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Energy and Economic Growth: The Stylized Facts

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Abstract: We summarize what we know about energy and economic growth in a set of stylized facts. We combine analysis of a panel data set of 99 countries from 1971 to 2010 with analysis of some longer run historical data. Our key result is that over the last 40 years there has been a stable cross-sectional relationship between per capita energy use and income per capita with an elasticity of energy use with respect to income of less than unity. This implies that energy intensity has tended to decrease in countries that have become richer but not in others. We also find that over the last two centuries there has been convergence in energy intensity towards the current distribution, per capita energy use has tended to rise, energy quality to increase, and, though evidence is limited, the cost share of energy has declined.

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1. Introduction

Kaldor (1957, 1961) highlighted six "stylized'' facts that summarized the patterns that economists had discovered in national income accounts with a view to shaping the growth models being developed to explain them. Recently, Jones and Romer (2010) introduced a set of "new Kaldor facts" for growth economics. In this paper, we attempt to summarize what we know about energy and economic growth in a similar set of stylized facts with the intention of informing the development of models of energy and economic growth. Though we examine the previous literature, we do not take on faith the facts laid out there. Rather, we carry out a systematic analysis of a global dataset covering the 1971-2010 period and also look at the longer run historical data that are available. This reveals a new set of stylized facts that is sometimes at odds with the received wisdom.

Stylized facts are empirical regularities that can be seen clearly without using sophisticated econometric techniques (Summers, 1991). Stylized facts are not relations that are true in all countries in all periods of time but are statistical tendencies. Such regularities are not necessarily structural relationships. Rather, they may be the outcomes of complex processes. The stylized facts discussed in this paper should, therefore, not be seen as necessarily describing functional relationships between the variables in question. Rather, they are historical characteristics of the data that models of energy and economic growth should be able to reproduce.

Several previous authors have attempted to characterize the stylized facts of energy and growth. Smulders and de Nooij (2003) sought to develop a model of the role of energy in economic growth that was consistent with the main stylized facts concerning energy use and growth. They list four such stylized facts, which they took from Jones (2002). For U.S. data over the period 1950-1998:

1. Energy intensity - the ratio of energy use to GDP - in the U.S. declined at an annual rate of 1.4% on average;

2. Per capita energy use increased at an average annual rate of about 1%;

3. The ratio of energy cost relative to GDP declined at an average of about 1% per annum, though in the 1970s the cost share rose temporarily;

4. The relative price of energy to labor declined. This fact is based on Nordhaus (1992), who shows that the relative price followed a negative trend since at least 1870.

Smulders and de Nooij (2003) showed that there were similar trends for the first two variables in Japan, France, West Germany, and the U.K. for the period from 1960 to 1990.

Kander *et al*. (2013) list several stylized facts for a set of today's developed countries over the past two centuries, though not all of these actually relate to energy. The energy-related facts are that over time:

1. The energy/capital ratio falls;
2. The energy cost share falls;
3. The real price of energy falls;
4. The quality of the energy mix increases; and that
5. In the 20th century energy intensity fell and converged across countries; and
6. There was a clear trend break in the energy services to GDP ratio in the 1970s.

Kander *et al*. (2013) and Smulders and de Nooij (2003), therefore, concur on some of the key features of the data for individual countries, but with the exception of Kander *et al*.'s comment on the convergence of energy intensity across countries, there is nothing in these stylized facts about how the relationship between energy and income varies across countries and no discussion of energy use in developing countries. Several studies have, however, examined these relationships.

Zilberfarb and Adams (1981) examined cross-sections of 47 developing countries in 1970, 1974, and 1976; finding that the elasticity of per capita energy with respect to purchasing power parity (PPP) adjusted income per capita was greater than unity. This implies that energy intensity increases with income. However, this data did not include traditional biomass use.[1] Ang (1987) found that, for a cross-section of 100 countries in 1975, energy intensity (including non-commercial energy) rose with PPP adjusted income. The effect was stronger when he excluded non-commercial energy and when non-PPP income was used there was a decline in energy intensity at high income levels. Medlock and Soligo (2001) examined the patterns of the development of energy use by end-use sector – transportation, industry,

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[1] Traditional energy includes a number of pre-modern forms of energy, such as biomass, wood, animal power or agricultural waste, which are still used in developing countries. Non-commercial energy is usually a synonym for traditional energy.

residential etc. for a panel of data from 28 countries.[2] They only included commercial energy, omitting traditional fuels (see also Galli, 1998). They concluded that energy intensity follows an inverted-U shaped curve with increasing income. They found that the share of industry in commercial energy use declines over time, that of transportation increases, and the share of residential and commercial use rises and then levels out. Judson *et al.* (1999), who examined a much larger sample of countries, found that the household sector's share of aggregate energy consumption tends to fall with income, the share of transportation tends to rise, and the share of industry follows an inverse-U pattern. Schäfer (2005), who, unlike Judson *et al.* (1999), included traditional biomass use, found similar results for the residential and industry sectors and that the share of services in energy use also rises monotonically.

In recent studies, Lescaroux (2011) looks at commercial energy only and uses market exchange rates and finds that energy intensity declines monotonically with income per capita. Jakob *et al.* (2012) examine a panel of 30 developing and 21 developed countries. They investigate the effect of income growth (market exchange rates) on total primary energy use (including biomass) as well as individual fuels and end-use categories for developed and developing countries separately. They find that the elasticity of total primary energy use with respect to income is 0.631 for developing countries and -0.181 (but statistically insignificant) for developed countries.[3]

A mixed picture emerges from these studies of the cross-sectional relationship. Some researchers find that energy intensity increases with income; some find it decreases; and others find that it follows an inverted U. This depends on the way the data are measured, the sample of countries used, and possibly the period of time considered too. There do not appear to be recent cross-sectional studies that both include traditional energy and use PPP adjusted income. Furthermore, studies appear to either investigate the time series behavior of energy and income or the cross-sectional behavior, but do not relate the two and, therefore, the linkages between the cross-section and time series behavior have not been explored.

[2] Sample periods for each of the studies discussed in the following: Medlock and Soligo (2001): 1978-1995; Judson *et al.* (1999): 1970-1991; Schäfer (2005): 1971-1998; Lescaroux (2010): 1960-2006; Jakob *et al.* (2012): 1971-2005.

[3] Using PPP adjusted GDP from the *World Development Indicators* Jakob *et al.* estimate elasticities of 0.626 (standard error, 0.180) and -0.353 (0.474) for developing and OECD countries respectively. However, applying Jakob *et al.*'s method to our panel of data on 99 countries from 1971 to 2010 and employing PPP adjusted GDP from the Penn World Table we find that the elasticity in non-OECD countries is 0.395 (standard error 0.081) and in OECD countries it is 0.479 (0.078).

The purpose of our paper is to determine what robust global patterns exist between energy use and economic growth in an up-to-date data set in both the cross-section and over time, by linking the cross section results to the time series dimension in a panel that is as large as possible in both the cross-section and time-series dimensions. Our data includes non-commercial energy and reports income in PPP-adjusted terms. Our main analysis uses an annual panel data set for 99 countries over the period from 1971 to 2010. Rather than carry out a standard panel regression analysis we look separately at the time series and cross-sectional dimensions of the panel and the relationship between them. We also examine some longer-run time series and cross-sections for the U.S., Canada, and several European and Latin American countries to determine whether the time series relationships appear to hold in the previous century and a half too. We also look at the issue of the cost share of energy for which we only have long-run data for two countries - the United Kingdom and Sweden.

Based on the literature we have reviewed above, we select the following variables and relationships for investigation: Energy use per capita, energy intensity, the energy/capital ratio, energy mix, and the energy cost share. Consistent with previous research, we measure energy use in joules of primary energy use. While it would be interesting to also examine quality-adjusted energy use, construction of such series requires detailed price data and the IEA Database only provides limited coverage of OECD countries. We include non-commercial energy despite greater uncertainty in estimates, because otherwise we would exaggerate the increase in energy use that occurs in the early stages of economic development and give the false impression that the poorest countries have very low energy intensity. We use purchasing power parity adjusted income because we aim to characterize the relationship between energy use and economic activity in each country, which is best compared across countries on a purchasing power parity basis.[4]

Our main conclusions are, first, that we find a stable relationship between energy use per capita and income per capita over the last four decades. The elasticity of energy with respect to income is less than unity. This implies that energy intensity is negatively correlated with income and that decreases in energy intensity are related to economic growth. Energy intensity does not decline and may even increase in the absence of growth. Thus, energy intensity has declined globally as the world economy has grown. Second, there is

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[4] Market exchange rates are appropriate in models of international energy trade or international climate policy, where we want to model countries interacting in a common market.

unconditional convergence in energy intensity over time, both in the recent period and over the last two centuries. This means that energy intensity tends to increase in countries that have relatively low energy intensity for their income level and that there was much greater variation in energy intensity at each given income level in the 19th Century than today. Third, though we have limited evidence, we find that the cost share of energy declines over time. We also show that the energy capital ratio behaves similarly to energy intensity and that energy quality increases with income and over time.

The next section of the paper introduces our methods. This is followed by the analysis of the global dataset for recent decades and examination of some additional long-run historical series. The paper concludes by presenting the stylized facts as they emerge from the data and then discussing their relation to existing literature. An appendix provides details of the data sources and the methods used for constructing the capital stock.

2. Methods

Detailed sources for all data are provided in the Appendix. For our 1971-2010 panel data set, we examine the relationship between energy and economic growth by systematically examining both the cross sectional relationships between energy use per capita (E/P), energy intensity (E/Y), and the energy/capital ratio (E/K) and income per capita (Y/P), as well as the time evolution of these three variables. The purpose of the paper is to link the time series dimension with the cross-sectional patterns, in search of stylized facts. To obtain somewhat more structural relations we could add covariates that are exogenous to the growth and development process such as climate, resource endowments, legal origin, and the age structure of the population etc. in a similar fashion to Stern (2012). But these would still not explain the reasons for the behavior we observe and would move away from pure stylized facts.

As our theoretical motivation is the potential role of energy in aggregate growth, we do not investigate the patterns of change in the sectoral use of energy. Also, our focus is on the relation between energy and output and energy as an input to production and so we do not investigate the behavior of energy prices themselves, for which there is little internationally comparable and easily accessible data. It does seem though that Nordhaus' (1992) finding on the time series evolution of the relative price of energy and labor is true also for other developed countries. This is certainly the case for Sweden (Stern and Kander, 2012).

Furthermore, the price of energy relative to that of output seems to follow a U-shaped trend in the very long run (Pindyck, 1999; Fouquet and Pearson, 2003).

Though we do examine the issue of the convergence of energy intensity and the energy capital ratio over time, we otherwise ignore dynamic issues and, in particular, the large literature on Granger causality between energy and income. Bruns *et al*. (2014) carry out a meta-analysis of this literature finding few robust results with the exception that income causes energy use when energy prices are controlled for.

We summarize the cross-section relations quantitatively by estimating regressions at ten-year intervals using OLS with heteroskedasticity robust standard errors. We compute global time trends in two ways - using the geometric mean of countries and the global aggregate mean. To compute the geometric mean, we first compute energy use, energy intensity, or the energy-capital ratio in each country, take its logarithm, and then weight each country equally to compute the mean of the logarithms. For example, for energy use per capita:

$$\ln\left(E/P\right)_t = \frac{1}{N}\sum_i^N \ln\left(E_{it}/P_{it}\right) = \frac{1}{N}\left(\sum_i^N \ln E_{it} - \sum_i^N \ln P_{it}\right) \qquad (1)$$

where N is the number of countries in our sample. This means that these series are more representative of the patterns seen in individual countries and are less influenced by the largest energy consumers or particularly energy intensive economies. The growth rate of the mean is equal to the mean of the growth rates in each individual country. For presentation purposes we take the exponential of (1) to return to natural units.

We also compute a global aggregate mean by summing energy use across all the countries in our sample and then dividing by total population, total GDP, or the total capital stock. For energy use per capita, the aggregate mean is:

$$\left(E/P\right)_t = \left(\sum_i^N E_{it}\right) \Big/ \left(\sum_i^N P_{it}\right) \qquad (2)$$

This mean is representative of the world as a whole and will be dominated by countries with high total energy use. Here, the growth rate of the global mean is not equal to a simple average of individual country growth rates.

