Energy and Economic Growth: The Stylized Facts

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12 April 2014

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 review of some longer run data. Our key result is that over the last 40 years there has been a stable cross-sectional relationship between energy use per capita and income with an elasticity less than unity of energy with respect to income. This implies that energy intensity has tended to decrease in countries that have become richer but not in others. Over the last two centuries there has been convergence in energy intensity towards the current distribution. In the long run, per capita energy use tends to rise and, though evidence is limited, the cost share of energy declines.

JEL Codes: Q43, O44, O13

Key Words: Economic development, energy intensity, energy efficiency

Acknowledgements: David Stern thanks the Australian Research Council for funding through grant DP120101088: “Energy transitions: Past, present and future.” M.d.Mar Rubio thanks Spanish Ministry of Science and Technology and the European Union through FEDER through research project grant ECO2010-15882. The authors thank Jesus Crespo Cuaresma, Stephan Bruns, Paul Burke, Christian Gross, and Chunbo Ma for very useful comments and suggestions and Astrid Kander for providing data on the energy cost share in England and Wales.
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), though econometrics can help validate them. 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 any model of energy and economic growth must 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 share 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. (2014) 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 capital-energy ratio rises;
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. (2014) 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 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. Ang (1987) found that, for 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, residential etc. for a panel of data from 28 countries. They concluded that energy intensity follows an inverted-U shaped curve with increasing income. This is because they only included commercial energy, omitting traditional fuels (see also Galli, 1998). 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

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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.
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 (2010) 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.

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.

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. 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., 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. 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 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.

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. An appendix provides details
of the data sources and methods for constructing the capital stock.

2. Methods

For our 1971-2010 panel data set, we examine the relationship between energy and economic growth
by systematically examining both the cross sectional relationship 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. Of course, not all the stylized facts that we find in the data
need hold into the future.

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 could be extended to other developed countries. This is certainly the case for Sweden
(Stern and Kander, 2012). Furthermore, 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 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. (in press) 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.

All variables are in natural logarithms. 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 geometric and arithmetic means. 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 in computing the global mean. For example, for energy use per capita:

$$\ln\left(\frac{E}{P}\right)_t = \frac{1}{N} \sum_{i=1}^{N} \ln\left(\frac{E_i}{P_i}\right)_t = \frac{1}{N} \left( \sum_{i=1}^{N} \ln E_i - \sum_{i=1}^{N} \ln P_i \right)$$

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. The growth rate of the mean is equal to the mean of the growth rates in each individual country.

We compare the growth rate of these geometric means to the growth rate of an arithmetic mean 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. For energy use per capita, our arithmetic mean is:

$$\left(\frac{E}{P}\right)_t = \left( \sum_{i=1}^{N} \ln E_i \right) / \left( \sum_{i=1}^{N} \ln P_i \right).$$

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

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

$$\ln X_{iT} - \ln X_{i1} = \alpha + \beta \ln X_{i1} + \varepsilon_i$$

where $X$ is the variable of interest and $i$ indexes countries. $T$ is the final year in the sample (2010) and 1 is the first year (1971). The null hypothesis of non-convergence is rejected if $\beta < 0$ (a one sided test). For sigma convergence, we plot first the development of the cross-sectional standard deviation over time. Decreasing cross sectional standard deviations are an indication of sigma convergence. To 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:

$$T_s = (N - 2.5) \ln \left( 1 + 0.25 \frac{(\hat{\sigma}_1^2 - \hat{\sigma}_T^2)^2}{\hat{\sigma}_1^2 \hat{\sigma}_T^2 - \hat{\sigma}_1^2} \right)$$
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 Data Set 1971-2010

a. 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.\(^3\) 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 arithmetic mean of world energy use per capita was only 0.72%. But the arithmetic mean was always higher than the geometric mean. 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 arithmetic mean increased over time and that of the geometric mean slowed down. This is probably explained by the increasing weight of rapidly-growing large middle-income countries, including China, over time.

Figure 1. Global Energy Consumption per Capita 1971-2010

Exceptions from the pattern of increasing per capita energy consumption over time include among others the following European countries: Albania (-0.28%), Denmark (-0.16%), Romania (-0.64%), and the United Kingdom (-0.35%), as well as a number of African and South American countries.

