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The relationship between energy intensity and economic growth: New evidence from a multi-country multi-sectorial dataset

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ABSTRACT

This paper revisits the relationship between energy intensity and economic growth, using a flexible piecewise linear regression model. Based on a panel data set of 137 economies during 1990–2014, the analysis identifies a threshold effect of income growth on energy intensity change: although energy intensity is negatively correlated with income growth throughout the entire sample and study period, the declining rate significantly slows by about 25 percent after the level of per capita income reaches $5,000. Based on index decomposition, the analysis also finds that although structural change is important for intensity levels in all countries, the efficiency effect is more important in higher-income countries. The results suggest that one can expect to see relatively rapid reduction in energy intensity as the economies in today's poor countries grow. However, when countries move beyond lower-middle-income levels, energy efficiency policies become far more critical for sustaining the rate of reduction in energy intensity.

1. Introduction

The energy sector plays an important role in economic development. But energy consumption is also associated with human-induced climate change because of the dominant role of fossil fuels in power production. Energy use tends to increase with development as countries shift from labor-intensive agriculture to capital and energy intensive industries. As the structural transformation proceeds, they subsequently move into information-intensive services. Energy intensity therefore initially increases with rising incomes and then decreases—a pattern comparable to the Environmental Kuznets Curve (EKC) that describes the relation between per capita GDP and environmental degradation.

The EKC pattern in the income and pollution relationship has been extensively documented (Dasgupta, Laplante, Wang, & Wheeler, 2002; Carson, 2010), although some studies caution whether this is universal for all settings and pollutants (Dinda, 2004; Stern, 2004). Over the past decade, also a growing literature on the validity of EKC in the context of energy use emerged. For example, Luzzati and Orsini (2009) analyze the relationship between per capita GDP and aggregate energy consumption for a sample of 113 countries over 1971–2004. Their findings based on different econometric techniques (parametric and semi-parametric) and across different sample groups (world, cross-countries, and individual countries) do not support the energy-EKC hypothesis. On the other hand, Medlock and Soligo (2001), van Benthem and Romani (2009) and van Benthem (2015) document an S-shaped relationship between energy intensity and economic growth. Specifically, they find that the income elasticity of energy demand peaks at a GDP per capita level between $5,000 and $10,000, and trends towards zero for high-income levels. Burke and Csereklyei (2016) present disaggregated analyses of the elasticity of energy demand. Their findings suggest substantial heterogeneity in income elasticity of energy use across sectors: industry and services sectors are most responsive to income growth, followed by residential and agricultural sectors.

Another strand of related literature tests the hypothesis of cross-country convergence of energy intensity. Specifically, these studies examine whether cross-country variation in energy intensity is getting smaller (so called sigma-convergence) and whether less efficient countries reduce their energy intensity faster than more efficient ones (beta-convergence). While the majority of

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studies find convergence across developing and developed countries (such as Mielnik & Goldemberg, 2000; Markandya, Pedroso-Galinato, & Streimikiene, 2006; Ezcurra, 2007; Csereklyei, Rubio-Varas, & Stern, 2016; Burke & Csereklyei, 2016), others argue for a more nuanced picture of convergence in energy intensity. For example, Le Pen and Sévi (2010) do not find evidence for global convergence for a group of 97 countries during 1971–2003. When looking at subgroups, they find non-convergence is "less strongly rejected" for the Middle East, OECD and Europe sub-groups. Ezcurra (2007) show that developing counties tend to converge at a higher level of energy intensity, while for developed countries at least two different levels of convergence are observed. Stern (2012) shows that divergence in energy efficiency is mostly associated with economies that are lacking in economic progress.

A third strand of literature explores the determinants of the growth rate of energy intensity. For example, using data for 51 sectors in 19 OECD countries from 1980 to 2005, Mulder and de Groot (2011) find that reductions in energy intensity have been driven more by within-sector energy efficiency improvements than by changes in the composition of activities at the economy level or within manufacturing and service sector. In another paper, Mulder and de Groot (2012) show that aggregate convergence in energy intensity of 18 OECD countries from 1970 to 2005 are almost entirely driven by convergence of within-sector energy intensity levels, and not by convergence of the sectorial composition of economies. By using output distance functions, Wang (2013) decomposes energy intensity change across 100 countries from 1980 to 2010 into five components: technological catch-up, technological progress and changes in the capital-energy ratio, labor-energy ratio and output structure. Technological progress, capital accumulation and changes in output structure contributed positively to lowering energy intensity while a decrease in the labor-energy ratio increased intensities.

As this brief survey shows, the existing EKC and convergence literature does not present conclusive evidence on the relationship between energy intensity and economic growth. In this paper we therefore revisit this question using a large dataset of 137 countries over the period of 1990 to 2014. We amend the existing literature by focusing on three aspects of the path of energy intensity to provide a comprehensive analysis of the relationship:

Firstly, we re-examine the link between energy intensity and economic growth beyond the EKC. More specifically, we adopt a novel piece-wise regression method in our main estimation model which imposes less structure on the relationship between the level of economic growth and energy intensity. We find a negative correlation between GDP per capita and energy intensity across the entire sample and study period. However, the downward slope flattens out at higher values of GDP. The inflection point is at a per capita income level of around $5,000.

Secondly, we analyze the cross-country convergence in energy intensity. We find evidence that countries with a high level of energy intensity experience a stronger reduction in energy intensity. Also, the conditional convergence rate for countries below and above the inflection point of $5,000 GDP p.c. are rather similar, with a slightly larger convergence for countries with a higher income.

Finally, based on index decomposition, we investigate the extent to which shifts in economy-wide energy intensity are affected by structural vs. efficiency changes at the country level. The analysis shows that while structural change is important for intensity levels in all countries, the efficiency effect is more important for higher-income countries. This finding supports the income threshold effect identified earlier: the relatively automatic efficiency gains (accompanying income gains) are at lower levels of GDP (and thus the steeper slope), while the harder problem (improving efficiency) is more important in higher income countries. The results imply that to sustain continued reduction in energy intensity, more aggressive energy efficiency policies are needed as incomes rise to achieve a decoupling of energy consumption and economic growth.

The remainder of the paper is structured as follows. Section 2 presents the data, Section 3 explores the relationship between energy intensity and economic development via within-countries correlations, fixed-effects regression and a novel piecewise linear method. Section 4 and 5 present results from convergence analyses and index decomposition and Section 6 concludes with a summary of the main findings and a discussion of the policy implications.

2. Data

Energy consumption data are obtained from the International Energy Agency (IEA) World Energy Statistics and Balances dataset. The IEA total final energy consumption is the sum of end-use sector consumption and measured in tons of oil equivalents. In contrast to the data on energy consumption provided by BP, the IEA data includes non-commercial energy sources, which is an important contributor to overall energy demand especially in low-income countries (Ang, 2006). Moreover, it contains several low- and middle-income countries for which BP provides only aggregates. We use final energy consumption rather than primary energy supply to reflect the energy needed for "production" of GDP and to circumvent accounting problems stemming from the IEA method of input efficiency (Moriarty & Honnery, 2010). However, with an increasing role of electricity for energy use, consumption and production measures are more and more falling apart (Moriarty & Honnery, 2010).

