordance index)	Commercial electricity intensity converging toward single-mode; industry electricity intensity converging toward bimodal distribution
Le Pen & Sevi (2010)	97 countries x 1971-2003; national aggregates	TFC per GDP PPP	Stochastic (pair-wise unit root tests)	No world-wide convergence; convergence for OECD & Middle-East
Liddle (2010)	111 countries x 1971-2006 & 134 countries x 1990-2006; national aggregates	TPES per GDP PPP	Beta (absolute), Sigma (density functions, CV), Gamma (rank concordance index)	Continued convergence for OECD & Eurasia; No convergence to divergence for Latin America, Middle-East, & Africa

Notes: [a] methods are described in text; VA is value added; CV is coefficient of variation.

Table 2. Summary of types of conditional convergence analyzed.

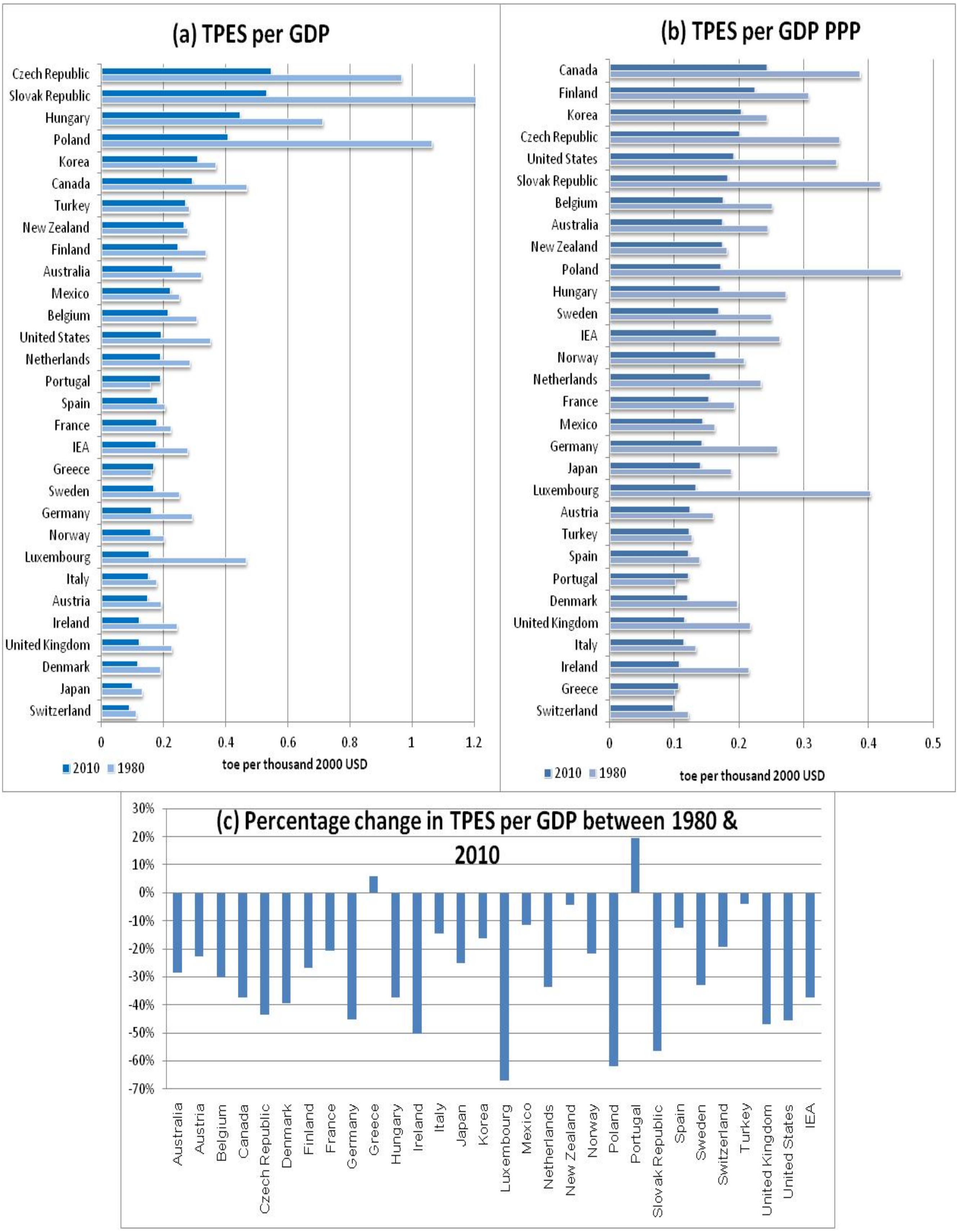
Measure	Method(s)	Questions addressed
Beta/relative rates of change	Regress average rate of change on initial energy intensity for cross-section	Is there a catch-up process? Do countries with lower/higher initial levels have faster rates of change?
Sigma/change in the distribution	Estimate kernel density of distribution at different times	Has the shape of the distribution narrowed? Is it multi-model—“convergence clubs”?
	Plot coefficient of variation (standard deviation/ average) over time	Have differences in countries decreased/increased (converged/diverged)? Has that change occurred consistently or in stops and starts?
Gamma/intra-distribution mobility	Plot index of rank concordance over time	Do initial differences in levels persist even if those differences narrow? Or do countries criss-cross over time?