We test for the convergence of energy intensity and the energy/capital ratio across countries using beta and sigma convergence tests (Barro and Sala-i-Martin, 1992; Quah, 1996). We test for unconditional beta convergence by estimating the following regression:

$$\frac{1}{T-1}\left(\ln X_{iT} - \ln X_{i1}\right) = \alpha + \beta \ln X_{i1} + \varepsilon_i \qquad (3)$$

where X is the variable of interest and i indexes countries. T is the final year in the sample and 1 is the first year, that is 2010 is designated as year 40 and 1971 as year 1. The null hypothesis of non-convergence is rejected if $\beta < 0$ (a one-sided test). This test makes the strong assumption that all countries are converging to the same steady state. We also test for conditional convergence, which allows for countries to have different steady states. We base our test on that of Mulder and de Groot (2012), who in turn base their test on that of Islam (1995). We estimate the following regression using the fixed effects panel estimator:

$$\frac{1}{j}\left(\ln X_{i\tau+j} - \ln X_{i\tau}\right) = \alpha_i + \eta_\tau + \beta \ln X_{i\tau} + \varepsilon_{i\tau}\,, \qquad (4)$$

Here the dependent variable is the average of the change in the log of the relevant variable, X, over a period of five years or for the first period in the sample, 1971-1975, four years. Therefore, τ takes the values 1, 5, 10, 15, 20, 25, 30, and 35 and j takes the value of 5 except for the first period where it takes the value of 4. α_i is, therefore, a country fixed effect that makes the assumption that country steady states permanently differ from each other by constant amounts. η_τ is a global time effect that allows for the global steady state to evolve with technological progress as in Islam (1995).

Dalgaard and Vastrup (2001) show that the choice of dispersion indicator can dramatically affect whether sigma convergence is found or not. So, to test for sigma convergence, we plot the development of the cross-sectional dispersal of our variables using both indicators examined by Dalgaard and Vastrup (2001). These are the cross-sectional standard deviation of the logarithm of our variables and the coefficient of variation of the level of the variables. Decreasing dispersion indicates sigma convergence. Additionally, to formally test whether the cross-sectional variance changes over time, we compute the Carree and Klomp (1997) test statistic, which is distributed as chi-squared with one degree of freedom:

$$T_2 = (N - 2.5)\ln\left(1 + 0.25\frac{(\hat{\sigma}_1^2 - \hat{\sigma}_T^2)^2}{\hat{\sigma}_1^2\hat{\sigma}_T^2 - \hat{\sigma}_{1T}^2}\right) \quad (5)$$

where N is the number of countries, $\hat{\sigma}_t$ is the variance of ln$X$ across countries in year t and $\hat{\sigma}_{1T}$ is the covariance of ln$X$ in years 1 and T. Again, the null hypothesis is non-convergence.

3. Analysis of Global Dataset 1971-2010

a. Descriptive Statistics

Table 1 presents some descriptive statistics for our 1971-2010 dataset – the levels of our main variables in 1971 and 2010 and the intervening growth rates. The Table gives statistics for the distribution of the variables across countries and the global aggregate. Like GDP per capita, energy use per capita and the two ratios vary by around two orders of magnitude across countries. The energy/capital ratio is the most dispersed of the variables but its standard deviation almost halved over the four decades.

The level of the global aggregate is between the median and the mean of countries for all our variables showing the influence of both high-income countries and large middle-income countries such as China and India on the distribution. The mean, median, and global aggregate growth rate of GDP per capita are similar but the median growth rate of energy use was less than the mean of countries and the global aggregate lower still. Therefore global aggregate energy intensity and the energy capital ratio declined much faster than they did in the typical country.

b. Energy use per capita

i. Time series

Figure 1 shows that the geometric mean of energy consumption per capita has increased more or less continuously over the four decades. The average annual rate of change, which is equivalent to the mean of the average annual growth rate over 39 years of each individual country, is 1.35%. The annual growth rate of the global aggregate mean of world energy use per capita was only 0.72% but the global aggregate mean was always higher than the geometric mean of countries. This is because energy consumption grew more slowly in high-income countries, whose economies also grew slower than average, and which accounted for the majority of energy use in our sample at the beginning of the 1970s. Also, the growth rate of the global aggregate mean increased over time and that of the geometric mean of countries slowed down. This is probably explained by the increasing weight of rapidly growing large middle-income countries, including China, over time.

Exceptions from the pattern of increasing per capita energy consumption over time include the United States (-0.24%), the following European countries: Albania (-0.28%), Denmark (-0.16%), Luxembourg (-1.11%), Romania (-0.64%), and the United Kingdom (-0.35%), as well as a number of African and South American countries, such as Congo (-0.22%), Cameroon (-0.16%), Gabon (-0.96%), Haiti (-0.81%), Mozambique (-1.15%), Nicaragua (-0.11%), Sudan (-0.74%), Zambia (-0.71%), and Zimbabwe (-0.37%). In Nicaragua, Zambia, and Zimbabwe, GDP per capita declined over the period, and so we would expect energy intensity to increase, in Haiti there was almost no improvement in income per capita.

ii. Cross-section

Figure 2 shows that the logarithm of energy use per capita increases with the log of income per capita in the most recent year in the sample, 2010. As shown by the fitted regression line the relationship is fairly linear or maybe convex down.[5] As shown in Table 2, a similar relationship can be found in previous years too.

Cross section regressions carried out at decadal intervals provide "snapshots" of the relation between primary energy consumption and income per capita thus enabling us to investigate how the movement over time relates to cross sections. All results in Table 2 show a highly significant slope. Looking first at the full sample, we see that the elasticity is remarkably consistent over time at around 0.7. This implies, as we will see below, that energy intensity declines moderately with increasing income with an elasticity of around -0.3.

Between 1971 and 1980 the intercept decreased, though the difference is not statistically significant. Somewhat surprisingly there is no further decrease in the intercept over time. If the cross-sectional relationship remains stable over these intervals, then the movement in the energy per capita variable will be only due to countries changing their "position" on the cross sectional dimension - that is getting richer.

[5] Note that when market exchange rates are used instead of PPP-adjusted exchange rates, the picture changes somewhat. Then energy use per capita is a concave or S shaped function of income per capita (Medlock and Soligo, 2001; Lescaroux, 2010).

Dropping the two lowest income countries – Zimbabwe and DR Congo - which both experienced declining income per capita over the period and are relatively energy intensive, increases the regression slope and R-squared. There is also more evidence for a decline in the intercept though it is still not a statistically significant change.

The coefficient of determination increases over time – the significant variation around the main trend in Figure 1 was greater in the past. But variation in energy use at any level of income remains important. As shown by the bubble markers in Figure 2, the two largest economies – the United States (top right) and China (middle of graph) – use more energy per capita than the norm for their income level as predicted by the regression fit. The largest bubble to the left of China is India, which uses less energy per capita than the norm for its income level.

Of course, these results are just a general tendency and individual countries show a variety of behaviors. It is true that there does seem to be "decoupling" in some developed countries such as the U.K., which has had flat energy use per capita throughout the sample period. It migrated from the left-hand side of the band of data points in Figure 2 to the right-hand side over this period. In other words, in 1971 it was a high energy user for its income level and in 2010 a low energy user for its income level. But our results show that this decoupling has occurred in an insufficient number of countries to change the overall pattern.

c. Energy Intensity

Energy intensity is the ratio of energy use to GDP and can be seen as simply a different way of presenting the energy-GDP relationship data presented above. But examining energy intensity dynamics allows a deeper investigation of the relation between energy and income as it evolves over time. Also, energy intensity is a very commonly referenced ratio, which is widely used as an, albeit crude (Ang, 2006), proxy for energy efficiency and is, therefore, worth examining separately.

i. Time series

Figure 3 shows the development of the geometric mean of energy intensity and the aggregate average world energy intensity over time. Again there is a notable difference between the two series. The annual rate of decrease of the former is -0.40% and of the latter -1.07% per annum. The global aggregate mean energy intensity declines fairly consistently over time but there are important variations across countries. The reason for the discrepancy between the two trends is that there are negative correlations in the sample between the rate of change in energy intensity and the size of the GDP and the level of total energy use. So, the aggregate mean is dominated by large countries, which mostly had declining energy intensity. These include most developed countries and China (from 1979) and India (from 1991). There was much more variability in trend among smaller economies. As we will see below, in the first half of the period there was strong convergence in energy intensity with energy intensity rising in roughly the same number of countries as it was falling. Therefore, the geometric mean of energy intensity did not decline in the first half of the period. In the second half of the period, there was mainly convergence from above with energy intensity falling in most countries, but especially in countries with high initial energy intensities.

ii Cross-section

Figure 4 shows a cross sectional snapshot of energy intensity mapped against real income per capita as of 2010. Energy intensity declines with higher income per capita.[6] We do not, however, find any relationship between the growth rate of energy intensity and the level of income per capita (Figure 5).[7] However, as can be seen in Figure 6, there is a negative relationship between the growth rate of energy intensity and the growth rate of income per capita, meaning that faster growing countries also have faster declining energy intensity. Energy intensity does not decline in the absence of economic growth. In fact, the intercept in Figure 6 is positive ($p = 0.04$) so that energy intensity tends to increase when economic growth is zero.

Table 3 presents the results of cross-section regression results at decadal intervals. As expected from the discussion of energy use per capita above, there is a significant negative correlation between energy intensity and GDP per capita. This implies that, at least in the last four decades, at any point in time richer countries tended to have lower energy intensity than poorer countries with an elasticity with respect to income of between -0.25 and -0.3. When we drop Zimbabwe and DR Congo, there is still a significantly negative relationship between income per capita and energy intensity, though both the slope and R-squared are lower.

[6] Research shows (e.g. Banks *et al.*, 1997; Fouquet, 2014) that the income elasticity of consumer energy demand is less than unity though in the 18th and 19th Centuries it may have been unity (Fouquet, 2014).
[7] We estimated a regression of the growth rate on the log of initial GDP per capita obtaining a slope coefficient of 0.0017 with a standard error of 0.0016 ($p = 0.31$).

As was also implied by our regressions of energy use per capita on GDP per capita, the relationship between energy intensity and GDP per capita is fairly constant over the past forty years with little consistent change in the slope or intercept. This implies that the decline in global energy intensity over time has been due to countries getting richer, thus moving from the top left to the bottom right of Figure 4 over time. As the elasticity of energy intensity with respect to income per capita is less than unity in absolute value and the overall relationship has not shifted down significantly over time, energy use per capita has increased consistently over time as economies have grown (Figure 1).

It is likely that either technological or structural change or some combination of the two is involved in the decline of energy intensity as countries' income increases. Existing research shows that technological change within industries explains more of the decline in energy intensity globally than does broad structural change (Stern 2011, 2012; Henriques and Kander, 2010; Mulder and de Groot 2012, Voigt *et al*., 2014). Our results show that such technological change must be strongly correlated with the technological change that drives economic growth so that improvements in energy intensity come in tandem with increases in GDP as there is no general improvement in energy intensity that is common to all countries whether they are growing or not.

iii Convergence

Despite the general global decline, energy intensity has notably increased in a few South-American countries and in many African and Middle Eastern countries. In a few sub-Saharan African countries, including Zimbabwe, Côte d'Ivoire, Congo, Nigeria, and Togo, GDP per capita declined over the period, and so based on the cross-sectional relationship described above we would expect their energy intensity to increase.[8] But in other countries, this was not the case, yet energy consumption increased faster than GDP per capita. These countries are mostly in North Africa and the Middle East including Algeria, Bahrain, Jordan, Lebanon, Iraq, Morocco, Oman, Syria, Tunisia, and Turkey or in Latin America and the Caribbean including Bolivia, Ecuador, Mexico, Trinidad and Tobago, and Venezuela. All of these Latin

[8] The effect on energy use of a temporary recession in GDP – for example in the recent global recession in 2008-9 may be quite different to the effects of a long-term decline in the productive capacity of the economy seen in some developing countries. The effect of recessions on energy use and greenhouse gas emissions is an under-researched topic (see Jotzo *et al*., 2012; York, 2012). Jotzo *et al*. (2012) find that energy intensity declines fastest at the peak of the economic cycle just before a recession. It declines slowest or increases at the beginning of the recovery after the recession.

American and Caribbean countries and some of the Middle Eastern countries are oil producers. Cheap energy and growth of the energy intensive petroleum sector might explain the rising energy intensity in these countries. However, the majority of these countries also had relatively low energy intensity for their income level in 1971, so that they are converging from below towards the average level of energy intensity for countries at their income level. Table 4 presents the results of the unconditional beta convergence test (equation 3) for the energy intensity ratio. The rate of convergence is slow – only 1.4% per year – but the coefficient is highly significant. We, therefore, find strong evidence for unconditional beta convergence. Figure 7 depicts this relationship, showing clearly that energy intensity growth is lower the higher initial levels of energy intensity are. Table 4 also presents results for conditional convergence. The rate of conditional convergence is 4% per annum – around three times the unconditional rate.

To test for sigma convergence, we calculate the cross sectional standard deviation of the log E/Y ratio and the coefficient of variation of the level of the E/Y ratio in each year. The cross sectional standard deviation shows a downward trend until the early 1980s (Figure 8), after which it fluctuates around a constant or possibly slightly increasing level. By contrast, the coefficient of variation declined until the early 1990s and then increased. However, the picture is very different when we drop the two low-income, declining, energy intensive economies of Zimbabwe and DR Congo, which are on the top left of Figure 4. Now, the coefficient of variation continues to decline throughout the sample period. Removing the two outliers has similar but less pronounced effects on the standard deviation. It too, now declines throughout the entire period. As in economic growth models, convergence is probably conditional on countries experiencing economic growth. Stern (2012) finds that an estimate of underlying energy efficiency also converges across countries over time and that countries that diverged mostly did so because their GDP per capita was declining rather than growing.