Data on GDP, population and value added of agriculture, services, and industry and manufacturing sectors are from World Bank World Development Indicators (WDI).[1] For comparison across countries and over time, all values are converted into PPP-based constant 2011 prices. We calculate aggregate energy intensity as total final energy consumption divided by total GDP. Sectorial-level energy intensity is defined as energy consumption of agriculture, industry and services divided by sectorial value added.

Overall, we have an unbalanced panel of 137 countries from 1990 to 2014, and a balanced panel of 64 countries during the same period (Table A1). Since the attrition rate is relatively high, it may be difficult to tell whether a change over time is picking up a real development or just a change in the composition of the sample. However, eliminating countries with missing data could cause sample selection bias if countries with missing data are systematically different from those that have complete observations over the study period. In the following we report results from the unbalanced panel. For robustness check, we also estimate the models using the balanced panel and with data from the Penn World Tables (1980–2014). Conclusions of the paper are robust to these alternative data sources.

Table 1 reports descriptive statistics for the 137 countries in the unbalanced sample. The variables reported are GDP (PPP) per capita, total final energy consumption and population size. The numbers are period averages. The sample covers the entire spectrum from poor to rich countries (Fig. 1).

3. Relationship between energy intensity and economic development

3.1. Descriptive analysis

We are interested in the relationship between energy intensity and economic development. One hypothesis that can be derived

[1] Last updated: 05/26/2017.

Table 1
Summary statistics for 1990 and 2014.

	N	Mean	Median	Min	Max
1990					
GDP p.c. (thsd.)	118	14.19	8.23	0.38	114.52
Total final energy consumption (Mtoe)	129	46.07	8.98	0.27	1293.50
Population (mio.)	137	37.19	8.56	0.26	1135.18
2014					
GDP p.c. (thsd.)	134	21.03	14.78	0.71	132.12
Total final energy consumption (Mtoe)	136	64.98	12.00	0.44	1987.83
Population (mio.)	135	51.07	10.60	0.42	1364.27

GDP per capita data are obtained from the World Bank World Development Indicators and presented in thousands of PPP-based constant 2011 international $. Total final energy consumption data are obtained from the International Energy Agency and presented in Mega tons of oil equivalent. Population data are obtained from the World Bank World Development Indicators and presented in millions.

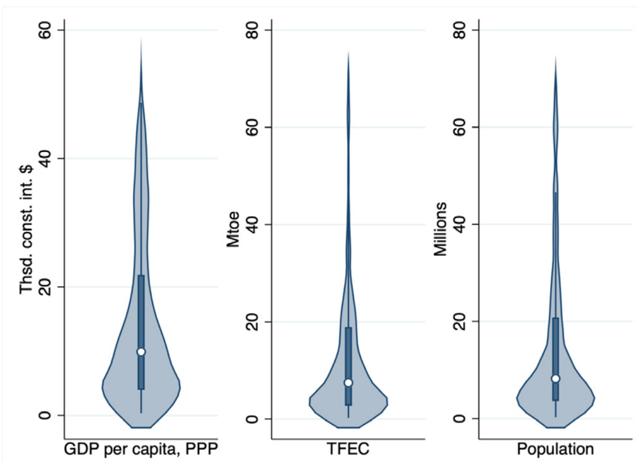

Fig. 1. Violinplots for GDP per capita, total final energy consumption and population. GDP per capita data are obtained from the World Bank World Development Indicators and presented in thousands of PPP-based constant 2011 international $. Total final energy consumption data are obtained from the International Energy Agency and presented in Mega tons of oil equivalent. Population data are obtained from the World Bank World Development Indicators and presented in millions. Outliers (values 1.5*IQR above the third quartile) are not depicted.

from the literature is that the relationship between energy intensity and economic development follows an environmental Kuznets curve (inverted u-shape). Energy intensity increases in early stages of development (industrialization) and it decreases in later stages of development (transition to a services economy). Structural change of the economy is a long process that is unlikely to be reflected in a panel of only 24 years. However, it is still possible to study this hypothesis. If it were true, we would expect a negative association between energy intensity and GDP per capita for developed countries and a positive association for developing countries (and possibly no association for countries that are in the middle of the transition).

Another hypothesis is that there is a negative association between energy intensity and economic development with no trend shift. The theoretical justification behind this hypothesis is that economic development increases opportunities to make production processes more efficient and therefore reduces energy intensity. Alternatively, an improvement in energy efficiency could trigger economic growth due to more efficient resource-use (Stern, 2011). If this negative association was preceded by an initial positive one, as the EKC hypothesis suggests, it would have pre-dated the compilation of reliable cross-country data. The remaining possibilities are that there is no association between growth and energy intensity or that energy intensity keeps rising with incomes (a positive association). These patterns are not supported by any theories or evidence.

Exploratory data analysis suggests it is appropriate to take logs of both variables. Taking logs does not change the direction of the relationship and therefore does not affect our conclusions regarding the main hypotheses. But the logarithm makes an exponential shape linear and allows correlation and regression analysis of the data.

As a first step we calculate the correlation coefficient between energy consumption per $PPP and GDP per capita PPP for all 137 countries in the dataset (Table A2). For about 40 percent of the countries we find a very strong negative linear association between the two variables with a correlation coefficient of −0.9 or smaller. For another 35 percent of the countries we find a moderate to strong negative association with correlation coefficients between −0.9 and −0.5. Of the remaining countries, 16 show a weak to very weak negative association and 15 countries show a weak positive association. The overall impression from the correlation analysis is that there is a fairly strong negative association between energy consumption per $PPP and GDP per capita PPP for most countries. If the relationship followed a Kuznets curve, we would expect a negative association in developed countries and a positive association in developing countries. Even a cursory look at Table A2 contradicts this hypothesis: We find the same strong negative linear association for countries like India, Nigeria and China as for countries like the United States, the United Kingdom and Germany. On the other hand, the relatively rich EU members Spain and Portugal show only a weak negative or even a positive association between the two variables.

3.2. Econometric analysis

The scatter plot in Fig. 2 and also the country by country correlation analysis in the previous section indicate that the relationship between log GDP per capita and log energy intensity is not perfectly linear, because there are a few countries with no or a positive association. We thus specify the following fixed effects model to test the relationship between energy intensity and economic development

$$logEI_{it} = \beta_1 \cdot logGDP_{it} + \beta_2 \cdot logGDP^2_{it} + \gamma \cdot E_{it} + \mu_i + \rho_t + v_{it} \qquad (1)$$

where EI_{it} is log energy intensity of country i in year t, $logGDP_{it}$ is log GDP per capita, and $logGDP^2_{it}$ is squared log GDP per capita. The inclusion of a squared term of log GDP per capita allows to test for an inverted U-shaped relationship. Results for a linear underlying function can be found in the technical appendix.