\(^3\) The sources of the data used in all Figures are reported in the Appendix.
including Congo (-0.22%), Cameroon (-0.16%), Gabon (-0.96%), Mozambique (-1.15%), Nicaragua (-0.11%), Sudan (-0.74%), Zambia (-0.71%), Zimbabwe (-0.37%), and Haiti (-0.81%). 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. As we will see in the following sub-section, energy use per capita continues to vary widely across countries at any given level of income though there has been a reduction in the variability of energy use at any given level of income.

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 and that the relationship is fairly linear or convex down. As shown in Table 1, a similar relationship can be found in previous years too. It is true that there does seem to be “decoupling” in some developed countries such as the U.K. but this decoupling has occurred in an insufficient number of countries to change the overall pattern.

Figure 2. Log of Energy Consumption per Capita by GDP per Capita, 2010

4 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).
Table 1. Cross Section Regressions: ln E/P

<table>
<thead>
<tr>
<th>Year</th>
<th>Constant</th>
<th>ln Y/P</th>
<th>R-Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>-2.177</td>
<td>0.693</td>
<td>0.638</td>
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<tr>
<td></td>
<td>(0.561)</td>
<td>(0.067)</td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>-2.434</td>
<td>0.730</td>
<td>0.763</td>
</tr>
<tr>
<td></td>
<td>(0.444)</td>
<td>(0.051)</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>-2.456</td>
<td>0.736</td>
<td>0.790</td>
</tr>
<tr>
<td></td>
<td>(0.412)</td>
<td>(0.046)</td>
<td></td>
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<tr>
<td>2000</td>
<td>-2.209</td>
<td>0.707</td>
<td>0.808</td>
</tr>
<tr>
<td></td>
<td>(0.419)</td>
<td>(0.046)</td>
<td></td>
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<tr>
<td>2010</td>
<td>-2.325</td>
<td>0.716</td>
<td>0.782</td>
</tr>
<tr>
<td></td>
<td>(0.491)</td>
<td>(0.053)</td>
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OLS estimates with heteroskedasticity robust standard errors in parentheses

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. 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. All results in Table 1 show a highly significant slope. 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.

We will discuss the implications of this in more detail when we discuss energy intensity in the following section. The coefficient of determination increases over time – the significant variation around the main trend in Figure 1 was greater in the past. But still variation in energy use at any level of income remains important.

Of course, these results are just a general tendency and individual countries show a variety of behaviors. As noted above, the U.K., for example, has had flat energy use per capita throughout the sample period. It migrated from 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.

b. 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 geometric mean energy intensity and the arithmetic average world energy intensity over time. The annual rate of decrease of the former is -0.40% and of the latter -1.07% per annum. Again there is a notable difference between the two series. The global arithmetic 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 arithmetic 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. 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. This can be explained by a shift down over time in the energy intensity convergence curve shown in Figure 4. There was also less convergence overall in the second half of the period as shown in Figure 5.

Figure 3. Global Energy Intensity: 1971-2010
Despite the general global decline, energy intensity has notably increased in a few South-American countries, but especially in many African and Middle Eastern countries. In a few sub-Saharan African countries, including Zimbabwe and Côte d’Ivoire, Congo, Nigeria, and Togo, GDP per capita declined over the period, and so based on the cross-sectional relationship described below we would expect their energy intensity to increase. 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 American and Caribbean countries and some of the Middle Eastern countries are oil producers. Liddle (2010) similarly found that certain geographical subgroups such as Latin America and the Caribbean, and Middle Eastern and North African countries exhibit no convergence or even diverged in energy intensities. It turns out that the majority of these countries 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 2 presents the results of the conventional unconditional beta convergence test (equation 3) for the energy intensity ratio. We, therefore, find strong evidence for unconditional beta convergence. Figure 4 depicts this

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5 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.
relationship, showing clearly that energy intensity growth is lower with higher initial levels of energy intensity.

<table>
<thead>
<tr>
<th>Table 2. Unconditional Beta Convergence for Energy Intensity</th>
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<tr>
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</tr>
<tr>
<td>-2.7335</td>
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<tr>
<td>(0.1705)</td>
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</tbody>
</table>

Robust standard errors in parentheses. Dependent variable is the change in the log of energy intensity from 1971 to 2010, see equation (3).

To test for sigma convergence, we first calculated the cross sectional standard deviation of the E/Y ratio as a function of time. The results can be seen in Figure 5. The cross sectional standard deviation shows a downward trend until the early 1980s, after which it seems to be fluctuating around a fairly constant and perhaps slightly increasing level.