We also formally test for sigma convergence using the test statistic (5). This statistic has a value of 2.80 ($p = 0.094$) and so we cannot reject the null hypothesis of sigma non-convergence at the 5% level, but we can reject it at the 10% level. Dropping observations for Zimbabwe and DR Congo results in a test statistic of 8.25 ($p = 0.004$).

All our tests, therefore, indicate that energy intensity converged. Our findings on beta convergence are similar to those of Liddle (2010) for a 111-country sample, and Mulder and de Groot (2012) for 18 OECD countries. For sigma convergence, our results are also similar to the findings of Ezcurra (2007) and Liddle (2010), who both find that the greatest amount of sigma convergence occurred in the 1970s. On the other hand, using a pairwise cointegration test for conditional convergence, Le Pen and Sévi (2010) rejected the global convergence hypothesis for a panel of 97 countries. Previous work discussed by Le Pen and Sévi (2010) had mostly found convergence of energy intensity among developed economies but not in samples of both developed and developing countries.

d. Energy/Capital

The energy intensity of a country does not only depend on the level of energy-related technology, but also on climatic conditions, the structure of the economy, and other variables (Stern, 2012). The energy-capital ratio might be a better aggregate level indicator of pure energy efficiency (Stern, 2012; Kander *et al.*, 2013). If the elasticity of substitution between capital and energy is zero and there are no differences in energy quality across countries or industries then this ratio should only reflect differences in technology. In reality the elasticity of substitution is greater than zero but less than unity (Koetse *et al.*, 2008; Stern and Kander, 2012) and there are substantial differences in the quality of energy used as described below. Therefore, neither energy intensity nor the energy/capital ratio is an unbiased estimator of economy-wide energy efficiency. On the other hand, studies that attempt to estimate energy efficiency using econometric (e.g. Stern, 2012) or decomposition (e.g. Voigt *et al.*, 2014) techniques also must make strong identifying assumptions.

i. Time series

As shown in Figure 9, the geometric mean of the energy/capital ratio decreased over time at an annual rate of -0.10% but the aggregate mean energy/capital ratio decreased more rapidly, at an average of -0.81% per annum. This difference is explained by the tendency of the largest economies in terms of energy use or income to have a declining energy capital ratio on average over the period. The reason that both these time trends decline more slowly than do the time trends for energy intensity, despite there being a stronger negative cross-sectional relationship between the energy/capital ratio and income per capita (Table 5) is because convergence from below is stronger and more persistent over time for the energy/capital ratio than for energy intensity. Compared to energy intensity, there was much more variability in trend among smaller economies with a rising energy/capital ratio in many developing countries, particularly in Africa and in Latin America.

ii. Cross-section

Figure 10 plots the cross-sectional snapshot of energy/capital against real income per capita in 2010. There is a negative correlation between the variables, which is also supported by our cross sectional regressions in Table 5. The elasticity is around -0.4, which is a bit more negative than that for energy intensity. Movements in both the slope and intercept over time are statistically insignificant. This suggests that the global decline in the energy/capital ratio is also largely due to countries becoming wealthier rather than due to shifts in the cross-sectional relationship. The coefficient of determination increases over time showing that the variance around the regression line decreases. The results for 1971 might be biased by the low accuracy of our estimates of the initial capital stock. Dropping the observations for Zimbabwe and DR Congo again reduces the slope and the R-squared a little.

iii Convergence

We find empirical evidence for unconditional beta convergence of the energy/capital ratio (Table 6). The coefficient on the natural logarithm of initial E/K is negative, indicating unconditional convergence at a rate of 1.5% per annum. This can be clearly seen in Figure 11 as well. Table 5 also presents results for conditional beta convergence. The rate of conditional convergence is 3.3% per annum – just over twice the unconditional rate. The cross-sectional standard deviation shows a downward trend over the examined period (Figure 12). It is very similar to that for energy intensity but shows stronger convergence over time. On the other hand, the coefficient of variation is very high and does not show convergence. However, as in the case of energy intensity, when we drop observations for Zimbabwe and DR Congo the coefficient of variation shows strong convergence. The Carree and Klomp (1997) test statistic is 14.902 ($p = 0.0001$), allowing us to strongly reject the null hypothesis of sigma non-convergence.

e. Energy Mix/Energy Ladder

Figure 13 shows the average mix of fuel types for a country in each of five income quintiles in 1971 and 2010. This illustrates the cross-sectional relationship between energy mix and income per capita and how that has changed over time. An important caveat is that due to economic growth the composition of countries in each quintile and the maximum and minimum income for those quintiles has changed from 1971 to 2010. In particular, the first quintile in 2010 not only includes the income range for the first quintile in 1971 but much of the range of the second quintile in 1971. Similarly, the second quintile in 2010 more closely matches the income range of the third quintile in 1971, the third quintile in 2010 more closely matches the fourth quintile in 1971, and the lower end of the fourth quintile in 2010 is close to the lower end of the fifth quintile in 1971. When this shift of quintiles is taken into account there has been less shift in the pattern over time though both natural gas and primary electricity have gained share from oil. This shows structural change taking place across all income levels, reducing the dependency of economies on crude oil.

There are some apparent anomalies in Figure 13. For example, the coal share of total energy use increases slightly from the fourth to the fifth quintile. This is largely due to the mix of countries in these quintiles. The top quintile includes the United States, most Western European countries, Australia etc. The fourth quintile in 2010 included such countries as Mexico, Malaysia, Greece, and New Zealand that do not have large coal endowments. The same pattern over time is shown in Figure 14. The share of oil has declined over time as the shares of primary electricity and natural gas have increased. This Figure also shows an increase in the share of coal. This is because of the growth of coal use in China and to a lesser degree India that have a large weight in total global energy use but little effect on the country averages in Figure 13. This data differs slightly from that presented in the Global Energy Assessment (Grübler *et al.*, 2012) because due to data availability our sample does not cover all countries. The most important countries that we exclude are Russia and other former members of the Soviet Union and Saudi Arabia and some other Arab countries.

We note that while the share of oil in total energy usage is shrinking, that does not mean that the actual amount consumed in joules has decreased. In general, with the probable exception of draft animal power, the global use of each energy carrier has not declined despite the shares of some falling as energy transitions took place.

Returning to the cross-sectional relationship between energy mix and income, the following tendencies are obvious. The share of biomass declines and the share of natural gas and primary electricity increases. The share of oil first increases and then decreases. This largely matches the “energy ladder” hypothesis that as incomes rise, the shares of higher quality - more productive, cleaner, and more flexible (Cleveland *et al.*, 2000; Stern, 2010) - energy carriers increase (Burke, 2013), though steps may be skipped in individual countries (Rubio and Folchi, 2012). Burke (2013) carried out a detailed quantitative analysis of the energy mix-income relationship. Based on an econometric analysis of 134 countries for the period 1960–

2010 that controls for endowments of natural resources and other factors, he shows that economic development results in an overall substitution from the use of biomass to energy sourced from fossil fuels, and then increasingly towards primary electricity. The process results in the carbon intensity of energy evolving in an inverse-U manner as per capita incomes increase.

4. Long-Run Historical Evidence

In this section, we investigate the historical patterns of energy use and economic growth, and check whether these patterns are different from those of the past forty years. These longer-term trends mostly confirm our results for recent decades. Long-run historical time series for the variables considered above exist for several countries including Sweden, Spain, Italy, the Netherlands, the U.S., Canada, England and Wales (Henriques, 2011), Argentina, Brazil, and Uruguay (Rubio and Folchi, 2012; Yañez *et al*., 2013). While there are historical observations on energy prices (Fouquet and Pearson, 2003), energy quantities for traditional energy use in the pre-industrial era must always be reconstructed. Therefore, data are very uncertain for the earlier part of each series.

Gales *et al*. (2007) find that energy use per capita in Sweden, Spain, Italy, and the Netherlands was flat prior to the take off of rapid economic growth. After that, it rose strongly in all four countries before slowing after the oil price shocks in the 1970s. Figure 15 shows per capita energy use in the U.S. and several European and South American countries from 1800 or the earliest date available till the present.

The energy histories of the U.S. and Sweden are somewhat similar, though the U.S. level of energy use in 1800 was twice that of Sweden and has always remained higher. Up till 1875, both countries had fairly flat energy use per capita. Then, while energy use per capita approximately quadrupled in Sweden from the late 19th century to the late 20th century it less than tripled in the U.S. In both countries, energy use per capita has been essentially flat since the early 1970s. By contrast, in England and Wales per capita energy use rose fairly continuously till 1913 after which it has fluctuated. Of course, modern economic growth commenced in the 18th Century in the UK and only after 1850 in Sweden (Stern and Kander, 2012). While Sweden and England and Wales had similar levels of energy use per capita in 1800, by the later 19th century England and Wales reached U.S. levels of per capita energy use. Southern European countries such as Spain and Italy have seen significant increases in their per capita energy usage in the past forty years, yet they have never exceeded the per capita energy consumption level of the U.S. around 1800. South American countries such as Argentina are currently at levels comparable to Sweden in the 19th Century.

While energy use per capita has been increasing in the Southern European and South American countries in our sample, in Sweden, the U.S., and England and Wales energy use per capita has been essentially flat since the early 1970s and in England and Wales U.K. since the First World War. How can we reconcile these periods of flat energy use with the cross-sectional relationship between energy use per capita and GDP per capita discussed in Section 3, above? As we will show below, these countries have been converging in energy intensity from above. In the post-1970 period, England and Wales has gone from being one of the most energy intensive countries for its income level to one of the least.

Figure 16 presents the history of energy intensity versus income per capita for the same set of countries and years as Figure 15. Also included is the distribution of energy intensity in 2010.[9] The history of Sweden, Brazil, and Uruguay is within the current distribution of energy intensity by income, though Sweden does start a little above the current distribution. England and Wales and the U.S. are greater outliers from the current distribution in the 19th Century, but first England and Wales and then the U.S. converge to this current distribution. Spain and Italy commence their energy intensity paths below the current distribution and converge to it over time. This behavior suggests that the current distribution is a long-run attractor, but in the 19th century there was a much more dispersed distribution of energy intensity and there has been convergence over the long run. In general, both colder (e.g. United States, Sweden) and more energy abundant countries (e.g. US, UK, Brazil) had higher energy intensities in the 19th Century but these differences between countries have become smaller over time. There was also a noticeable rise in energy intensity in England and Wales in the 19th Century. This might be due to the heavy reliance of the UK on coal, a lower quality fuel, in its period of industrialization.

We also examined the cross-sectional relationship between energy intensity and real income per capita for all countries that have available data in 1870, 1890, and 1937. We estimated cross-sectional regressions equivalent to those in Table 4. The results (Table 7) partially confirm the negative relationship between energy intensity and income per capita that we found in the data from recent decades. The first group of ten countries - Canada, France,

[9] Because of minor differences between the historical GDP dataset we use and the Penn World Table version 7, the time series do not always end at a 2010 data point. We decided to preserve the integrity of both datasets rather than attempt to exactly align them.

Germany, Italy, the Netherlands, Portugal, Spain, Sweden, the U.K. and the U.S. - show a positive but marginally significant (p=0.096) relationship between the log of energy intensity and the log of real income per capita in 1870 with an elasticity of 0.68. This would at first glance indicate that higher income was accompanied by higher energy intensity in the 19th Century. Adding seven Latin American countries in 1890 and an additional eight in 1937 to this sample decreases, but does not change the positive relationship (elasticities of 0.501 (p = 0.023) and 0.369 (p = 0.023), respectively).

However, it seems that these results are predominantly driven by the original (European and North American) set of countries, especially by the United States, the United Kingdom and Canada, which all have high GDP per capita levels and until recently very high energy intensity. Excluding these early industrializers from the sample, results in a negative relationship in both 1890 (-0.261, p = 0.206) and 1937 (-0.463, p = 0.002). Similar results are found in 1937 for just the countries added in that year (-0.656, p = 0.061) and for just the countries added in 1890 (-0.648, p = 0.007).

The choice of sample is, thus, very important. While our dataset of 99 countries shows a negative relationship between energy intensity and income per capita, the early-industrialized group maintains a positive relationship also during the past 40 years (Table 7, first column). Despite the great decline in energy intensity in both the United States and the United Kingdom over the past two centuries, the US is still more energy intensive that the UK. Whether the difference between the early industrialisers and other countries is simply the result of the differences in climate and resource endowments between them and other countries or something more fundamental deserves further investigation in the future. The countries added in 1890 have an insignificant slope from 1971 to 2010 (Table 7, Column 3), while the countries added in 1937 have a negative and some times very significant slope (Table 7, Column 5). All these samples are very small.