Previous studies suggest the importance of controlling for sectorial composition of an economy when analyzing the relationship between income and energy intensity (Burke & Csereklyei, 2016; Medlock & Soligo, 2001). We therefore include on the

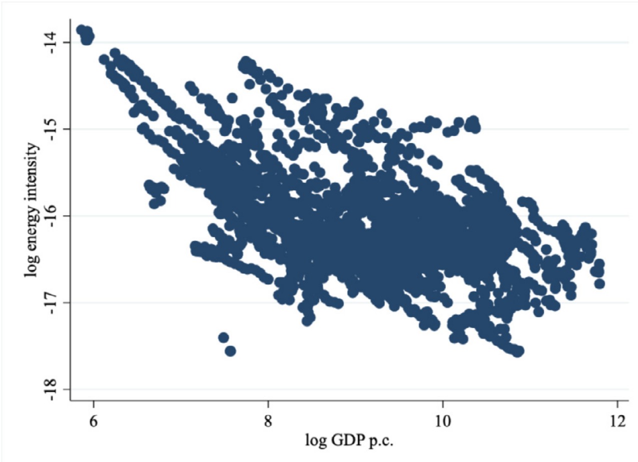

Fig. 2. Scatterplot of log energy intensity and log GDP per capita.

right-hand-side of the equation (1) a vector E_{it}, which is a set of control variables for the composition of final energy demand. It includes the percentage of total energy consumption used in industry, transport, residential, services, agriculture and non-energy use. The reference category is non-specified other energy consumption, all variables are coded between 0 and 1. μ_i is a country fixed effect capturing time-invariant country specific characteristics; ρ_t is a time fixed effect controlling for yearly shocks that are common to all countries; and υ_{it} is the error term.

The results are reported in Table 2. The coefficients of log GDP per capita are always negative and significant, and the coefficients of log GDP per capita squared are always positive and significant. This is an indicator for a U-shaped relationship. However, when we calculate the minimum of the parabola ($= -\beta_1/(2 \cdot \beta_2)$), we find that the minimum is always near the right border of the observed values range of log GDP per capita (except for the pooled OLS regression). It is thus not a real minimum, in fact we are fitting the left-hand side of a parabola to the data, thus the relationship between log GDP per capita and log energy intensity is always negative but flattening out for higher values of log GDP per capita. In other words, these regressions do not show evidence for a u-shaped or inverted u-shaped relationship between the two variables.

Imposing a parabola on the data might mask different GDP-energy intensity regimes or kink relationships. To adopt a more flexible functional form without imposing structure on the relationship between GDP and energy intensity, we apply a piecewise linear model similar to the one Myrskylä, Kohler, and Billari (2009) implemented. The starting point is a piecewise linear relationship that fits two different linear models to the left and to the right of a critical value of log GDP per capita:

$$logEI_{it} = (\alpha^{pre} + \beta^{pre} \cdot logGDP_{it}) \cdot B^{pre}_{it} + (\alpha^{post} + \beta^{post} \cdot logGDP_{it}) \cdot B^{post}_{it} + \gamma \cdot E_{it} + \mu_i + \rho_t + \upsilon_{it} \quad (2)$$

where B^{pre}_{it} is an indicator variable that is equal to 1 to the *left* of the critical value of log GDP per capita and 0 otherwise. B^{post}_{it} is an indicator variable that is equal to 1 to the *right* of the critical value of log GDP per capita and 0 otherwise. This specification allows us to examine the relationship between GDP and energy intensity beyond the hypothesis of an EKC. If β^{pre} is negative and β^{post} is positive, then the relationship is V-shaped (or U-shaped). If β^{pre} is positive and β^{post} is negative, then the relationship is inverted V-shaped. If both coefficients have the same sign, it is interesting to compare the magnitudes of the coefficients, because the piecewise linear model can also show that parts of the relationship are steeper/flatter than others. If $\beta^{pre}$is flatter than β^{post}, this suggests an acceleration of energy intensity improvements at higher GDP levels, thus allowing an EKC interpretation in which the included countries already surpassed the peak of energy intensity. If $\beta^{pre}$is steeper than β^{post}, this strengthens the case of a flattening relationship between GDP and energy intensity, negating an EKC.

Before we explain how to obtain the critical value of log GDP per capita, we first note that we don't estimate Eq. (2) directly but rather in its differences-in-differences version

$$\Delta logEI_{it} = \alpha \cdot \Delta B^{pre}_{it} + \beta^{pre} \cdot B^{pre}_{it} \cdot \Delta logGDP_{it} + \beta^{post} \cdot B^{post}_{it} \cdot \Delta logGDP_{it} + \gamma \cdot \Delta E_{it} + \Delta\rho_t + \Delta\upsilon_{it} \quad (3)$$

where Δ is the difference operator $\Delta x_t = x_t - x_{t-1}$. The differencing implicitly controls for the country fixed effects and accounts for autocorrelation in the residuals. The coefficients obtained from the differences-in-differences model come closer to a causal

Table 2
Panel regressions. Dependent variable: log energy intensity, Eq. (1).

	(1)	(2)	(3)	(4)
log GDP p.c.	−2.06***	−1.08***	−1.14***	−1.54***
	(0.094)	(0.104)	(0.105)	(0.096)
log GDP p.c. sq.	0.10***	0.02***	0.03***	0.05***
	(0.005)	(0.006)	(0.006)	(0.006)
E(Industry, %)				0.86***
				(0.078)
E(Transport, %)				−0.27***
				(0.088)
E(Residential, %)				−0.83***
				(0.069)
E(Services, %)				−0.32**
				(0.134)
E(Agriculture, %)				−0.07
				(0.187)
E(Non-energy, %)				1.48***
				(0.142)
Observations	3238	3238	3238	3238
R-squared	0.357	0.490	0.494	0.605
Country Effects	No	Yes	Yes	Yes
Year Effects	No	No	Yes	Yes

Standard errors in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1.

Table 3
Differences-in-Differences Regressions, Eqs. (3) and (4).

	Eq. (3)	Eq. (4)
β^{pre}	−0.67***	−0.15***
	(0.028)	(0.032)
β^{post}	−0.51***	−0.08***
	(0.028)	(0.030)
Observations	3099	2968
R-squared	0.312	0.134
Statistically different (p-value)	0.000	0.094

Standard errors in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1.

interpretation than the coefficients obtained from a levels equation since it explicitly includes different trends in low- and high-income countries based on a data-driven inflection point. As additional robustness check we estimate the same model with the first lag of the log GDP per capita variable.

$$\Delta logEI_{it} = \alpha \cdot \Delta B_{it}^{pre} + \beta^{pre} \cdot B_{it}^{pre} \cdot \Delta logGDP_{i(t-1)} + \beta^{post} \cdot B_{it}^{post} \cdot \Delta logGDP_{i(t-1)} + \gamma \cdot \Delta E_{it} + \Delta \rho_t + \Delta \nu_{it} \quad (4)$$

We use maximum likelihood estimation to find the optimal value for the threshold between the two linear models as described in the technical appendix. Fig. A1 in the technical appendix displays a plot of the likelihoods of all models with critical values between 5.8 and 11.8. The maximum is at 8.5 log GDP per capita or approximately $5,000 GDP per capita (PPP). Thus, we estimate Eqs. (3) and (4) with critical values of 8.5, that is B_{it}^{pre} is equal to 1 if log GDP per capita is smaller than 8.5 and 0 otherwise, and B_{it}^{post} is 1 if log GDP per capita is greater or equal 8.5 and 0 otherwise.