Figure 5. Cross Sectional Standard Deviation of Energy Intensity 1971-2010

![Graph showing cross sectional standard deviation of energy intensity from 1971 to 2010.](image)

We also formally test for sigma convergence using the test statistic (6). This statistic has a value of 2.8012, which is distributed as $\chi^2(1)$, 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.

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. There is also a literature that uses cointegration methods to test for conditional convergence. Le Pen and Sévi (2010) applied a pairwise cointegration test to convergence of energy intensities in 97 countries. They rejected the global convergence hypothesis. 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. Results in this literature seem to depend critically on the time period, sample of countries, and methods used. For example, looking at Figure 5, there would be no sign of convergence in the period after 1980.

**Cross-section**

Figure 6 shows a cross sectional snapshot of energy intensity mapped against real income per capita as of 2010. There is a clear negative relationship so that energy intensity declines with higher income per capita. We do not, however, find any relationship between the growth rate of energy intensity and the level of income per capita. However, as can be seen in Figure 7, 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 7 is positive (p = 0.04) so that energy intensity tends to increase when economic growth is zero.

**Figure 6. Log of Energy Intensity by GDP per Capita 2010**

![Energy Intensity vs GDP per Capita](image)

Table 3 presents the results of cross-section regression results for the 99 sample countries 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 but the elasticity with respect to income is -0.3 or less.

**Figure 7. Average Annual Growth Rates of Energy Intensity and GDP per Capita 1971-2010**

![](#)

Table 3. Cross Section Regressions: ln E/Y

<table>
<thead>
<tr>
<th>Year</th>
<th>Constant</th>
<th>ln Y/P</th>
<th>R-Squared</th>
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<td>1971</td>
<td>-2.178</td>
<td>-0.307</td>
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<td>(0.561)</td>
<td>(0.067)</td>
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<tr>
<td>1980</td>
<td>-2.434</td>
<td>-0.270</td>
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<td>(0.444)</td>
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<td>1990</td>
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<td>(0.412)</td>
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<td>2010</td>
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<td>(0.491)</td>
<td>(0.053)</td>
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OLS estimates with heteroskedasticity robust standard errors in parentheses

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 6 over time. This does not mean that technological change is not involved in the change in energy intensity over time. 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. But this technological and structural 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. There is no general improvement in energy intensity that is common to all countries whether they are growing or not. Existing research shows that technological change within industries explains more of the decline in energy intensity globally than broad structural change (Stern 2011, 2012; Henriques and Kander, 2010; Mulder and de Groot 2012).

c. 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). Thus the energy-capital ratio might be a better aggregate level indicator of pure energy efficiency (Stern, 2012; Kander et al., 2014). 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 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.

i. Time series

As shown in Figure 8, the geometric mean of the energy/capital ratio decreased over time at an annual rate of -0.10%, which to the degree that this is an indicator of energy efficiency means that energy efficiency increased very slowly over the last 40 years. However, the arithmetic mean energy/capital ratio decreased more substantially, at an average of -0.81% per annum. This difference is explained again 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 in fact 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 the 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. Nearly all countries with increasing energy intensity also have an increasing energy/capital ratio.
We next test the energy/capital ratio for unconditional beta convergence and for sigma convergence. Based on our sample, we find empirical evidence for unconditional beta convergence of the energy/capital ratio (Table 4). The coefficient on the natural logarithm of the initial E/K indicator is negative, indicating that countries with higher E/K ratios at the beginning of the period are converging towards lower values. This can be clearly seen in Figure 9 as well. For sigma convergence we measure first the cross sectional standard deviation of the E/K ratio as a function of time. The results can be seen in Figure 10.

The cross-sectional standard deviation shows a downward trend over the examined period. The Figure is very similar to that for energy intensity above but shows stronger convergence over time. The Carree and Klomp (1997) test statistic is 14.902, allowing us to strongly reject the null hypothesis of sigma non-convergence. Stern (2012) finds that an estimate of underlying energy efficiency also converges across countries over time.

| Table 4. Unconditional Beta Convergence for the Energy/Capital Ratio |
|------------------|------------------|--------|
| Constant         | ln E/K 1971      | R-Squared |
| -3.4235          | -0.5944          | 0.5024   |
| (0.3487)         | (0.0601)         |          |

Robust standard errors in parentheses. Dependent variable is the change in the log of the capital/energy ratio from 1971 to 2010, see equation (3).
ii. Cross-section

Figure 11 plots the 2010 cross-sectional snapshot of energy/capital against real income per capita. 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.