The pattern of changes in energy mix over longer periods simply extends the pattern we see across income groups in recent decades. The transition from traditional fuel to coal took place in the U.K. from the mid-16th Century till 1900 (Fouquet and Pearson, 2003). This transition occurred from 1850 in the Netherlands and the U.S. and around the turn of the 20th century in Sweden, Italy, and Spain (Gales *et al.*, 2007; Schurr and Netschert, 1960).

Long-term data on the energy cost share is only available for two countries (Figure 17). In Sweden the ratio of the value of energy to GDP has declined consistently over time (Kander, 2002; Stern and Kander, 2012). When expressed as the share of the cost of energy in the cost of energy, capital, and labor, the share has declined from around 35% in 1800 to 11% in 2009. Data for England and Wales also show a declining cost share over time from as high as 23% of total costs in 1800 to 8% today (Gentvilaite *et al.*, in press). Stern and Kander (2012) interpret the decline in the energy cost share over time as indicating that the elasticity of substitution between energy and capital and labor is less than unity.

As mentioned in the Introduction, Nordhaus (1992) found that the price of energy relative to the price of labor had declined over time. Data from Sweden (Stern and Kander, 2012) confirm this. In Sweden, the price of energy relative to output remained fairly constant over two centuries while real wages rose consistently.

5. The Stylized Facts

In this section, we summarize the evidence, presenting the stylized facts as they emerge from our data. We find evidence for the following stylized facts of energy and economic growth:

1. A stable relationship between energy use per capita and income over the last four decades with an elasticity of energy with respect to income of less than unity. This implies the following:

    a. Increasing energy use per capita over time as incomes grow. Yet energy use per capita varies widely across countries despite a reduction over time in the variability at any given level of income. It is true that there does seem to be "decoupling" in some developed countries, but it has occurred in an insufficient number of countries to change the overall pattern.

    b. Decreasing energy intensity with income and over time in terms of the global mean. Energy intensity declines moderately with increasing income with an elasticity of around -0.3. Our results suggest that energy intensity declines over time simply because countries are getting richer rather than because of a shift down over time of the relationship between energy use and income per capita. This also implies that over the past 40 years richer countries tend to have lower energy intensity than poorer countries. Based on data from far fewer countries, we found that the elasticity of energy intensity with respect to income was positive in the 19th Century. However, this result is due to a small number of countries, which have also maintained a positive relationship between energy intensity and income per capita among themselves in recent decades. So this does not negate our main result.

c. The growth rate of energy intensity is negatively correlated with the growth rate of income. Also, in the absence of growth, energy intensity does not improve.

2. Convergence in energy intensity and the energy capital ratio over time both in the recent period and over the last two centuries. Both unconditional and conditional beta convergence tests are highly significant. Sigma convergence tests are strongly affected by outliers with declining economies. Removing these outliers, we find strong sigma convergence too. This results in energy intensity and the energy/capital ratio tending to increase in less energy intensive countries. Many of the seemingly idiosyncratic trends in individual countries can be understood as part of a global convergence. There is also strong historical evidence for convergence in energy intensity over the last two centuries from both above and below to the energy intensity distribution we see today. There was much greater variation in energy intensity at each given income level in the 19th Century than today.

3. The energy/capital ratio declines with income and over time with the elasticity with respect to income being a bit more negative (-0.4) than for energy intensity (-0.3). This suggests that improving energy efficiency mostly drives the decline in energy intensity but that there are also some other factors that increase energy intensity at high income levels. The energy/capital ratio has been declining over time, however, there are some countertrends in Africa and South-America. Nearly all countries with increasing energy intensity have an increasing energy/capital ratio, but in addition to that, low or fluctuating investment rates in physical capital have resulted in fluctuating capital stock in a number of countries, which have a decreasing energy intensity ratio, but increasing energy/capital ratio.

4. The cost share of energy declines over time. However, we only have empirical evidence for three countries – Sweden, the U.K, and the U.S. If the elasticity of substitution between energy and capital-labor is less than unity and effective energy per effective worker increases over time then the cost share will go down (Stern and Kander, 2012). It seems likely that this characterizes the growth process, but this stylized fact is still more of a prediction than a proven regularity. Based on the literature reviewed in the Introduction, the relative price of energy to output follows an inverted U shape path and

the price of energy relative to the price of labor falls.

5. Increasing energy quality with income. In general energy carriers do not decline in actual use when their share falls as an energy transition takes place. Due to the structural change of economies the relative importance of oil has been falling at all income levels over recent decades.

6. Discussion

The stylized facts laid out in the previous section will need to be taken into account in future studies of the relationship between energy use and economic development. Some of our findings confirm the existing literature, whereas others conflict with previous findings. Our finding that there is no general decoupling between growth and energy use in developed countries contrasts with research that shows such a general decoupling (e.g. Jakob *et al.*, 2012), which we do not find in our larger dataset. In fact, when we re-estimate Jakob *et al.*'s model with our data we find a higher elasticity of energy use with respect to income in the OECD countries than in the non-OECD countries. Our findings on the relationship between energy intensity and income contrast with most (e.g. Medlock and Soligo, 2001) but not all (e.g. Lescaroux, 2011) of the literature that omits non-commercial energy use, but also with earlier cross-sectional research that includes traditional biomass (e.g. Ang, 1987).

We extend the results of Gales *et al.* (2007) and Kander *et al.* (2013) who find convergence in energy intensity across economies in the long run with a trend to lower global energy intensity, by combining some of the data used in those studies with historical data from Latin America.

Our convergence results are similar to previous research using beta and sigma convergence such as Liddle (2010) and Ezcurra (2007) but contrast with research using cointegration tests (e.g. Le Pen and Sévi, 2010). Cointegration seems to be too strict a criterion to capture the notion that countries are converging.[10]

As far as we know, we are the first to present extensive cross-country evidence on the energy/capital ratio.[11] We find a slightly stronger negative relationship between income per

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[10] Le Pen and Sévi's (2010) test if the difference in energy intensity between countries is stationary around a constant. However, if stochastically trending time series have strong and appropriately sized drift terms, they may tend to converge during the period of observations even if they do not cointegrate according to this test.
[11] Kander *et al.* (2013) present historical data for a number of European countries.

capita and this indicator than we found for energy intensity but we find stronger convergence. This seems to be why the average energy/capital ratio declined more slowly over time than energy intensity did. There are more countries with positive trends in the energy capital ratio that are converging from below.

We confirm the well-known stylized fact of the energy ladder – energy quality increases with income (Burke, 2013). We also show that for England and Wales and Sweden the energy cost share declined over the last two hundred years. Our evidence on the energy cost share is extremely limited and we would also have liked to be able to present indicators using quality adjusted energy indices. To extend research in both these areas requires good databases on energy prices across a broad range of countries. This should be a priority for energy economics research.

Our findings also pose a challenge to ambitious policies that aim to reduce energy intensity at rates that are far faster than historical norms. We find that energy intensity has improved far slower than the rate of economic growth and so energy use tends to increase with growth. Furthermore, in the absence of growth there are no improvements in energy intensity on average. Therefore, ambitious energy efficiency policies will have to break this status quo in a dramatic way.

Appendix: Data Sources

Our main analysis is based on a balanced panel dataset for 99 countries covering the period 1971 to 2010. We use a balanced panel dataset so that changes in the sample means over time are not distorted by changes in the sample composition. Primary energy consumption data are from the International Energy Agency database and are measured in TJ. For the analysis of energy mix we use five energy carriers: coal, oil, natural gas, primary electricity, and biomass. We, therefore, aggregated together some of the energy carriers as follows: “Oil” is the sum of “crude, NGL, and feedstocks” and “oil products”. “Primary electricity” is the sum of “nuclear”, “hydro”, “geothermal”, “solar, wind, and other”, and “electricity”, “Coal” is the sum of “coal” and “peat”. While there is low uncertainty about data on fossil fuel and primary electricity use, biomass use is highly uncertain and data quality is particularly low for Africa (IEA, 2013). In many cases, the IEA estimates biomass use in years other than the benchmark year of 1995 using a variety of methods (IEA, 2013).

Real purchasing power parity adjusted GDP per capita, population, and the investment share of GDP are sourced from the Penn World Table, version 7.1 (Heston *et al*., 2012). We use the series "rgdpch" for per capita GDP, which is computed using a chained index and measured in constant 2005 international dollars. Our dataset unfortunately excludes the successor states of the former Soviet Union and a few Eastern European countries due to lack of data for the first two decades of the sample. Albania, Bulgaria, Hungary, Poland, and Romania, represent this geo-political region in our sample. Also excluded are several North African and Middle Eastern countries. Kuwait, Libya, Qatar, Saudi Arabia, UAE, and Yemen had to be dropped from our sample due to missing economic data for the first two decades in this edition of the Penn World Table. We still include several countries from this region including several countries with important oil production such as Algeria, Bahrain, Iran, Iraq, and Oman.

We estimate the physical capital series using the perpetual inventory method. In order to remove the effects of short-run economic fluctuations on the estimate of the initial capital stock, we use the regression approach of Nehru and Dhareshwar (1993). We estimate the following regression for each country, indexed by i, using annual data from 1971 to 2010 (indexed by t):

$$\ln I_{it} = \alpha_i + \beta_i t + \varepsilon_{it} \tag{A1}$$

where I is investment computed using the investment share series in the Penn World Table multiplied by real GDP in 2005 constant prices, t is a linear time trend, and ε is the error term. $\hat{\alpha}_i$ is then the fitted estimate of the log of investment in 1970, where a hat indicates an estimated parameter. Then, following Berlemann and Wesselhöft (2012), we estimate the capital stock at the end of 1970 and the beginning of 1971 as:

$$K_{i1971} = \frac{\exp\left(\hat{\alpha}_i\right)}{\hat{\beta}_i + \delta} \tag{A2}$$

where δ is the rate of depreciation, which following Bernanke and Gurkaynak (2001) is a uniform 6% rather than the varying rates used by Berlemann and Wesselhöft (2012). As a robustness check we also computed the capital stock using 4% and 8% depreciation rates. The relevant results are only a little different quantitatively and not at all different qualitatively using these alternative depreciation rates.[12] In this paper, the capital stock for a given year is

[12] Results are available on request.

always the stock at the beginning of the year. The capital stock in subsequent years is, therefore, computed as:

$$K_{it} = \left(1-\delta\right)K_{it-1} + I_{it-1} \quad \text{(A3)}$$

The capital series is used to compute the energy to capital ratio, which can be interpreted as an alternative proxy for energy efficiency (Stern, 2012) in addition to energy intensity, which is computed by dividing total primary energy used by total GDP. As we use the investment series from the national accounts, our estimated capital stock accumulates all forms of investment included in the national accounts including housing. This is appropriate for a macro-economic measure of energy efficiency.

The countries included in our sample are Albania, Algeria, Angola, Argentina, Australia, Austria, Bahrain, Bangladesh, Belgium, Benin, Bolivia, Brazil, Brunei Darussalam, Bulgaria, Cameroon, Canada, Chile, China, Colombia, Congo, Costa Rica, Cote d'Ivoire, Cuba, Cyprus, Democratic Republic of Congo, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Ethiopia, Finland, France, Gabon, Germany, Ghana, Greece, Guatemala, Haiti, Honduras, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Korea, Lebanon, Luxembourg, Malaysia, Malta, Mexico, Morocco, Mozambique, Nepal, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Senegal, Singapore, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syria, Tanzania, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, United Kingdom, United States, Uruguay, Venezuela, Vietnam, Zambia, and Zimbabwe.

For the long-run historical data we use Maddison's long-run data for population prior to 1971. We use GDP data from the first update of the Maddison Project (Bolt and van Zanden, 2013). Since the GDP data from the 2013 update was denominated in 1990 dollars, we converted the series to 2005 dollars, the base year used throughout this paper, by using the U.S. GDP deflator between 1990 and 2005 from the Bureau of Economic Analysis. To obtain GDP for England and Wales we scaled down the United Kingdom data using the share of population of the U.K. represented by England and Wales. We used the following sources for energy to construct Figures 15 and 16:

Sweden: Data are from Kander *et al.* (2013) up to 2009 and for 2010 we used the rate of change in the IEA data to extrapolate to 2010. We excluded data on food used by draught animals and human workers to make this data more comparable with our data for other countries. We also recomputed the contribution of nuclear power using the approach taken by the IEA, which assumes that electricity is produced at the average efficiency of thermal electric power plants.

U.S.A.: The source is the U.S. Energy Information Administration as described in Stern (2011). For early years, data are provided every 10 and then every 5 years. We interpolated between these to obtain a continuous time series.

England and Wales: We use Warde (2007) and updates he provided up to 1971 and IEA data to extrapolate to 2010. Here, too, we excluded data on food used by draught animals and human workers.

Spain: We use the data originally from Rubio (2005), updated for Kander *et al* (2013), excluding food for animals and humans, and replacing nuclear energy use with the IEA figures.

Italy: Data up till 1971 is from Malanima (2006), updated for Kander *et al*. (2013), excluding food for animals and humans. We use IEA data from 1971 to 2010.