The results for the two differences-in-differences regressions are reported in Table 3. For both equations, the coefficients are negative and highly significant, both to the right and to the left of the critical value of log GDP per capita. However, the slope is much steeper (we find a more negative coefficient) to the left of the critical value than to the right. These results confirm the previous finding from the fixed effects estimations. The relationship between log GDP per capita and log energy intensity is negative for the entire observation period, but the slope flattens out for higher values of GDP per capita. Specifically, when per capita GDP reaches around $5,000, the declining rate of energy intensity with respect to economic growth significantly slows down by about 25 percent. This finding suggests that energy productivity increases as income grows. However, the income elasticity of energy intensity increases with income. As a result, after exceeding a threshold of around $5,000 GDP per capita, the efficiency dividends of economic growth become much smaller.

4. Convergence of energy intensity

The flattening relationship between log GDP per capita and log energy intensity gives rise to the question whether countries with initially high energy intensity will at some point catch-up with countries with initially low energy intensity. Exploratory data analysis (time series plots of energy intensity) suggests that energy intensity is converging to the same level across countries. We will now investigate this hypothesis more systematically. Typically, convergence analysis is used in the context of economic growth and goes back to Barro and Sala-i-Martin (1992). In order to achieve convergence, two things are necessary: beta convergence and sigma convergence. We speak of beta convergence in this context if higher rates of reduction in energy consumption per dollar of GDP are associated with higher initial levels of energy consumption per dollar of GDP. Different from convergence of GDP per capita, in this context beta convergence is implied by a positive beta coefficient in the regression. Sigma convergence means that the standard deviation of energy intensity decreases over time. If we find both, we speak of convergence.

We calculate the total change in log energy consumption per dollar of GDP between 1990 and 2014 and divide it by the level in 1990. This is a simple measure for the rate of reduction in energy consumption per dollar of GDP. We then run a regression with the rate of reduction as a dependent variable and the initial level of log energy consumption per dollar of GDP as the explanatory variable according to Eq. (5):

$$\Delta I_{it} = \beta \log (I_{i0}) + \varepsilon_{it} \quad (5)$$

ΔI_{it} is the growth rate of energy intensity of country i during the period from 1990 to 2014. I_{i0} is the energy intensity of country i in year 1990 and ε_{it} is the error term. The result is shown in the left panel of Fig. 3. Indeed, the beta coefficient is positive and highly significant (beta = 0.030 and p < 0.01). Quite remarkably, the variation in the initial level of log energy consumption per dollar of GDP explains about 42 percent of the variation in the rate of reduction across countries. We thus find strong evidence for beta convergence.

In the right panel of Fig. 3, we show fitted normal densities for log energy consumption per dollar of GDP for 1990 and 2014. One can clearly see that the density became much narrower over time (and also that the mean shifted to the left). Indeed, the standard deviation decreases from 0.672 in 1990 to 0.515 in 2014. We thus find evidence for sigma convergence. As we find both beta and sigma convergence, we can thus conclude that countries with high initial levels of energy intensity are converging to the levels of countries with low energy intensity.

In Fig. 4 we show box plots for log energy intensity for 1990, 2000, 2010 and 2014. A box plot displays the median, the first quartile, the third quartile and the largest and smallest adjacent values.[2] The following observations are noteworthy: Despite some variation, first quartile, median, third quartile and largest value all decrease over time. The outside values get closer to the largest adjacent observation over time. The smallest adjacent value also decreases over time, and the small jump in 2010 is consumed by a larger decrease in 2014. The smallest value can be considered as the “technology frontier” or “minimal energy consumption required per unit of output”. According to this picture, the frontier did not move very much between 1990 and 2014, rather the rest of the distribution moved closer to the frontier. Given that there is a generally increasing trend for per capita income across the sample, this result appears to be consistent with our earlier conclusion that as income rises above a certain threshold, reducing energy intensity becomes more difficult.

To examine whether there is also a difference in the speed of convergence on different sides of the income threshold, we divide the sample into two subgroups based on whether a country-year observation lies below or above the cutoff point at log per capita GDP of 8.5. We calculate the conditional convergence rate according to $\rho = -\left[\left(\frac{1}{T}\right)\log(\beta + 1)\right]$ (Barro & Sala-i-Martin, 1992; Islam, 1995), where T is the length in the time dimension under consideration (25 years in our case) and β is the coefficient obtained from equation (5). The results are reported in Table 4. The rate of unconditional convergence for groups below and above the income threshold is roughly 0.10 percent and 0.14 percent, respectively. The difference between the two groups is small and the lower-income sample even has a lower convergence rate. The result could reflect different economic growth rates of the two groups.

[2] Values that are more than 1.5 times the interquartile range (distance between first and third quartile) away from the median are plotted separately.

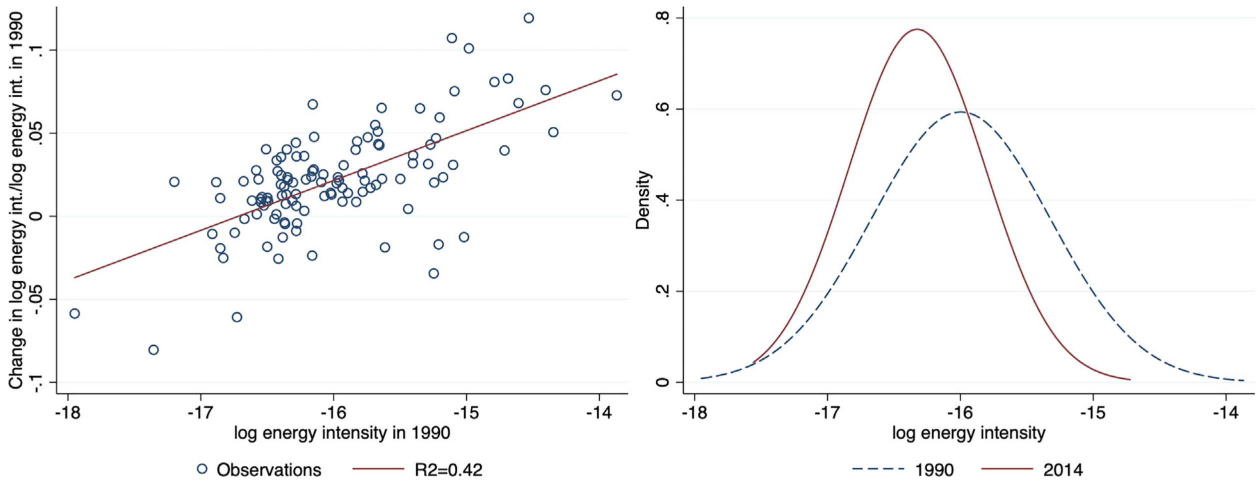

Fig. 3. Energy Intensity Convergence: Beta and Sigma Convergence.