Table 3. Beta convergence for OECD countries for two different time periods and samples. Dependent variable is average annual change in logged energy intensity.

	Value	t-Statistic
	1960-2006	
Constant	-0.032	-11.92
Beta	-0.017	-10.91
Adjusted R^2	0.84	
N	23	
	1971-2006	
Constant	-0.038	-10.46
Beta	-0.020	-8.47
Adjusted R^2	0.72	
N	28	

Table 4. Estimates of transition matrix and ergodic (long-run) distribution, OECD energy intensity, 1996-2006

Upper endpoint	Upper endpoint (ratio of national to OECD average energy intensity)				
	0.85	0.95	1.05	1.15	∞
0.85	0.931	0.069	0	0	0
0.95	0.036	0.909	0.054	0	0
1.05	0	0.019	0.904	0.077	0
1.15	0	0	0.094	0.868	0.0377
∞	0	0	0	0.0484	0.952
Ergodic	0.06	0.12	0.34	0.27	0.21



Figures 1-a-c. Energy intensity in terms of TPES per GDP converted with exchange rates 1-(a) and TPES per GDP converted with purchasing power parities 1-(b) at 2010 and 1980 for OECD countries. The percentage change over that period 1-(c) is also displayed.

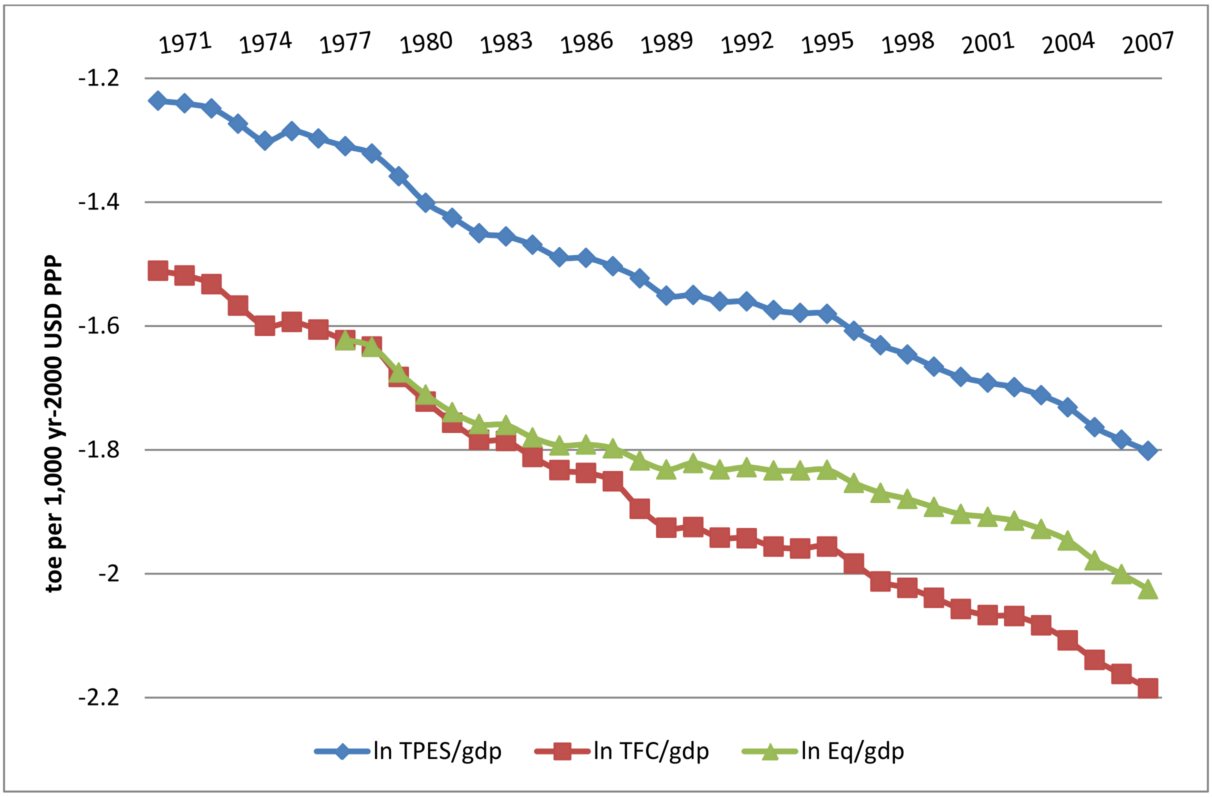


Figure 2. Traces of natural log of energy intensity for the OECD as a whole using three energy measures: total primary energy supply (TPES), total final energy consumption (TFC), and one derived from an energy quality index (Eq). The units for all three are tons of oil equivalent (toe) per thousand yr-2000 US dollars converted at purchasing power parity (PPP). The data spans from 1971-2007, except for the energy quality/gdp series, which begins in 1978. The data are negative because, in the above described units, energy intensity is less than one before natural logs are taken.