Uruguay: Data up till 1971 is from Bertoni *et al* (2009). We use IEA data from 1971 to 2010.

Argentina and Brazil: Coal consumption is from Yañez *et al*. (2013); oil and gas consumption from Rubio and Folchi (2012) for 1850-1950, continued with UN/WES (1976). Data on hydroelectricity is taken from Rubio and Tafunell (2013). Biomass corresponds to an unpublished estimate by J. Jofre based on UN/ECLA (1956) data. From 1971, IEA data are used.

For the historical cross sectional regressions for 1870, 1890, and 1937, we use the following sources for additional countries not already listed above. Primary energy data for France, Netherlands, Portugal, and Germany is from Kander *et al*. (2013). Primary energy data for Latin American countries is from the sources listed for Argentina and Brazil above, except for the year 1937, which originates from the UN/ECLAC (1956) database. Canadian primary energy consumption data is from Unger and Thistle (2013). The historical primary energy estimates include both modern energy carriers, (fossil fuels, hydroelectricity etc.) and traditional biomass.

For the energy cost share data, we use data for England and Wales compiled by Gentvilaite *et al*. (in press) and for Sweden from Kander (2002) updated to 2009. These cost shares exclude the value of human muscle power but include the value of animal power. The cost shares are computed using energy prices and GDP in current local currency. As the resulting shares are unitless they can be directly compared across countries.

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Table 1. Descriptive Statistics 1971-2010

	Country					Global Aggregate
	Mean	Standard Deviation	Min	Median	Max	
Levels 1971						
Energy per Capita, GJ	62	77	3	29	497	56
GDP per Capita, 2005 PPP $	7490	8255	369	4098	52418	5065
Energy Intensity, GJ/$	0.0118	0.0137	0.0010	0.0085	0.1076	0.0110
Energy/Capital, GJ/$	0.0095	0.0300	0.0003	0.0029	0.2398	0.0037
Average Annual Growth Rates 1971-2010						
Energy per Capita, GJ	0.013	0.016	-0.012	0.010	0.081	0.007
GDP per Capita, 2005 PPP $	0.017	0.014	-0.032	0.018	0.057	0.018
Energy Intensity, GJ/$	-0.004	0.016	-0.039	-0.005	0.052	-0.011
Energy/Capital, GJ/$	-0.001	0.024	-0.093	-0.002	0.068	-0.008
Levels 2010						
Energy per Capita, GJ	106	127	8	55	728	74
GDP per Capita, 2005 PPP $	15416	15403	241	9378	75588	10221
Energy Intensity, GJ/$	0.0098	0.0122	0.0021	0.0066	0.1082	0.0072
Energy/Capital, GJ/$	0.0058	0.0169	0.0007	0.0027	0.1685	0.0027

Notes: the global aggregate mean is computed by summing energy use across all the countries in our sample and then dividing by total population, total GDP, or the total capital stock.

Table 2. Cross Section Regressions: ln E/P

	Full Dataset			Without Outliers		
Year	Constant	ln Y/P	R-Squared	Constant	ln Y/P	R-Squared
1971	-2.178*** (0.561)	0.693*** (0.067)	0.638	-2.490*** (0.533)	0.728*** (0.095)	0.671
1980	-2.434*** (0.444)	0.730*** (0.051)	0.763	-2.748*** (0.403)	0.764*** (0.075)	0.791
1990	-2.456*** (0.412)	0.736*** (0.046)	0.790	-2.791*** (0.381)	0.773*** (0.058)	0.816
2000	-2.209*** (0.419)	0.707*** (0.046)	0.808	-2.727*** (0.334)	0.762*** (0.046)	0.845
2010	-2.325*** (0.491)	0.716*** (0.053)	0.782	-2.979*** (0.353)	0.784*** (0.047)	0.826

OLS estimates with heteroskedasticity robust standard errors in parentheses.
Significance levels are indicated as follows: *** 1%, ** 5%, * 10%.

Table 3. Cross Section Regressions: ln E/Y

	Full Dataset			Without Outliers		
Year	Constant	ln Y/P	R-Squared	Constant	ln Y/P	R-Squared
1971	-2.178*** (0.561)	-0.307*** (0.067)	0.252	-2.490*** (0.533)	-0.272*** (0.095)	0.221
1980	-2.434*** (0.444)	-0.270*** (0.051)	0.308	-2.748*** (0.403)	-0.236*** (0.075)	0.265
1990	-2.456*** (0.412)	-0.264*** (0.046)	0.321	-2.791*** (0.381)	-0.227*** (0.058)	0.278
2000	-2.209*** (0.419)	-0.293*** (0.046)	0.417	-2.727*** (0.334)	-0.238*** (0.046)	0.347
2010	-2.325*** (0.491)	-0.284*** (0.053)	0.358	-2.979*** (0.353)	-0.216*** (0.047)	0.264

OLS estimates with heteroskedasticity robust standard errors in parentheses. Significance levels are indicated as follows: *** 1%, ** 5%, * 10%.

Table 4. Beta Convergence for Energy Intensity

	Constant	**Initial Log Energy Intensity**	**R-Squared**
Unconditional convergence	-0.0701*** (0.0044)	-0.0140*** (0.0019)	0.3482
Conditional convergence		-0.0403*** (0.0121)	0.2965

Robust standard errors in parentheses. For unconditional convergence the dependent variable is the average annual change in the log of energy intensity from 1971 to 2010 and initial log energy intensity is the value for 1971 see equation (3). For conditional convergence we use the average annual change in the log of energy intensity over 5 year periods and the initial energy intensity in each period. Significance levels are indicated as follows: *** 1%, ** 5%, * 10%.

Table 5. Cross Section Regressions: ln E/K

	Full Dataset			Without Outliers		
Year	Constant	ln Y/P	R-Squared	Constant	ln Y/P	R-Squared
1971	-1.695* (0.891)	-0.481*** (0.102)	0.248	-1.928** (0.822)	-0.454*** (0.095)	0.237
1980	-2.202*** (0.767)	-0.399*** (0.087)	0.298	-2.489*** (0.649)	-0.367*** (0.075)	0.292
1990	-2.276*** (0.673)	-0.388*** (0.074)	0.329	-2.621*** (0.521)	-0.351*** (0.058)	0.326
2000	-2.178*** (0.567)	-0.394*** (0.061)	0.429	-2.535*** (0.424)	-0.357*** (0.046)	0.415
2010	-1.779*** (0.600)	-0.439*** (0.064)	0.491	-2.349*** (0.434)	-0.379*** (0.047)	0.439

OLS estimates with heteroskedasticity robust standard errors in parentheses. Significance levels are indicated as follows: *** 1%, ** 5%, * 10%.

Table 6. Beta Convergence for the Energy/Capital Ratio

	Constant	**Initial lnE/K**	**R-Squared**
Unconditional convergence	-0.0878*** (0.0089)	-0.0152*** (0.0015)	0.5024
Conditional convergence		-0.0328*** (0.0069)	0.4715

Robust standard errors in parentheses. For unconditional convergence the dependent variable is the average annual change in the log of the capital/energy ratio from 1971 to 2010 and initial ln E/K is the value for 1971 see equation (3). For conditional convergence we use the average annual change in the log of the capital/energy ratio over 5 year periods and initial ln E/K in each period. Significance levels are indicated as follows: *** 1%, ** 5%, * 10%.

Table 7: Cross-Section Energy Intensity-Income per Capita Regressions for Historical Samples

	Sample					
	1870	1890	New in 1890	1937	New in 1937	New in 1890 or 1937
1870	0.685*					
	(0.412)					
1890	0.866**	0.501**	-0.261			
	(0.344)	(0.221)	(0.207)			
1937	0.710***	0.481**	-0.648***	0.369**	-0.656*	-0.463***
	(0.187)	(0.239)	(0.238)	(0.162)	(0.350)	(0.153)
1971	1.447***	0.288**	-0.033	0.234**	-0.354	-0.036
	(0.237)	(0.117)	(0.150)	(0.094)	(0.290)	(0.173)
1980	1.333***	0.298***	0.276	0.204**	-0.543*	-0.047
	(0.227)	(0.113)	(0.304)	(0.094)	(0.272)	(0.205)
1990	1.154***	0.033	0.530	0.040	-0.369	-0.038
	(0.293)	(0.098)	(0.544)	(0.085)	(0.363)	(0.266)
2000	0.823***	-0.015	0.301	-0.021	-0.589***	-0.170
	(0.315)	(0.107)	(0.424)	(0.078)	(0.168)	(0.200)
2010	0.686**	-0.070	-0.137	-0.067	-0.623***	-0.288**
	(0.292)	(0.144)	(0.657)	(0.082)	(0.054)	(0.125)
Sample size	10	17	7	25	8	15

Notes: Figures are the regression slope coefficient, standard errors in parentheses. Significance levels are indicated by *** 1%, ** 5%, * 10%. The column headed 1870 presents results in each year for the countries in the 1870 sample. The column headed 1890 presents results for all countries in the 1890 sample and the column headed 1937 for all the countries in the 1937 sample. Other columns present results for countries that were new to the sample in 1890 or 1937.

Figure 1. Global Energy Consumption per Capita 1971-2010

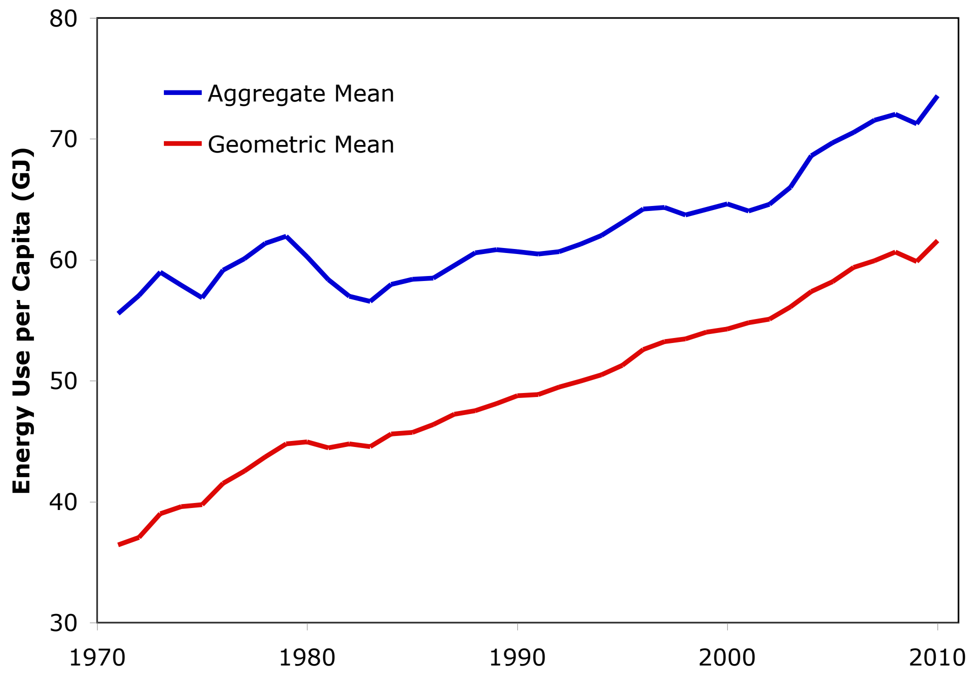


Figure 2. Energy Consumption per Capita by GDP per Capita 2010

Bubbles are proportional to total energy use.