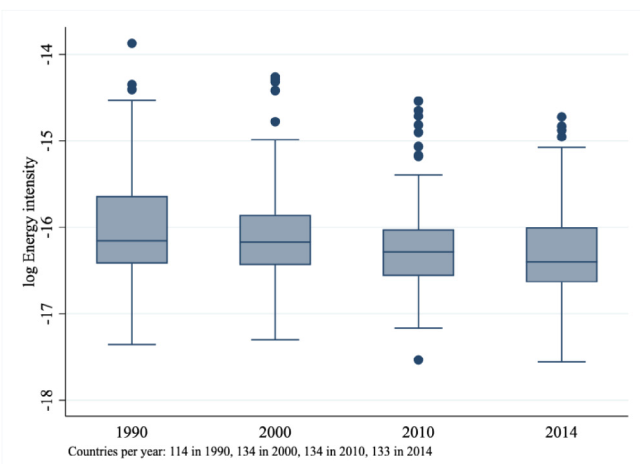

Fig. 4. Box plots of log energy consumption per dollar for selected years. This graph does not include Brunei, which had a log energy intensity of −18 in 1980 and thus constitutes an extreme outlier (because of oil price effects).

5. Index decomposition

In this section, we investigate how much of the improvement in energy intensity is due to structural change and how much is due to efficiency improvements, and whether the income threshold effect identified earlier plays a role in the relative importance of structural vs. efficiency changes. Index decomposition has been widely used to disentangle the roots of energy changes (Ang & Zhang, 2000; Ang, 2004; Su & Ang, 2012). As shown by Ang (2004), the Fisher Ideal Index Decomposition has favorable properties when using multiplicative decomposition. We employ the Fisher Ideal Index composition for structural change in energy intensity as described in Boyd and Roop (2004) considering three sectors: industry, agriculture and services. Details on the construction of the Fisher index can be found in the technical appendix.

Table 5 displays the summary statistics for the values of the Fisher index (aggregate, structure and efficiency) for the years 1995, 2005 and 2014 (base year 1990 = 1). Country-wise values are depicted in Table A3 in the appendix. The structural index ranges between 0.5 and 1.5 while the efficiency intensity ranges from 0.1 to 2.0.[3] To examine whether structural change or efficiency improvement plays a more important role in influencing aggregate energy intensity, we estimate the following country fixed-effects model.

Table 4
Beta-convergence Analysis.

	(1) Full sample	(2) Below	(3) Above
β	0.0300***	0.0265***	0.0345***
	(0.003)	(0.009)	(0.005)
Observations	114	23	70
R-squared	0.417	0.308	0.413
ρ	-0.0012	-0.001	-0.0014

Standard errors in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1.

$$F_{agg} = \alpha F_{str} + \beta F_{eff} + u_i + e_i \quad (6)$$

F_{agg} is the aggregate intensity index, F_{str} is the structural index and F_{eff} is the efficiency index. u_i are time-invariant country fixed effects. e_i is the error term. The aggregate Fisher index can be decomposed into the structural and the efficiency index as described in the technical appendix, such that Eq. (6) estimates the average contribution of changes in the structural and the efficiency index to changes in the aggregate index. Similar to the convergence analysis, we conduct both full sample analysis and sub-sample analysis based on the previously identified income threshold. Table 6 reports the estimation results, where column (1) corresponds to the full sample estimation, and columns (2) and (3) correspond to sub-samples below and above the income threshold, respectively.

The results suggest that structural change has made a higher contribution to variation in energy intensity for the full sample of observations. However, the difference between the structural and the efficiency index is only significant for country-year observations below the threshold. For country-year observations that are above the income threshold, efficiency change plays a relatively more important role in driving the change in aggregate intensity compared to observations below the threshold.

6. Conclusion

Reducing the amount of energy required to produce a unit of output is a priority in efforts to slow climate change. This paper contributes to the literature on the relationship between energy

[3] Malta is dropped as an outlier.

Table 5
Summary statistics for the Fisher indices in 1995, 2005, and 2014.

	N	Mean	Median	Min	Max
1995					
F_{agg}	82	1.4480	0.9838	0.2551	36.0064
F_{str}	82	0.9472	0.9681	0.5623	1.4468
F_i	82	1.4536	1.0345	0.3296	30.5665
2005					
F_{agg}	81	1.3395	0.8984	0.1208	33.4351
F_{str}	81	0.9732	0.9549	0.6060	1.5872
F_i	81	1.3160	0.9430	0.1137	27.8404
2014					
F_{agg}	82	1.4707	0.7321	0.0798	54.5493
F_{str}	82	0.9284	0.9055	0.4610	1.5123
F_i	82	1.4229	0.7931	0.0828	44.6114

Table 6
Determinants of Aggregate Energy Intensity Index, fixed effects estimation, Eq. (6).

	(1) Full sample	(2) Below	(3) Above
F_{str}	1.27***	1.07***	1.20***
	(0.036)	(0.030)	(0.067)
F_{eff}	1.22***	0.90***	1.23***
	(0.003)	(0.018)	(0.003)
Observations	2,007	471	1,136
R-squared	0.992	0.886	0.995
Statistically different (p-value)	0.145	0.000	0.672

Standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

use and economic growth by better describing the energy intensity trajectory as incomes grow. Specifically, our results confirm a negative correlation between GDP per capita and energy intensity as well as cross-country convergence in energy intensity. We also identify a transition from a relatively rapid lowering of energy intensity to slower gains. Using a flexible econometric approach, we show that as countries reach a per capita income of about $5,000 (PPP)—slightly above the level considered by the World Bank as upper-middle income—the downward sloping curve of energy use per unit of GDP flattens out. Index decomposition identifies the relative contribution of structural change versus energy efficiency to lowering energy intensity. It shows that the former is important at all income levels, while energy efficiency is more important at higher income levels.

The results suggest that we can expect to see relatively rapid improvements in energy intensity as the economies in today's poor countries grow. However, as they move beyond lower-middle income, the task gets increasingly harder. The role for energy efficiency policies then becomes far more critical (e.g., Deichmann & Zhang, 2013). Increased resource use efficiency and technical innovation are associated with faster economic growth (e.g., Stern, 2011) and should thus be in the interest of all countries. Moreover, theory and evidence suggest that improvements in energy efficiency can be a driver of the decarbonization of economic growth (Fankhauser & Jotzo, 2018; Le Quéré et al., 2019).