Figure 11: Log of Energy /Capital by GDP per Capita, 2010

Table 5. Cross Section Regressions: ln E/K

<table>
<thead>
<tr>
<th>Year</th>
<th>Constant</th>
<th>ln Y/P</th>
<th>R-Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>-1.695</td>
<td>-0.481</td>
<td>0.248</td>
</tr>
<tr>
<td>1980</td>
<td>-2.202</td>
<td>-0.399</td>
<td>0.298</td>
</tr>
<tr>
<td>1990</td>
<td>-2.276</td>
<td>-0.388</td>
<td>0.329</td>
</tr>
<tr>
<td>2000</td>
<td>-2.178</td>
<td>-0.394</td>
<td>0.429</td>
</tr>
<tr>
<td>2010</td>
<td>-1.779</td>
<td>-0.439</td>
<td>0.491</td>
</tr>
</tbody>
</table>

OLS estimates with heteroskedasticity robust standard errors in parentheses

d. Energy Mix/Energy Ladder

Figure 12 shows the average mix of fuel types for a country in each of five income quintiles in 1971 and 2010. This illustrates the relationship between energy mix and income per capita in the cross-section and how that has changed over time. An important caveat is that due to global economic growth the composition of countries in each quintile and the maximum and minimum income for the
Figure 12: Mean Primary Energy Use Mix by Income Quintile -1971 vs. 2010

1971

2010

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

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

2010: Q1 ≤ $2289, Q2 $2289-$6250, Q3 $6250-$11900, Q4 $11900-$31400, Q5 ≥$31400
quintile 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 12. 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 13. 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 12. 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.

Figure 13: World Primary Energy Mix 1971-2010

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, energy carriers, with the probable exception of
draft animal power, have not declined in actual use globally when their share fell as an energy
transition took place. For example, while the share of oil has declined in the world energy mix, the
total amount of oil consumed has increased over the last 40 years.

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. 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). These longer-term trends mostly confirm our results for
recent decades.

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 14 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 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. South European countries such as Spain and Italy have seen significant increases in their energy usage per capita in the past forty years, yet their per capita energy usage, even at its peak reached only the energy consumption level of the U.S. around 1800. South American countries are currently at levels comparable to Sweden in the 19th Century.

**Figure 14: Energy Use per Capita 1800-2010**

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 the U.K. energy use per capita has been essentially flat since the early 1970s. Data from the U.K. show flat per capita energy use 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 the U.K. has gone from being one of the most energy intensive countries for its income level to one of the least. Further future reduction in energy intensity in the U.K. at this rate would cause it to diverge instead of converge.

Figure 15 presents the history of energy intensity versus income per capita for the same set of countries and years as Figure 14. Also included is the distribution of energy intensity in 2010.6 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., in particular 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 as a much more dispersed distribution of energy intensity and there has been convergence over the long-run.

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 3. The results (Table 6) 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, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, the U.K. and the U.S. - show a slightly positive relationship (p=0.096) 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 South and Central 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).

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6 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.
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 the just the countries added in 1890 (-0.648, p = 0.007).
Table 6: Cross-Section Energy Intensity-Income per Capita Regressions for Historical Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>1870</th>
<th>1890</th>
<th>New in 1890</th>
<th>1937</th>
<th>New in 1937</th>
<th>New in 1890 or 1937</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>0.685*</td>
<td>(0.412)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1890</td>
<td>0.866**</td>
<td>(0.344)</td>
<td>0.501**</td>
<td>(0.221)</td>
<td>-0.261</td>
<td>(0.207)</td>
</tr>
<tr>
<td>1937</td>
<td>0.710***</td>
<td>(0.187)</td>
<td>0.481**</td>
<td>(0.239)</td>
<td>-0.648***</td>
<td>(0.238)</td>
</tr>
<tr>
<td>1971</td>
<td>1.447***</td>
<td>(0.237)</td>
<td>0.288**</td>
<td>(0.117)</td>
<td>0.033</td>
<td>(0.150)</td>
</tr>
<tr>
<td>1980</td>
<td>1.333***</td>
<td>(0.227)</td>
<td>0.298***</td>
<td>(0.113)</td>
<td>0.276</td>
<td>(0.304)</td>
</tr>
<tr>
<td>1990</td>
<td>1.154***</td>
<td>(0.293)</td>
<td>0.033</td>
<td>(0.098)</td>
<td>0.530</td>
<td>(0.544)</td>
</tr>
<tr>
<td>2000</td>
<td>0.823***</td>
<td>(0.315)</td>
<td>-0.015</td>
<td>(0.107)</td>
<td>0.301</td>
<td>(0.424)</td>
</tr>
<tr>
<td>2010</td>
<td>0.686**</td>
<td>(0.292)</td>
<td>-0.070</td>
<td>(0.144)</td>
<td>-0.137</td>
<td>(0.657)</td>
</tr>
<tr>
<td>Sample size</td>
<td>10</td>
<td>17</td>
<td>7</td>
<td>25</td>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>