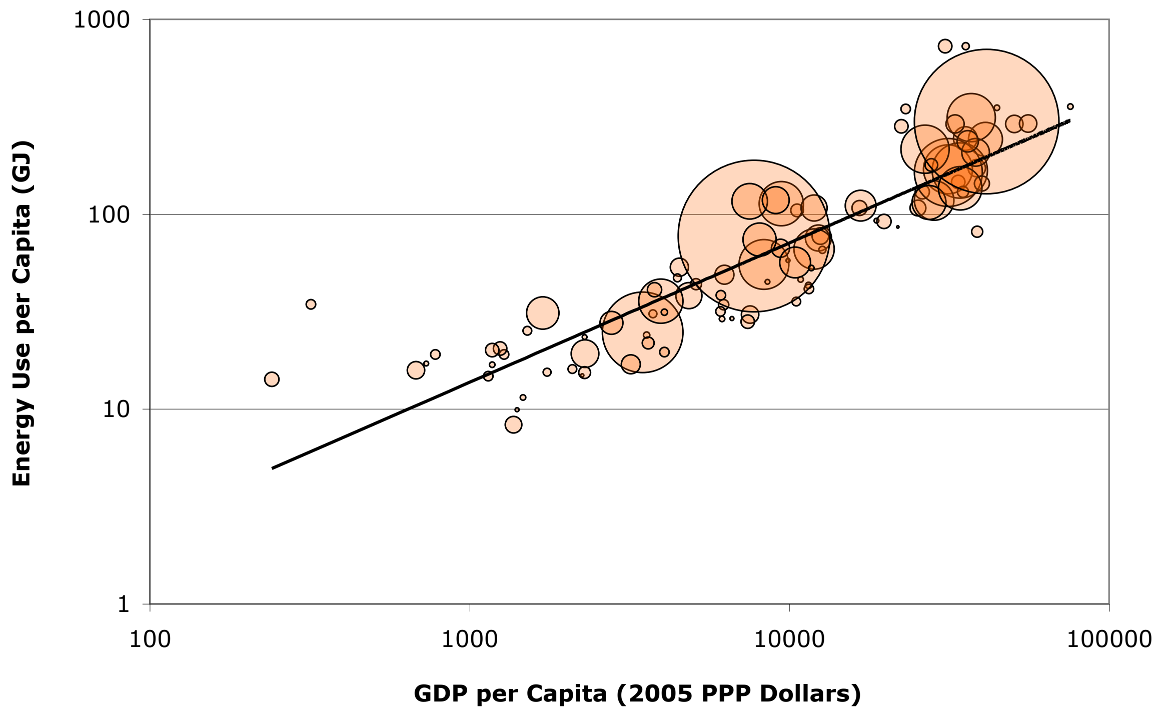


Figure 3. Global Energy Intensity 1971-2010

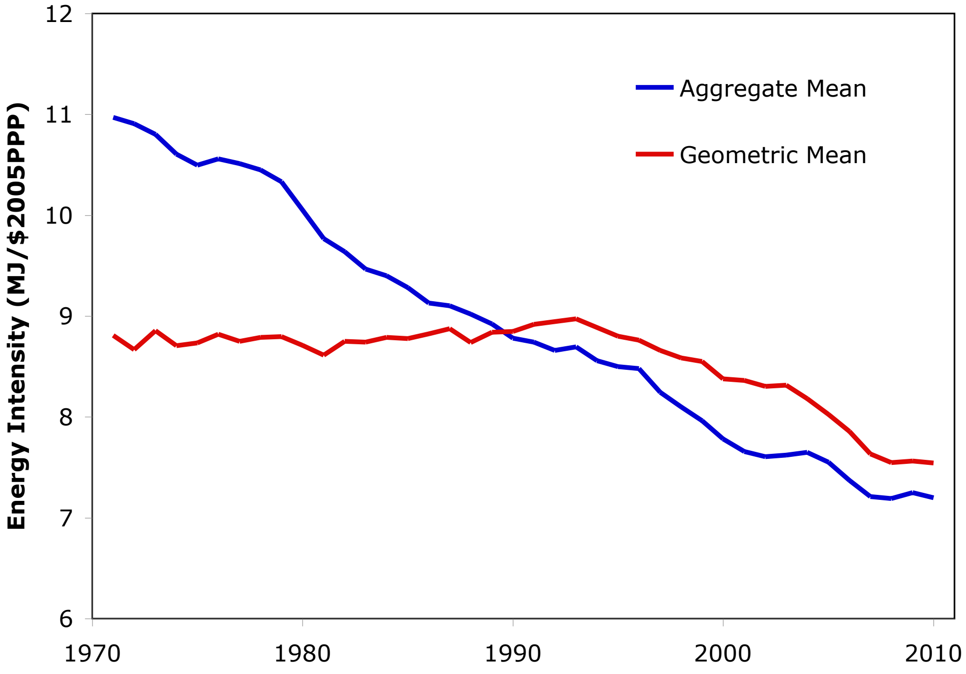


Figure 4. Energy Intensity by GDP per Capita 2010

Bubbles are proportional to total energy use.

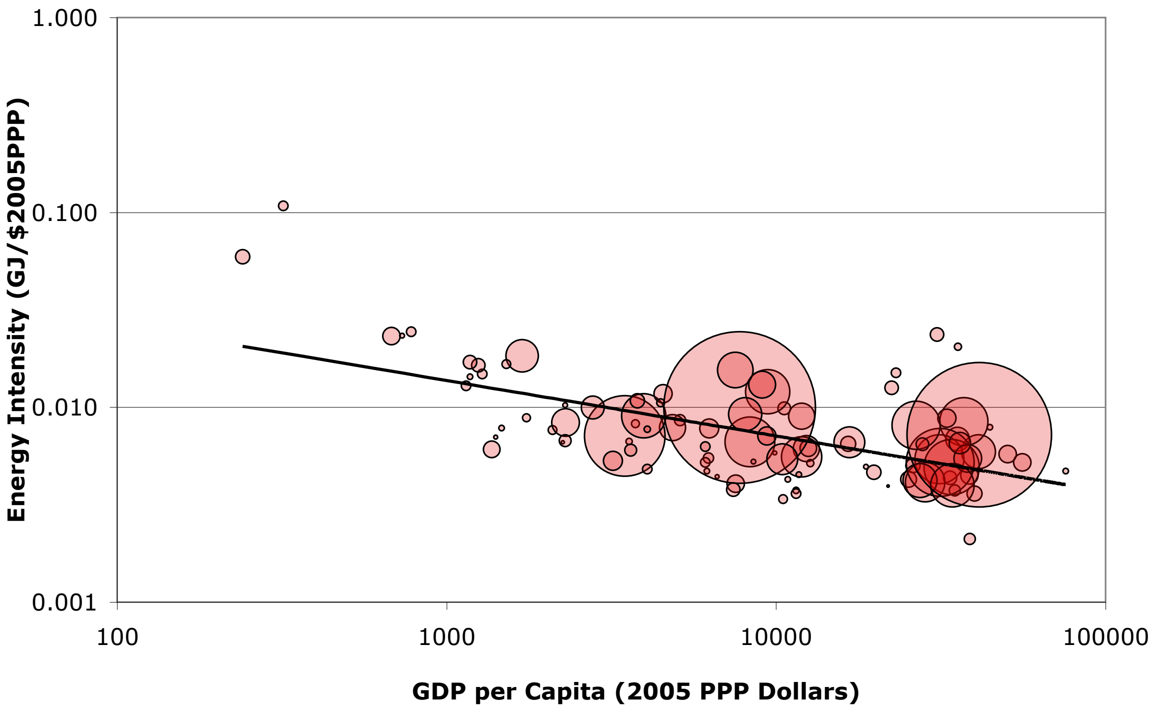


Figure 5. Average Annual Growth Rate of Energy Intensity 1971-2010 and the Level of GDP per Capita in 1971

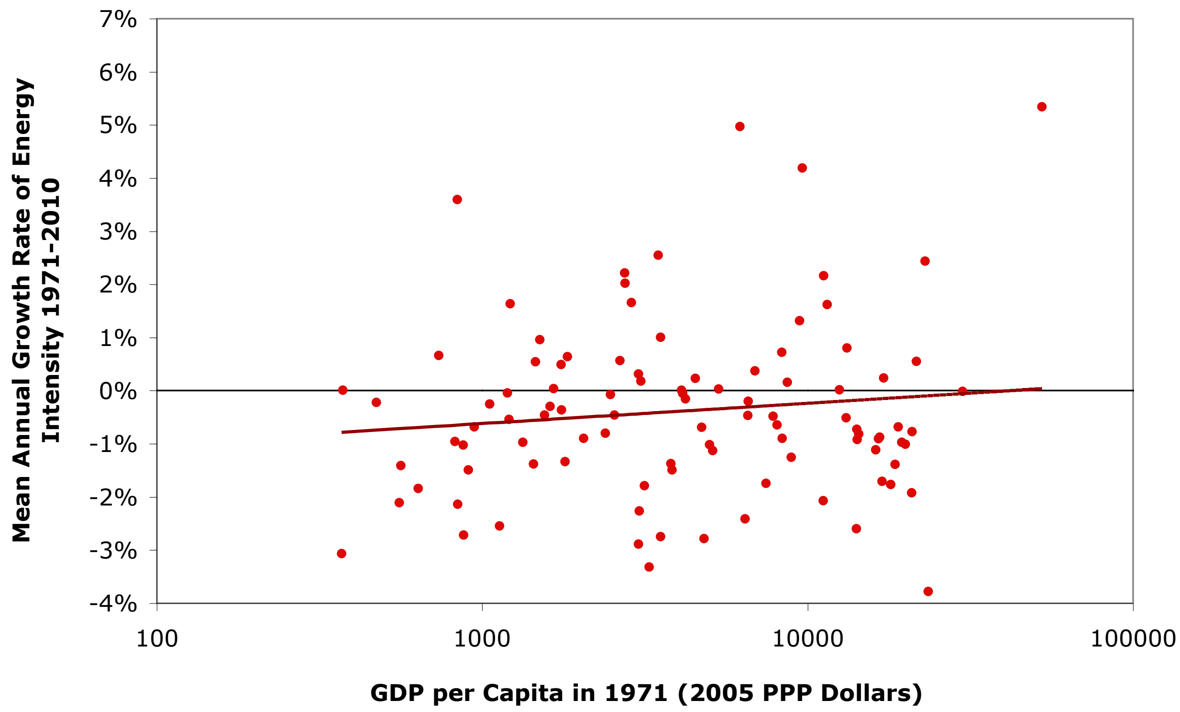


Figure 6. Average Annual Growth Rates of Energy Intensity and GDP per Capita 1971-2010