Our decomposition analysis provides possible explanations why energy intensity and GDP per capita follow a negative, though flattening relationship: Countries can reap big gains in energy productivity improvement as their economies shift from energy-intensive to less energy-intensive sectors through structural changes; increased efficiency of production (i.e., lower energy demand per unit of output) and fuel switching also contribute to declining energy intensity. This shift might as well involve an 'outsourcing' of energy-intensive sectors to lower-income countries, as shown by case studies on energy embodied in trade (Tang, Snowden, & Höök, 2013) and China (Liu, Xi, Guo, & Li, 2010). However, once major structural transformation is completed, and countries move beyond lower-middle-income levels, reduction in energy intensity becomes more difficult. The flattening of the slope implies higher importance of efficiency changes at higher levels of GDP per capita.

There is now a much better understanding of different policy instruments—even if we do not yet sufficiently understand why they are not adopted at a scale that would seem beneficial (e.g., Gillingham & Palmer, 2014). While an economy wide tax on emissions is considered the best instrument to encourage more efficient energy use and a switch to cleaner energy sources, such general taxes are politically difficult. More likely, energy efficiency gains will require numerous sector-specific instruments such as targeted revenue-neutral environmental taxation and other price instruments, stricter regulations, and public investments.

Declaration of Competing Interest

We declare no conflict of interest.

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Appendix

Table A1
Summary statistics (period averages 1990–2014) for the 137 countries.

Country	GDP p.c. (PPP cons 2011 int $)	TFEC (Mtoe)	Population (thsd)	Country	GDP p.c. (PPP cons 2011 int $)	TFEC (Mtoe)	Population (thsd)
Qatar	120,371	8,363	971	Costa Rica	10,718	2,608	4,004
UAE	91,285	29,787	4,593	South Africa	10,575	60,770	45,775
Brunei	83,208	860	341	Serbia	10,451	8,941	7,464
Kuwait	80,735	9,845	2,396	Iraq	10,425	18,483	25,292
Luxembourg	78,399	3,446	454	Belarus	10,262	20,989	9,847
Norway	57,065	19,581	4,594	Macedonia	9,491	1,665	2,019
Singapore	55,826	10,518	4,207	Colombia	9,338	22,091	41,398
Switzerland	50,961	19,507	7,363	Azerbaijan	8,777	8,456	8,264
United States	45,368	1,465,972	286,382	Jordan	8,600	3,799	5,198
Bahrain	42,200	3,673	841	Ecuador	8,458	7,890	13,066
Oman	41,481	6,673	2,542	Dom. Rep.	8,446	4,358	8,824
Denmark	41,260	14,363	5,378	Jamaica	8,320	2,178	2,612
Netherlands	40,688	59,770	16,015	Tunisia	8,128	5,772	9,804
Saudi Arabia	39,294	79,833	23,095	Egypt	7,956	37,571	71,593
Austria	38,803	24,594	8,122	Peru	7,620	11,515	26,521
Ireland	38,762	10,093	4,025	Turkmenistan	7,471	11,636	4,569
Hong Kong	38,451	7,862	6,610	Bos. & Herz.	7,148	2,626	3,912
Sweden	37,422	34,295	9,025	Kosovo	7,138	1,076	1,830
Germany	37,219	230,486	81,591	Namibia	7,015	1,119	1,921
Canada	37,139	186,403	31,501	Ukraine	6,982	87,717	48,604
Belgium	37,075	39,658	10,457	Indonesia	6,807	122,971	217,661
Australia	35,960	69,457	19,867	Albania	6,622	1,613	3,064
Italy	35,147	127,407	57,841	Paraguay	6,588	3,793	5,452
Finland	34,788	24,407	5,217	El Salvador	6,533	2,700	5,802
France	34,390	158,732	62,060	Sri Lanka	6,332	7,331	18,973
Japan	34,190	312,992	126,642	Guatemala	6,125	6,256	12,390
Unit. Kingdom	33,148	142,358	60,066	Mongolia	6,094	2,227	2,485
Cyprus	29,805	1,408	973	China	5,526	1,120,968	1,268,418
Spain	29,434	82,561	42,517	Morocco	5,180	9,892	29,466
New Zealand	29,240	12,180	3,975	Congo	5,065	904	3,332
Israel	25,725	11,519	6,516	Georgia	4,940	3,369	4,334
Slovenia	25,406	4,646	2,010	Angola	4,720	6,949	16,746
Greece	25,367	17,934	10,801	Philippines	4,713	23,033	80,880
Portugal	24,804	17,508	10,306	Bolivia	4,688	3,566	8,668
Malta	24,177	352	394	Armenia	4,460	1,967	3,120
Libya	23,898	9,076	5,492	Yemen	3,849	3,846	19,007
Czech Republic	23,395	27,003	10,332	Honduras	3,809	3,264	6,480
Korea	22,810	127,167	47,167	Pakistan	3,767	56,478	144,810
Trin. & Tobago	21,923	8,803	1,285	Nigeria	3,747	86,100	131,933
Estonia	20,317	3,175	1,395	Nicaragua	3,593	1,873	5,137
Hungary	19,404	17,949	10,159	Moldova	3,250	2,673	3,624
Slovak Republic	19,142	11,544	5,372	Uzbekistan	3,199	34,771	25,394
Russian Fed.	18,346	454,862	145,585	Vietnam	3,147	31,652	79,062
Gabon	18,176	2,406	1,299	India	3,059	359,441	1,087,461
Croatia	18,112	6,937	4,467	South Sudan	2,915	537	7,703
Lithuania	17,508	5,784	3,389	Cote d'Ivoire	2,884	4,652	17,104
Malaysia	16,782	32,673	24,128	Sudan	2,606	8,388	29,785
Poland	16,114	63,573	38,279	Ghana	2,565	5,282	20,189
Chile	15,868	19,762	15,510	Zambia	2,533	5,605	11,412
Latvia	15,738	4,146	2,317	Cameroon	2,486	5,722	17,013
Argentina	15,601	47,624	37,888	Kyrgyz Rep.	2,468	2,718	5,014
Venezuela	15,567	36,434	25,364	Kenya	2,336	10,274	33,288
Mexico	14,536	100,630	105,562	Zimbabwe	2,053	8,415	12,729
Kazakhstan	14,408	37,531	15,785	Myanmar	2,034	11,930	48,184
Turkey	14,384	61,553	65,149	Senegal	1,974	1,755	10,653
Cuba	13,768	8,324	11,106	Bangladesh	1,892	17,234	134,500
Uruguay	13,666	2,728	3,298	Cambodia	1,861	3,539	12,447
Romania	13,640	26,475	21,652	Tajikistan	1,855	2,292	6,581
Iran	13,605	113,367	67,204	Tanzania	1,729	13,673	36,987
Lebanon	12,816	3,337	3,699	Benin	1,653	2,302	7,587
Montenegro	12,240	805	613	Nepal	1,638	8,315	24,044
Panama	12,197	2,190	3,151	Haiti	1,637	2,118	8,836
Brazil	12,192	164,671	179,867	Eritrea	1,516	566	3,755
Mauritius	12,065	665	1,186	Togo	1,251	1,391	5,257
Suriname	11,818	515	480	Niger	813	1,820	12,570
Bulgaria	11,510	10,647	7,926	Ethiopia	785	27,916	71,227
Algeria	11,191	19,515	32,155	DR Congo	667	15,007	52,737
Botswana	11,075	1,431	1,791	Mozambique	659	7,055	19,728
Thailand	10,721	60,940	63,170				

GDP per capita data are obtained from the World Bank World Development Indicators and presented in PPP-based constant 2011 international $. Total final energy consumption data are obtained from the International Energy Agency and presented in Mega tons of oil equivalent. Population data are obtained from the World Bank World Development Indicators and presented in thousands.