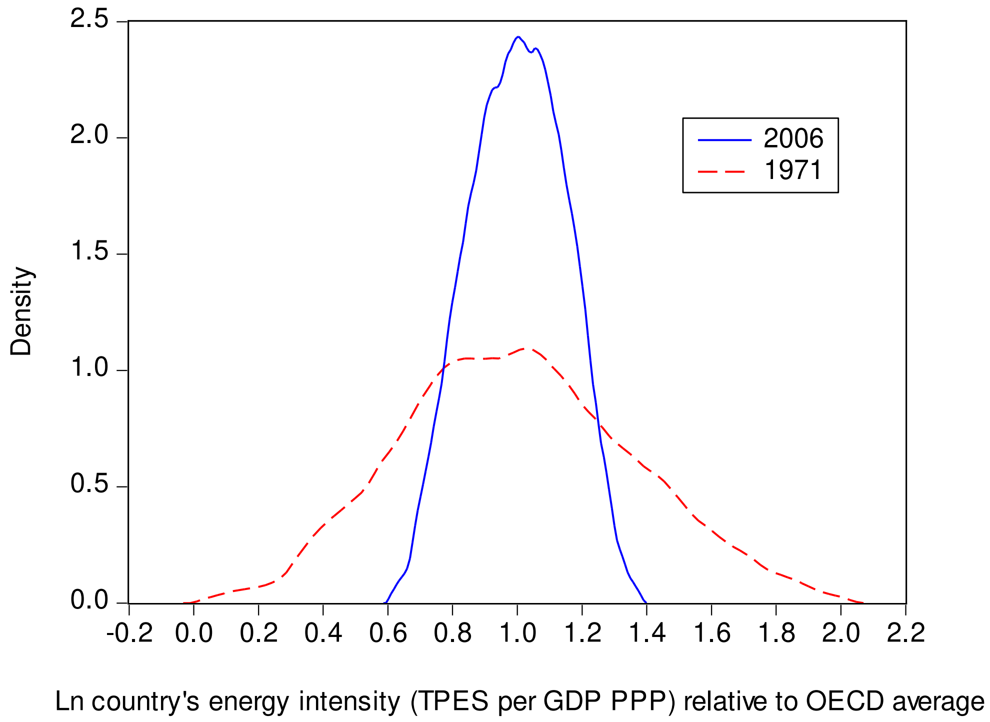


Figure 3. Estimated kernel density functions of relative energy intensity (country intensity divided by the sample average intensity) for 1971 and 2006.