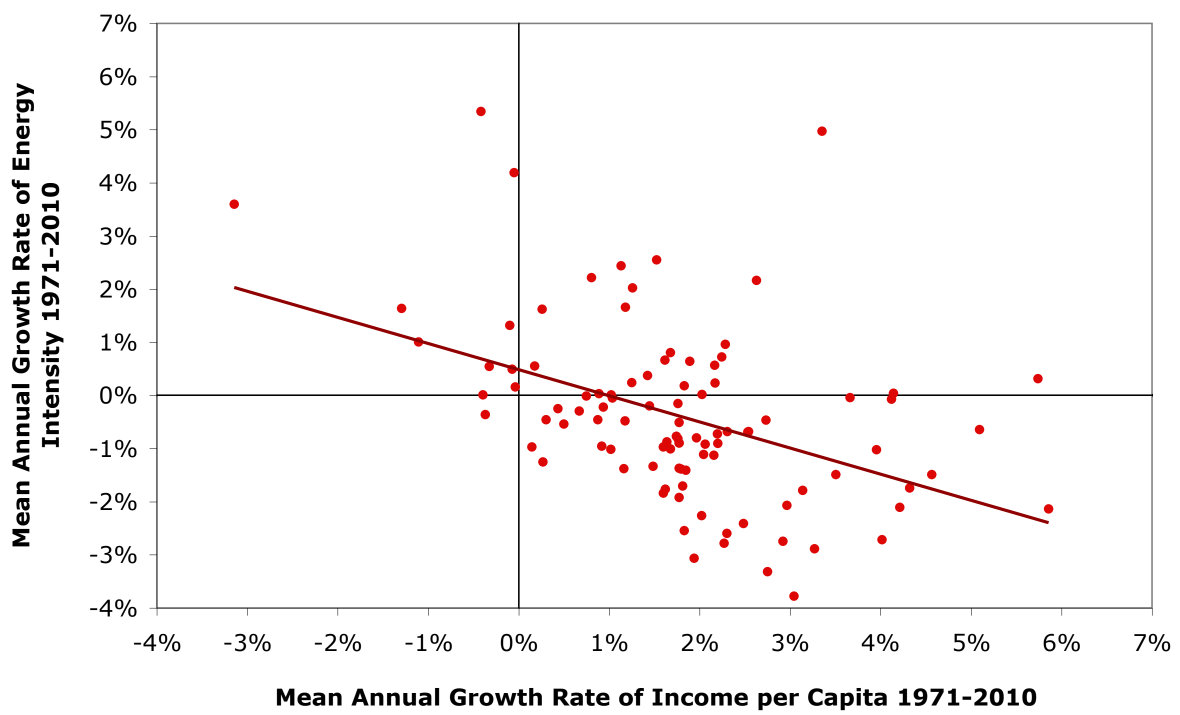


Figure 7. Unconditional Beta Convergence of Energy Intensity 1971-2010

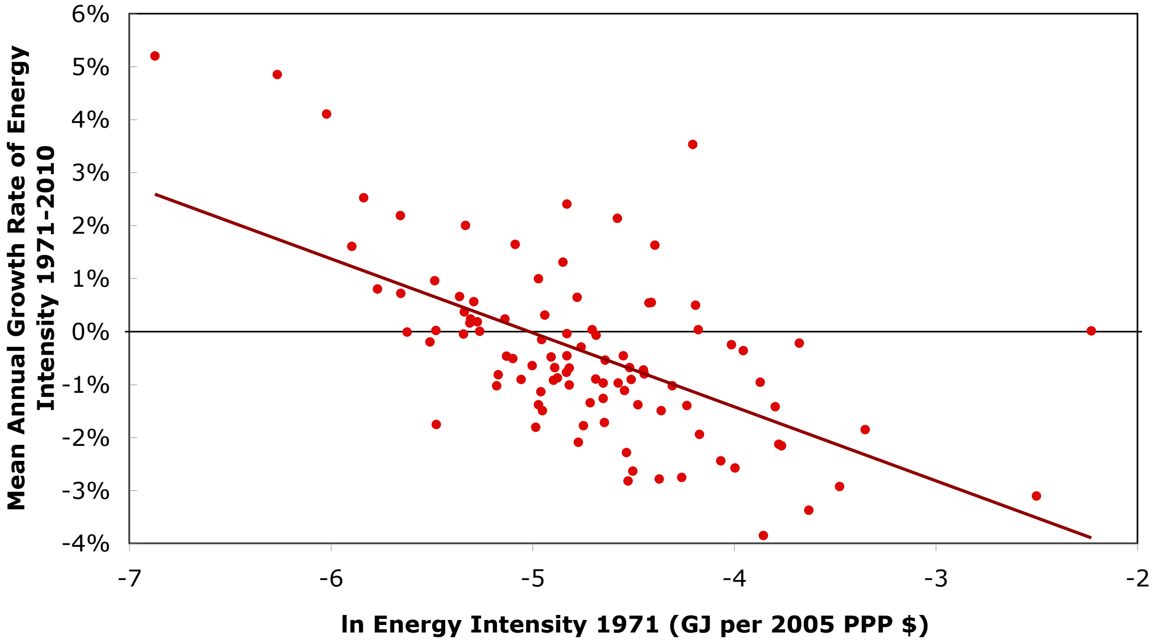


Figure 8. Cross Sectional Dispersion of Energy Intensity 1971-2010

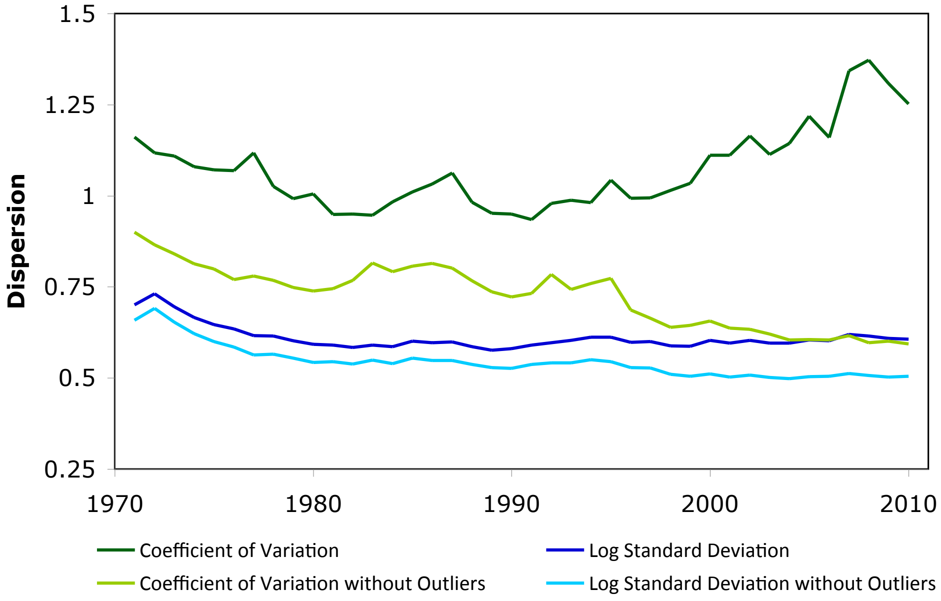


Figure 9: Global Energy/Capital Ratio 1971-2010

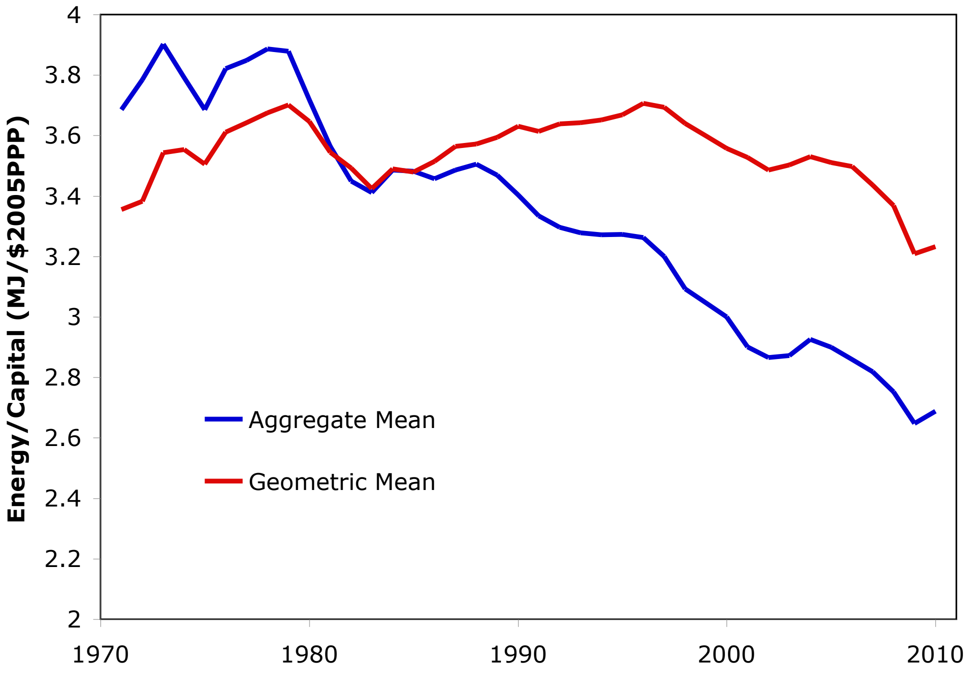


Figure 10: Energy /Capital by GDP per Capita 2010

Bubbles are proportional to total energy use.