Table A2
Correlation of energy consumption per $PPP and GDP per capita PPP for 137 countries.

Country	Corr.	n	Country	Corr.	n	Country	Corr.	n
Ethiopia	−1,000	25	New Zealand	−0,923	25	Montenegro	−0,733	10
South Sudan	−0,998	3	Romania	−0,920	25	Ukraine	−0,708	25
Myanmar	−0,997	25	Croatia	−0,919	20	Namibia	−0,687	24
Nigeria	−0,996	25	South Africa	−0,919	25	Mongolia	−0,684	25
Mozambique	−0,993	25	Denmark	−0,917	25	Cote d'Ivoire	−0,679	25
Mauritius	−0,993	25	Belarus	−0,913	25	Cyprus	−0,633	25
Slovak Republic	−0,989	23	Luxembourg	−0,907	25	Albania	−0,630	25
Germany	−0,987	25	Indonesia	−0,907	25	Georgia	−0,628	25
Tanzania	−0,985	25	Azerbaijan	−0,906	25	Greece	−0,626	25
Poland	−0,984	25	Cuba	−0,902	25	Kuwait	−0,619	20
India	−0,983	25	Vietnam	−0,902	25	Brunei Dar.	−0,606	25
Zimbabwe	−0,982	25	Botswana	−0,895	25	Argentina	−0,598	25
Australia	−0,982	25	Pakistan	−0,894	25	Armenia	−0,528	25
DR Congo	−0,982	25	Turkmenistan	−0,893	25	Tajikistan	−0,503	25
Latvia	−0,981	20	Tunisia	−0,892	25	Costa Rica	−0,485	25
Nepal	−0,981	25	France	−0,891	25	Niger	−0,355	15
Zambia	−0,981	25	Mexico	−0,886	25	United Arab Emir.	−0,337	25
Nicaragua	−0,980	25	Jordan	−0,882	25	Benin	−0,273	25
Bangladesh	−0,979	25	Netherlands	−0,881	25	Italy	−0,262	25
Uzbekistan	−0,979	25	Qatar	−0,880	15	Spain	−0,250	25
Sri Lanka	−0,977	25	Russian Federation	−0,877	25	Togo	−0,234	25
Angola	−0,974	25	Korea	−0,873	25	Bahrain	−0,191	25
Sudan	−0,974	25	Cambodia	−0,865	20	Eritrea	−0,170	20
Finland	−0,973	25	Haiti	−0,858	19	Guatemala	−0,141	25
Estonia	−0,972	20	Macedonia	−0,854	25	Egypt	−0,135	25
Sweden	−0,970	25	Chile	−0,848	25	Lebanon	−0,106	25
Czech Republic	−0,969	25	Malta	−0,847	25	Brazil	−0,094	25
Kenya	−0,968	25	Turkey	−0,846	25	Morocco	−0,081	25
Philippines	−0,966	25	Suriname	−0,841	15	Ecuador	−0,068	25
Hungary	−0,955	24	Hong Kong	−0,832	25	Uruguay	−0,054	25
China	−0,954	25	Kosovo	−0,830	15	Singapore	0,060	25
United States	−0,954	25	Israel	−0,824	25	Portugal	0,077	25
Canada	−0,953	25	Honduras	−0,822	25	Kyrgyz Republic	0,107	25
Slovenia	−0,950	20	Cameroon	−0,819	25	Malaysia	0,148	25
Lithuania	−0,949	20	Gabon	−0,811	25	Jamaica	0,210	25
Norway	−0,948	25	Japan	−0,809	25	Oman	0,305	25
Colombia	−0,947	25	Moldova	−0,800	20	Senegal	0,404	25
Switzerland	−0,942	25	Belgium	−0,792	25	Saudi Arabia	0,496	25
Iraq	−0,942	25	Austria	−0,788	25	Yemen	0,634	25
Ghana	−0,941	25	El Salvador	−0,778	25	Bolivia	0,659	25
Peru	−0,935	25	Serbia	−0,764	20	Iran	0,688	25
Panama	−0,934	25	Kazakhstan	−0,758	25	Algeria	0,703	25
Bulgaria	−0,934	25	Bosnia & Herzegovina	−0,752	21	Thailand	0,819	25
Libya	−0,933	13	Paraguay	−0,749	25	Trinidad & Tobago	0,820	25
Ireland	−0,931	25	Venezuela	−0,747	25	Congo	0,897	25
United Kingdom	−0,923	25	Dominican Republic	−0,745	25			

Technical appendix

Econometric analysis with a linear function of log GDP per capita

We start with a standard EKC regression as in Luzzati and Orsini (2009).

$$logEI_{it} = f(logGDP_{it}) + \mu_i + \rho_t + \upsilon_{it} \quad \text{(B1)}$$

where EI_{it} is log energy intensity of country i in year t, f (log GDP_{it}) is a function of log GDP per capita, μ_i is a country fixed effect capturing time-invariant country specific characteristics; ρ_t is a time fixed effect controlling for yearly shocks that are common to all countries; and υ_{it} is the error term. Further control variables are derived from the literature as described in the main text. We use a linear functional form of log GDP p.c. and run the following fixed effects model to test the relationship between energy intensity and economic development:

$$logEI_{it} = \beta_1 \cdot logGDP_{it} + \gamma \cdot E_{it} + \mu_i + \rho_t + \upsilon_{it} \quad \text{(B2)}$$

The results of these regressions are shown in Table B1. In the first column we report the result of a simple pooled OLS specification, in the second column we add country fixed effects, and in the third column we add time fixed effects. The coefficient of log GDP per capita is negative and highly significant in all three cases, but its magnitude changes when the country and time fixed effects are included. Adding the control variables for the composition of energy consumption changes the explanatory power of the model, but the coefficient of log GDP per capita remains relatively stable. Overall, these regressions are strong evidence for a negative association between GDP per capita and energy intensity. An increase of GDP per capita by one percent is associated with a decrease of energy intensity by 0.62 percent.

Piecewise linear regression

To find the optimal value for the threshold between the two linear models, we use the following numerical procedure: We estimate Eq. (3) for any possible critical value within the range of observations (within 5.8 and 11.8 log GDP per capita) in steps of 0.1. We calculate the likelihood for each model and then pick the critical value for which the model has the largest likelihood (maximum likelihood estimation) (Fig. A1).