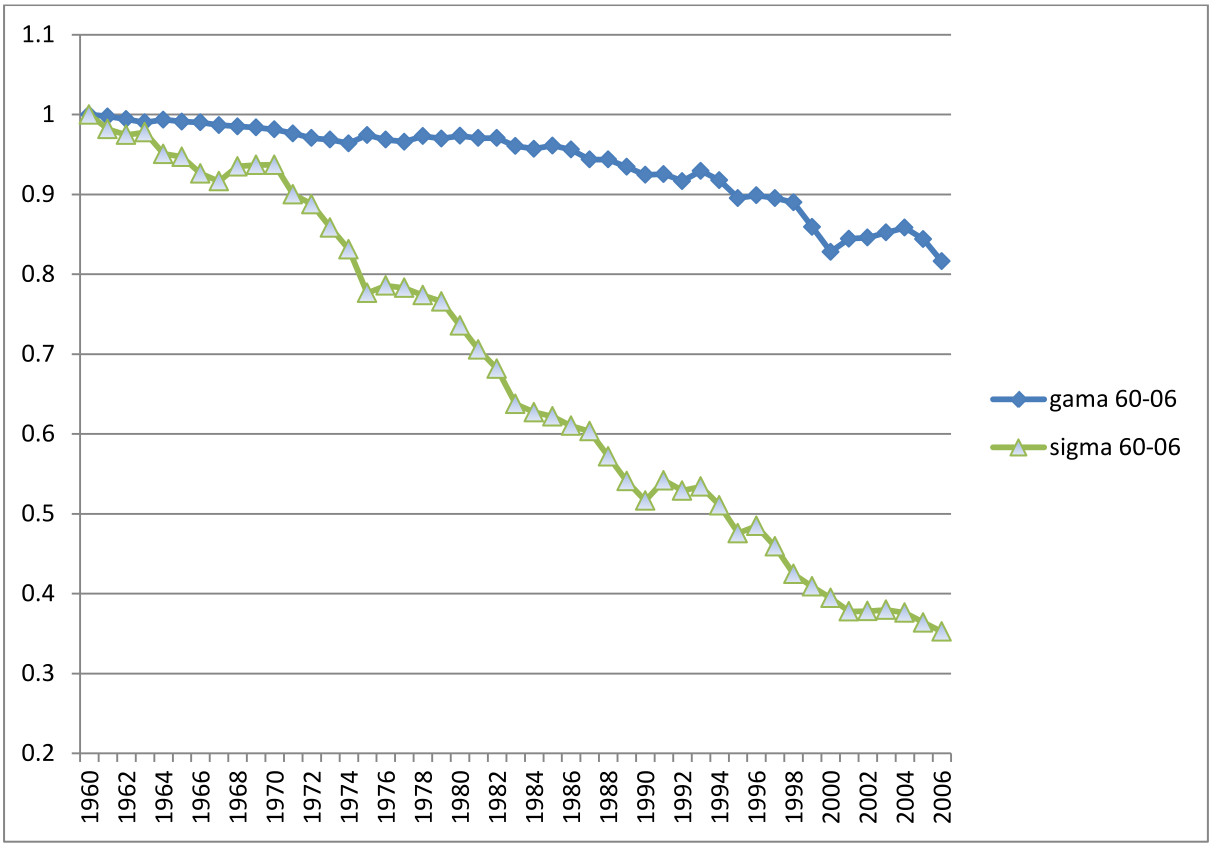


Figure 4. Sigma- (CV) and gamma-convergence (intra-distribution mobility) in energy intensity (TPES per GDP PPP) for OECD countries (23 countries over 1960-2006). Series have been normalized to their initial year. (The two traces are essentially the same if the shorter, 1971-2006, 28 country sample is used.)

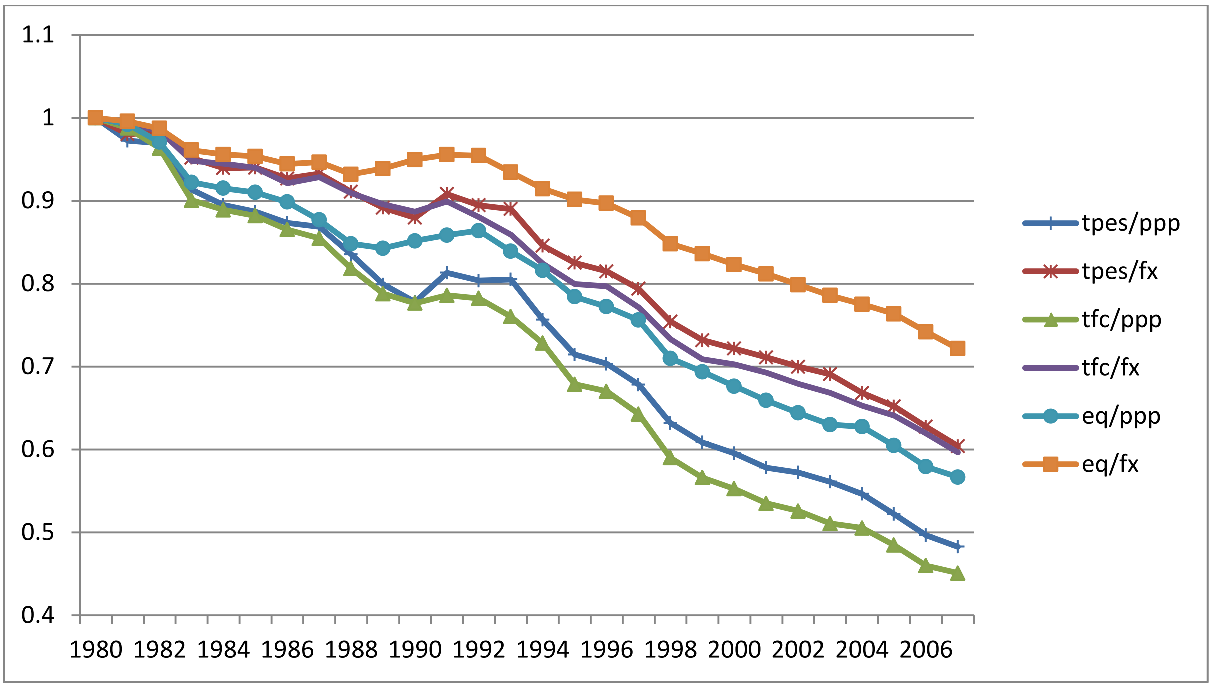


Figure 5. Sigma- (CV) convergence in energy intensity for OECD countries (23 countries over 1980-2007). Considered are six different measures of energy intensity that depend on the definition of energy consumption (total primary energy supply or tpes, total final consumption or tfc, and quality weighted consumption or eq) and on how GDP is converted into common terms (by purchasing power parities or PPP and exchange rates or fx). Series have been normalized to their initial year.