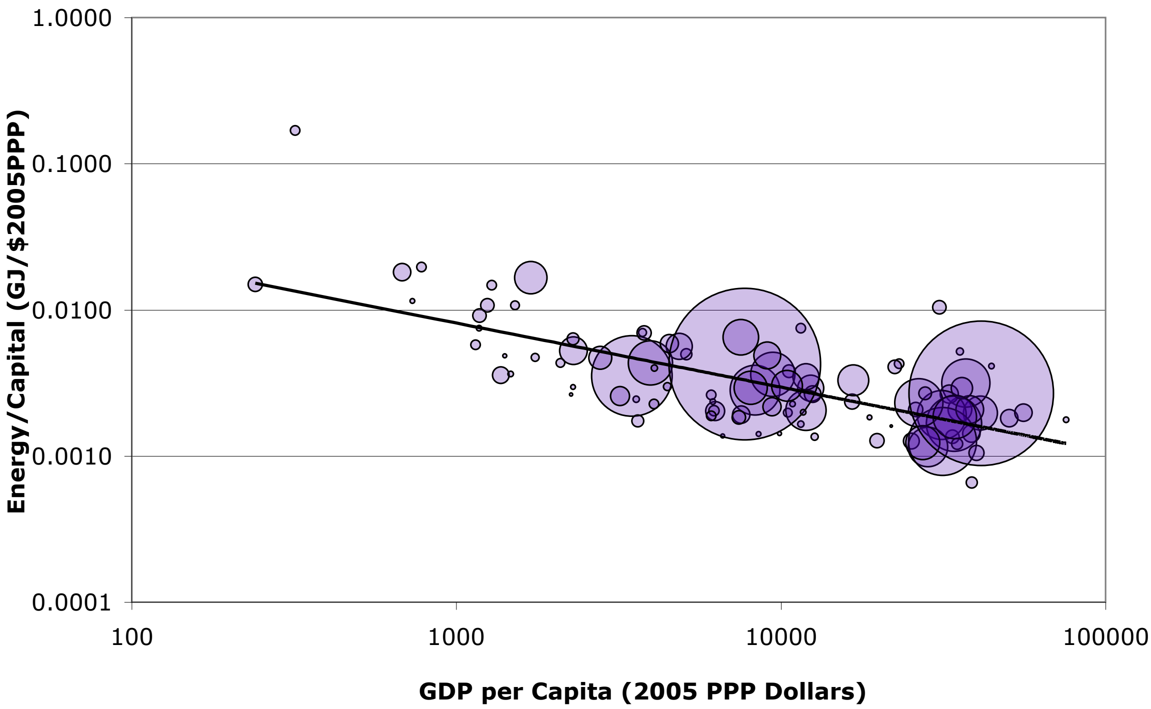


Figure 11: Unconditional Beta Convergence of Energy / Capital 1971-2010

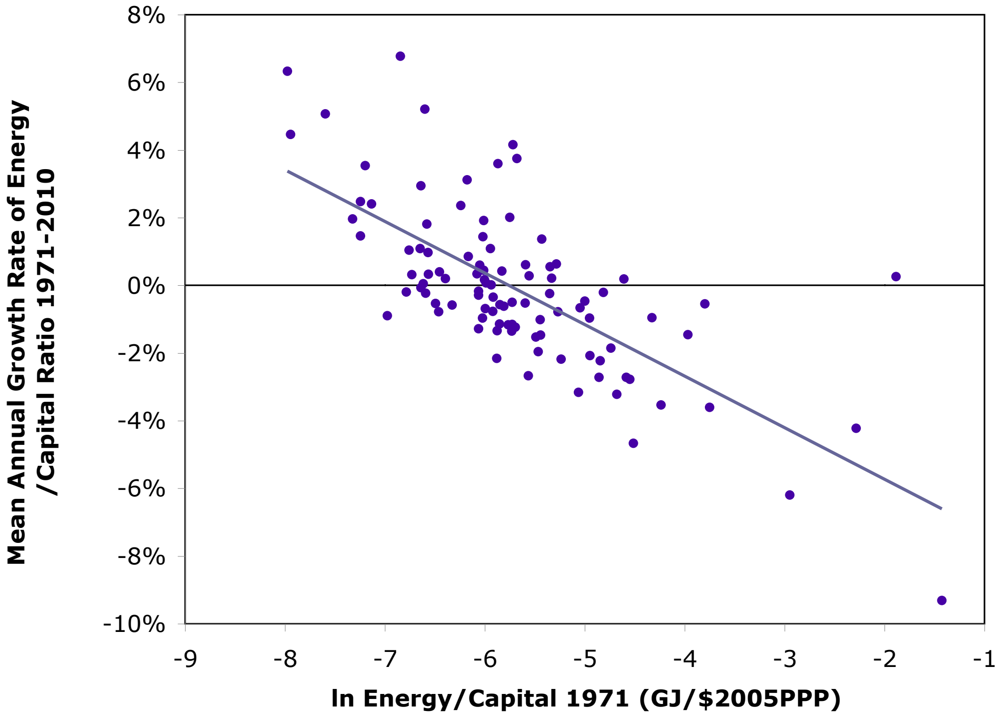


Figure 12: Cross Sectional Standard Deviation of Energy / Capital 1971-2010

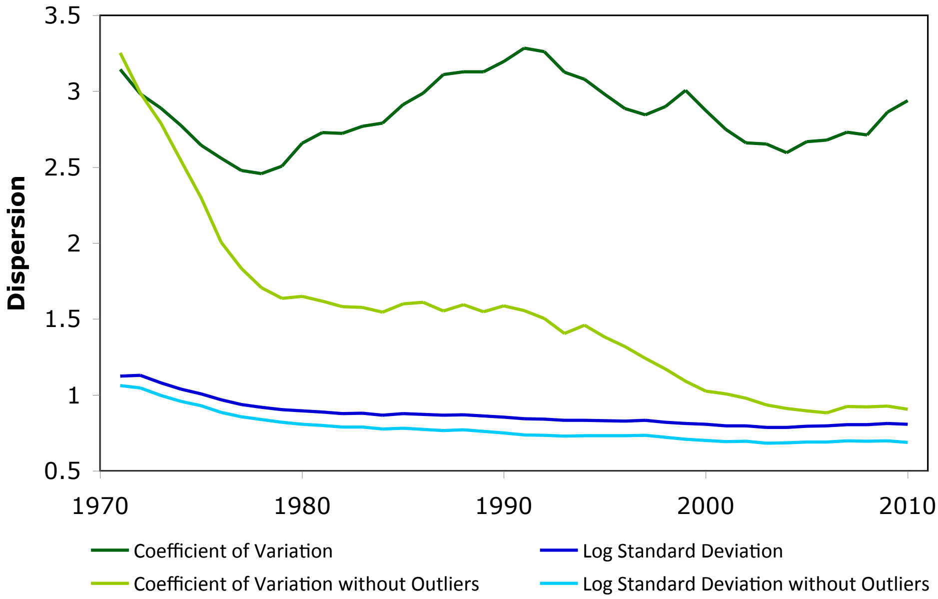
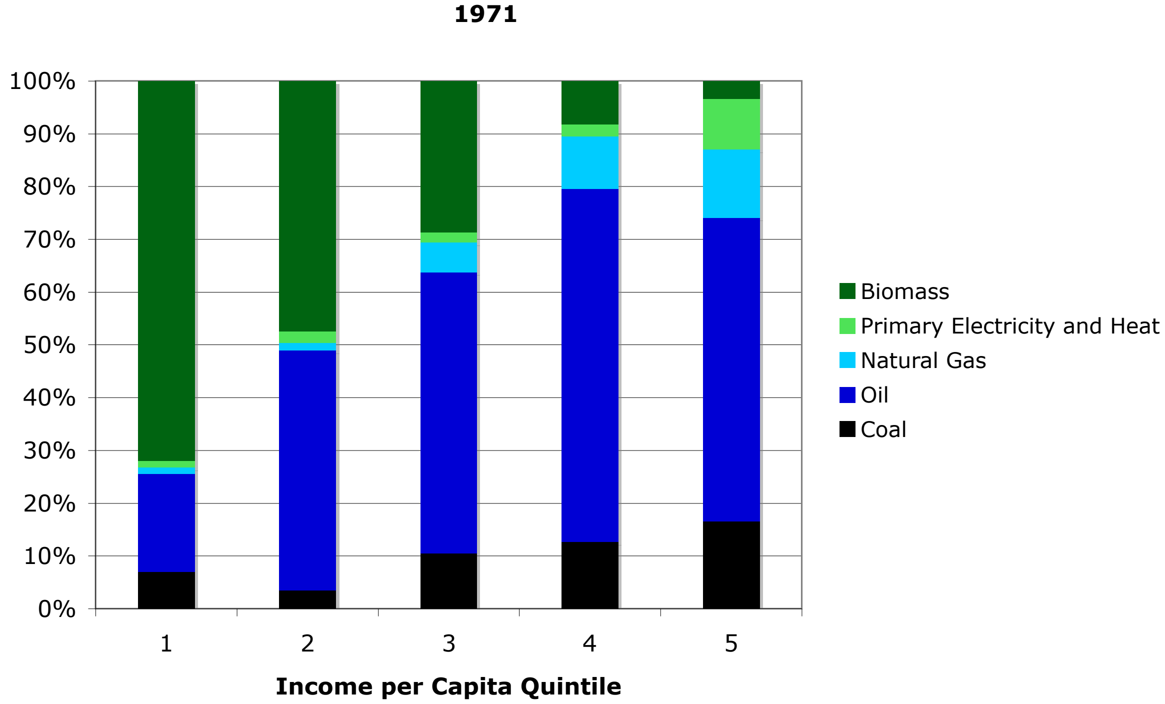
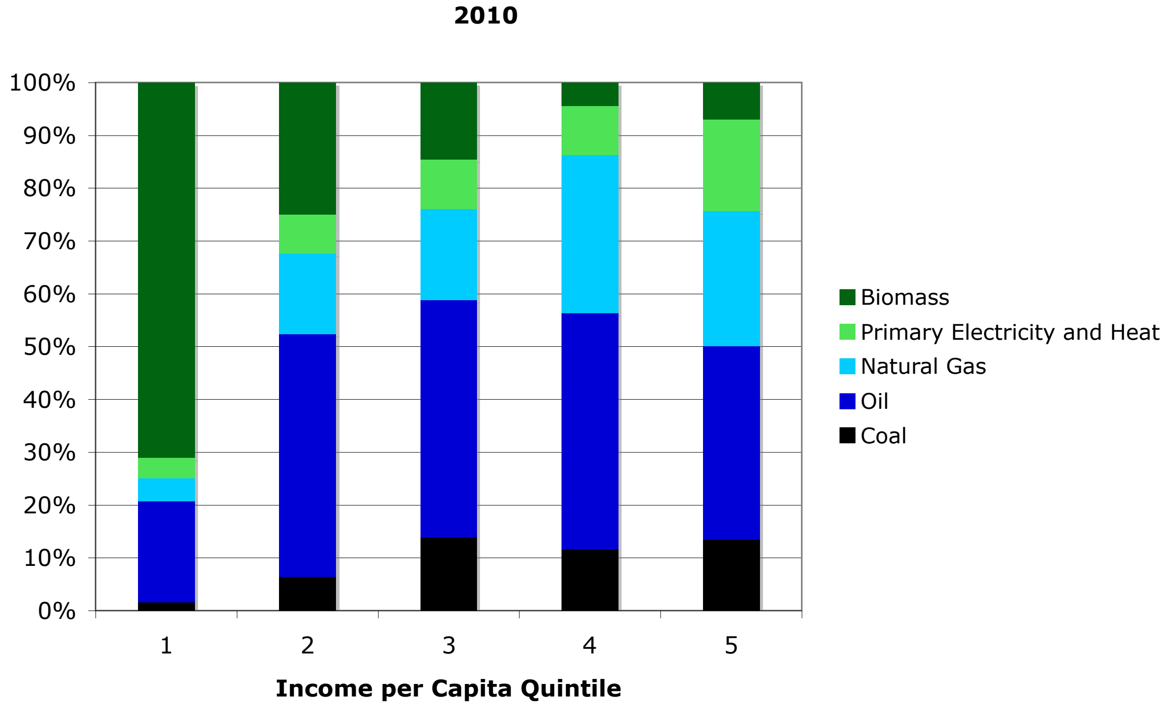


Figure 13: Mean Primary Energy Use Mix by Income Quintile 1971 vs. 2010





Notes: Limits of income quintiles in 1971 and 2010 in 2005 PPP adjusted U.S. dollars:

1971: Q1 ≤ $1275, Q2 $1218-$3019, Q3 $3019-$6300, Q4 $6300-$14125, Q5 ≥$14125

2010: Q1 ≤ $2289, Q2 $2289-$6250, Q3 $6250-$11900, Q4 $11900-$31400, Q5 ≥$31400

Figure 14: World Primary Energy Mix 1971-2010

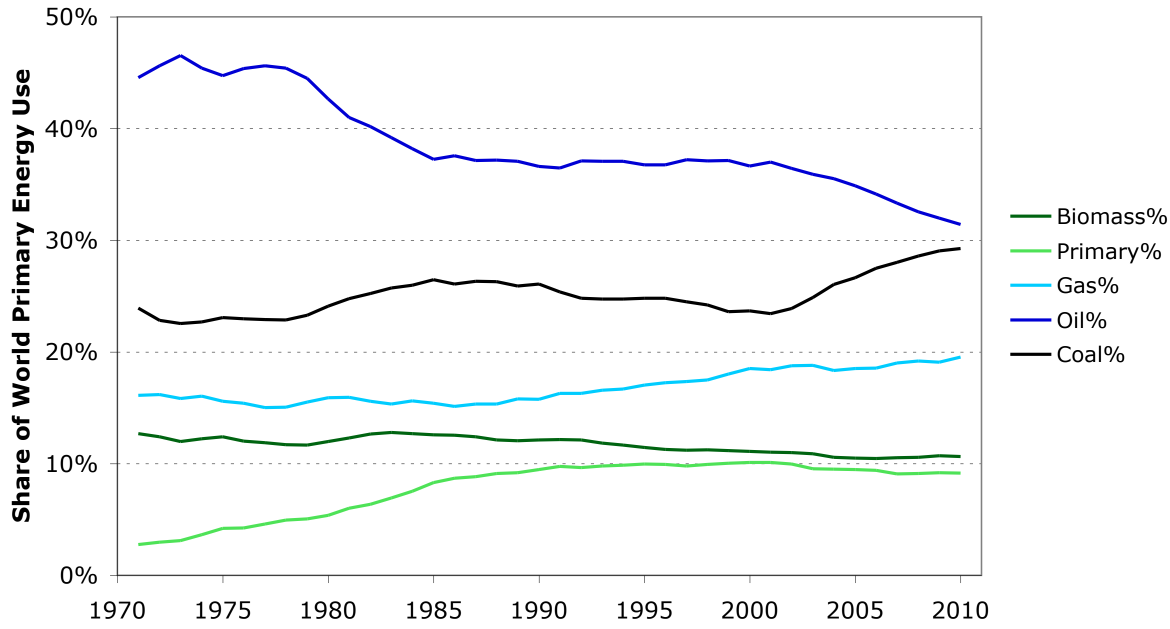


Figure 15: Energy Use per Capita 1800-2010

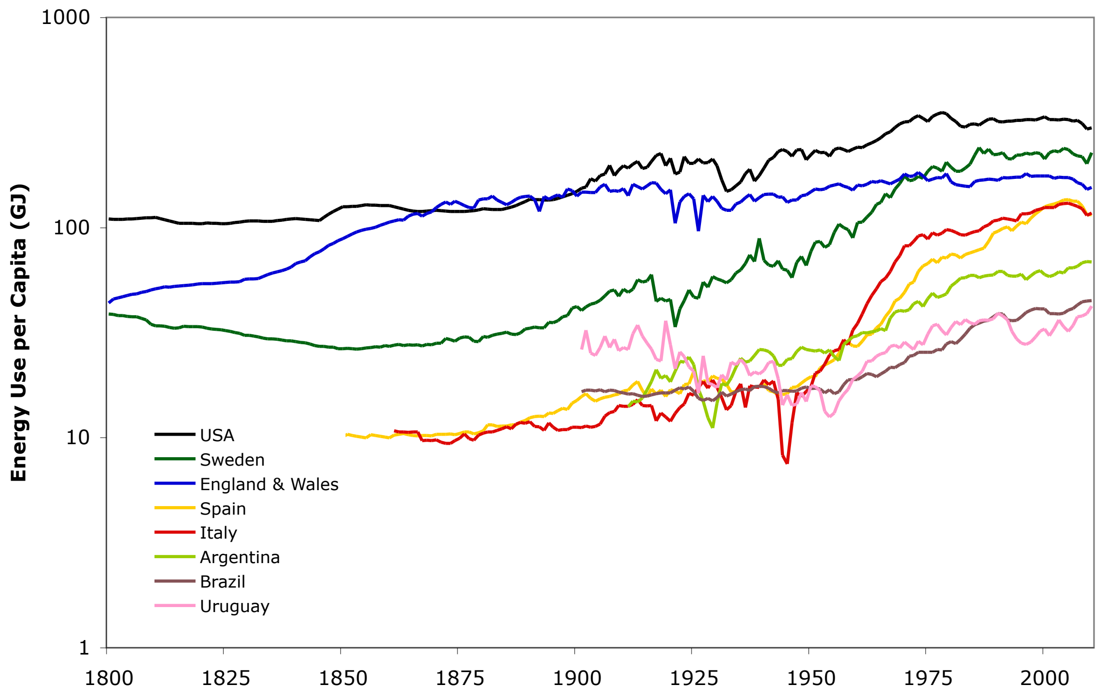


Figure 16: Energy Intensity by Income per Capita 1800-2010 and the Distribution of Energy Intensity in 2010

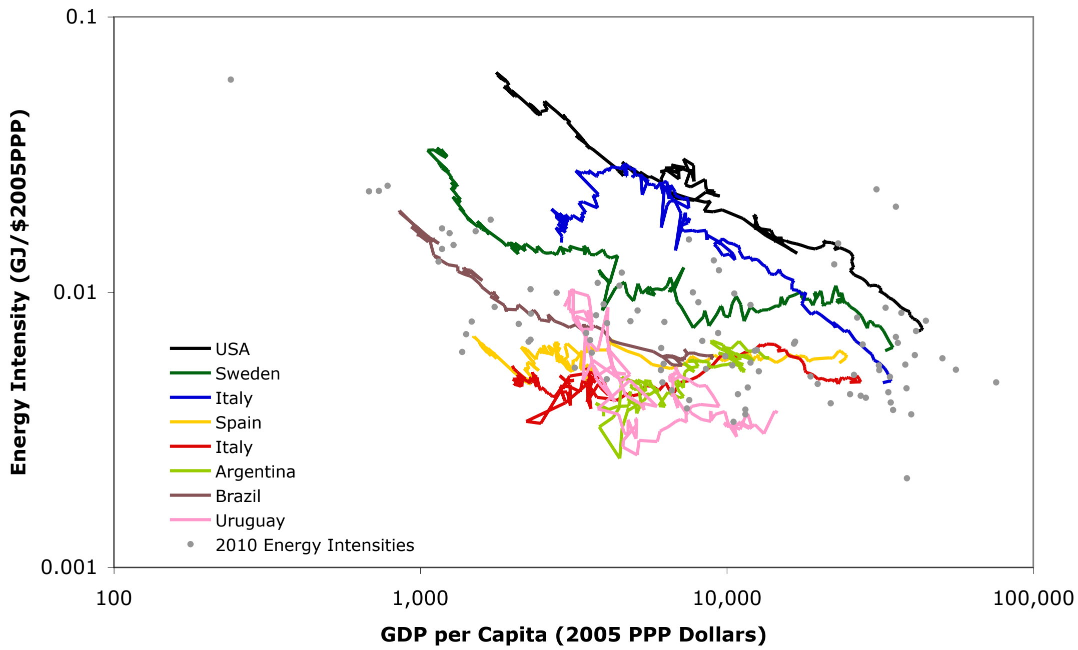


Figure 17: Energy Cost Share – England and Wales and Sweden 1800-2009