Construction of the fisher ideal index

As described in Boyd and Roop (2004) we first calculate a Laspeyres and a Paasche index of energy intensity for structure and efficiency using the following formulas from Boyd and Roop (2004):

Table A3
Aggregate, Structural and Efficiency Index in 2014 based on Fisher Ideal Index Decomposition (1990 = 1).

Country	Total	Struct.	Inten.	Country	Total	Struct.	Inten.
Azerbaijan	0.080	0.964	0.083	Korea	0.733	0.979	0.749
Armenia	0.116	0.857	0.136	Cyprus	0.751	0.560	1.341
Romania	0.212	0.716	0.296	Nigeria	0.752	1.009	0.746
Belarus	0.246	0.917	0.268	Morocco	0.756	0.945	0.800
Bulgaria	0.259	0.593	0.437	Costa Rica	0.759	0.808	0.940
Georgia	0.264	0.902	0.293	Japan	0.772	0.804	0.959
Kyrgyz Republic	0.275	0.796	0.346	Indonesia	0.772	1.042	0.741
Cuba	0.332	1.096	0.303	Italy	0.806	0.833	0.968
Mongolia	0.338	0.881	0.384	Ethiopia	0.811	1.286	0.631
Mauritius	0.375	0.748	0.501	Pakistan	0.817	0.864	0.946
China	0.397	0.994	0.399	Finland	0.858	0.809	1.061
Albania	0.453	0.596	0.759	Kenya	0.887	1.014	0.875
Ukraine	0.465	0.623	0.747	Argentina	0.899	0.881	1.020
Honduras	0.469	1.029	0.455	Tanzania	0.919	1.170	0.785
Tajikistan	0.531	0.776	0.684	Austria	0.920	0.861	1.068
Russian Federation	0.538	0.741	0.725	Venezuela	0.953	0.757	1.259
United Kingdom	0.539	0.809	0.667	Chile	0.962	0.878	1.096
Zimbabwe	0.559	0.896	0.624	Benin	0.970	1.099	0.883
Norway	0.561	1.047	0.536	Panama	1.000	1.300	0.769
Sweden	0.576	0.864	0.667	Brazil	1.020	0.670	1.522
Cameroon	0.581	1.032	0.562	Congo	1.056	1.426	0.741
El Salvador	0.583	1.009	0.578	Dominican Republic	1.058	0.832	1.272
Colombia	0.590	0.807	0.731	Trinidad and Tobago	1.078	1.033	1.044
Mozambique	0.594	1.109	0.536	Algeria	1.156	0.946	1.221
Denmark	0.602	0.841	0.716	Thailand	1.199	0.973	1.233
India	0.621	1.068	0.582	Ecuador	1.201	1.201	1.000
Sudan	0.625	0.461	1.357	Turkey	1.206	0.822	1.467
Ghana	0.643	1.512	0.425	Iran	1.212	1.039	1.167
Macedonia	0.645	0.681	0.948	Senegal	1.226	1.031	1.189
France	0.653	0.831	0.786	Uruguay	1.239	0.857	1.445
Zambia	0.678	0.739	0.918	DR Congo	1.244	1.145	1.087
Australia	0.679	0.874	0.777	Singapore	1.261	0.905	1.394
Botswana	0.683	0.728	0.938	Uzbekistan	1.331	0.906	1.468
Netherlands	0.698	0.753	0.927	Togo	1.360	0.880	1.547
Tunisia	0.711	0.866	0.821	Bahrain	1.511	1.011	1.495
Switzerland	0.717	0.924	0.776	Bolivia	1.671	1.002	1.668
South Africa	0.723	0.764	0.946	Bangladesh	1.685	1.107	1.523
Philippines	0.724	0.978	0.741	Saudi Arabia	1.709	1.125	1.519
Egypt	0.727	1.212	0.600	Nepal	1.997	1.007	1.983
Jordan	0.730	1.006	0.725	Malta	54.549	1.223	44.611
Mexico	0.731	1.081	0.676				

Table B1
Panel regressions. Dependent variable: log energy intensity, Eq. (B2).

	(1)	(2)	(3)	(4)
log GDP p.c.	−0.26***	−0.64***	−0.62***	−0.68***
	(0.007)	(0.012)	(0.017)	(0.016)
E(Industry, %)				0.78***
				(0.079)
E(Transport, %)				−0.35***
				(0.088)
E(Residential, %)				−0.79***
				(0.070)
E(Services, %)				−0.27**
				(0.135)
E(Agriculture, %)				−0.05
				(0.189)
E(Non-energy, %)				1.53***
				(0.144)
Observations	3,238	3,238	3,238	3,238
R-squared	0.284	0.487	0.490	0.595
Country Effects	No	Yes	Yes	Yes
Year Effects	No	No	Yes	Yes

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

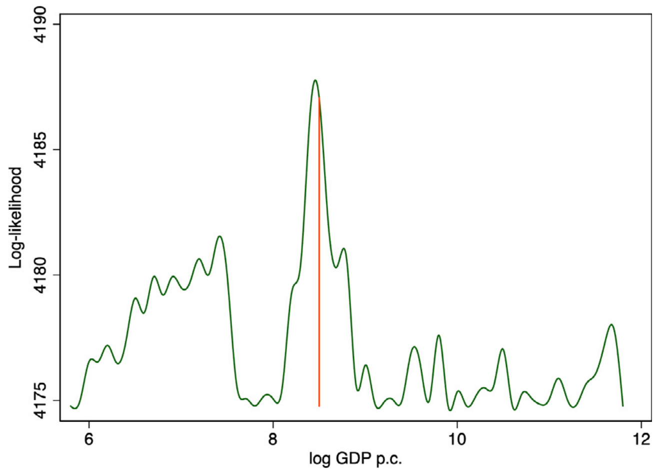

Fig. A1. Likelihood for cut-off in piecewise linear regression.

Laspeyres	Paasche
$L_{Str} = \sum_i S_{i,T} I_{i,0} / \sum_i S_{i,0} I_{i,0}$	$P_{Str} = \sum_i S_{i,T} I_{i,T} / \sum_i S_{i,0} I_{i,T}$
$L_{Int} = \sum_i S_{i,0} I_{i,T} / \sum_i S_{i,0} I_{i,0}$	$P_{Str} = \sum_i S_{i,T} I_{i,T} / \sum_i S_{i,T} I_{i,0}$

S: agriculture, industry and services share of GDP
I: energy intensity
0: first year
T: last year
i: industry, agriculture, service

The Fisher index is the geometric mean of the Laspeyres and the Paasche index:

$$F_{Str} = \sqrt{L_{Str} P_{Str}}$$

$$F_{Int} = \sqrt{L_{Int} P_{Int}}$$

The aggregate Fisher index is the product of the structural part and the intensity part:

$$F_{Total} = F_{Str} F_{Int}$$

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