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.

The choice of sample is, thus, very important. While our dataset of 99 countries shows a clear negative relationship between energy intensity and income per capita, the early-industrialized group maintains a positive relationship also during the past 40 years (Table 6, first column). 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 6, Column 3), while the countries added in 1937 have a negative and some times very significant slope (Table 6, 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 1800 in the Netherlands and from around 1850 in Sweden, Italy, and Spain (Gales et al., 2007) and the U.S. (Schurr and Netschert, 1960).

We have not presented any evidence in the paper so far on trends in the energy cost share. Long-term data on the energy cost share is so far only available for a couple of countries (Figure 16). 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 38% in 1800 to 9% in 2009. There are historical observations on energy prices (Fouquet, 2008) while energy quantities from the pre-industrial era must always be reconstructed. Data for the early decades is, therefore, very uncertain due to the reconstruction of traditional energy use and also to the assumption that the price data we have for specific locations applies to other locations too, which may not be the case. Data for England and Wales also show a declining cost share over time from around 15-20% of total costs in 1800 to 8% today. When the value of human muscle power is included the decline is more pronounced in England and Wales.

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.

**Figure 16: Energy Cost Share, England Wales and Sweden 1800-2009**
5. The Stylized Facts

In this concluding section we summarize the evidence presenting the stylized facts as they emerge from our data. These facts will need to be taken into account in future studies of the relationship between energy use and economic development. 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 in the variability at any given level of income. Energy use per capita increases with income per capita. 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 richer countries over the past 40 years 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 but does not decrease when there is no change in income.

2. Convergence in energy intensity and the energy capital ratio over time both in the recent period and over the last two centuries. This results in energy intensity and the energy/capital ratio trending to increase in less energy intensive countries: Energy intensity has been converging over the past four decades (beta convergence and sigma convergence at 10% level). There has, however, been little sigma convergence since the 1970s. The energy/capital ratio also converges over time in at least the last few decades, we find evidence for both beta and sigma 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 the decline in energy intensity is mostly driven by improving energy efficiency but that there are some factors that also increase energy use at high income levels. The energy/capital ratio has been declining over time, however there are some countetrends 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 in all income levels over the past decades.

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: including 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”.

All economic output variables are adjusted for purchasing power parity. Real GDP, real GDP per capita, population, and investment are sourced from the Penn World Table, version 7.1 (Heston et al., 2012). 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 $t$):

$$\ln I_i = \alpha_i + \beta_i t + \varepsilon_i$$

(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 $\varepsilon$ is the error term. $\hat{\alpha}_i + \hat{\beta}_i$ is then the fitted estimate of the log of investment in 1971, where hats indicate estimated parameters. Then, following Berlemann and Wesselhöft (2012), we estimate the capital stock at the end of 1970 and the beginning of 1971 as:

$$K_{i1971} = \exp(\hat{\alpha}_i + \hat{\beta}_i)$$

(A2)

where $\delta$ 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). In this paper, the capital stock for a given year is always the stock at the beginning of the year. The capital stock in subsequent years is, therefore, computed as:

$$K_{it} = (1 - \delta)K_{i,t-1} + I_{i,t-1}$$

(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.

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 the 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:

Sweden: Data are from Kander et al. (2014) 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 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 (2014), 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. (2014), excluding food for animals and humans. 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 regression for 1870, 1890, and 1937, we use the following sources for countries not already listed above. Primary energy data for France, Netherlands, Portugal, Germany is
from Kander et al. (2014). 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 (forthcoming). 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 unpublished data for England and Wales compiled by Ruta Gentvilaite and Astrid Kander and for Sweden we use data from Kander (2002) updated to 2009. In order to conform with the definition of energy use in this paper, we do not include the value of human food in our measure of energy costs.

References


