Will History Repeat Itself? Economic Convergence and Convergence in Energy Use Patterns

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Abstract

In this paper, a difference-in-differences estimator on panel data for 30 developing and 21 industrialized countries is employed over the period 1971-2005 to examine how patterns of energy use (characterized by the consumption of primary energy carriers and sectoral energy use and carbon emissions) are changing in the process of economic development. For the average developing country in our sample, the results indicate that economic catch-up has been accompanied by a convergence towards the global average regarding the use of most primary energy carriers, the consumption of final energy in most sectors and total CO_2 emissions. For industrialized countries, we find that economic growth is partially decoupled from energy consumption and that above average rates of economic growth were accompanied by larger improvements in energy efficiency. These results emphasize the need to identify the relevant engines of economic growth, their implications for energy use and possibilities to achieve low-carbon growth centered on productivity and efficiency improvements rather than on capital accumulation.

Key words: Structural Change, Convergence, Energy Use Patterns, Decoupling, Leap-frogging

JEL classifications: O13, O33, Q43, Q56

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1. Introduction

Significant reductions of global carbon emissions - at least in the mid to long-term - are a necessary prerequisite to prevent dangerous anthropogenic climate change. Stern (2006) e.g. recommends that emissions peak no later than 2020 and a reduction of at least 50% below 1990 levels by 2050. Ambitious climate targets require a reduction of CO_2 emissions in industrialized countries and to limit their increase in developing countries (IPCC, 2007). In theory, ‘leapfrogging’ to more efficient and cleaner technologies in poor countries could allow for improvements in human development without increasing the pressure on limited fossil fuel resources and the natural environment (Goldemberg, 1998). However, recent developments go into an opposite direction. Raupach et al. (2007) for instance demonstrate that in the period 2000-2004, economic growth in developing and least developed countries was the main driver for increasing global CO_2 emissions. Gaining a deeper understanding on how development issues are related to climate policy requires information on how patterns of energy use and carbon emissions change in the process of economic development which is the subject of this paper.

The ability to control energy and material flows is arguably one of the most crucial factors for the socio-economic development of any society (Cleveland et al., 1984) and access to energy stored in the form of fossil fuels has been identified as one key aspect of the Industrial Revolution (Smil, 2000; Krausmann et al., 2007). The Industrial Revolution also marks the beginning of the ‘great divergence’ (Pomeranz, 2000) characterized by steady increases in per capita incomes in a small number of countries while the rest of the world’s population lived in poverty. Only recently, coinciding with the acceleration of the ‘second wave of globalization’ (Baldwin and Martin, 1999), industrialization has become more widespread in poor countries. If the process of economic catch-up in developing countries however follows the energy and carbon-intense growth paths of industrialized countries, it will very likely aggravate existing environmental pressures and become a major challenge for global sustainability (Haberl, 2006).

The analysis conducted in this paper is based on the idea that - maybe with the exception of a small number of heavy resource exporters - catching up economically to the rich world involves a process of successful industrialization that also affects energy use. We proceed on the assumption that it is possible to identify broadly characteristic patterns of energy use (defined by the mix of primary energy carriers and the economic sectors in which final energy is consumed) corresponding to particular stages of economic development.

The econometric approach applied in this paper employs a difference-in-differences estimator on panel data for 30 developing and 21 developed countries over the period 1971-2005. We regress growth rates (i.e. first differences) of per capita consumption of primary energy carriers, energy use in economic sectors as well as CO_2 emissions per capita (relative to the world average) on the growth rate of per capita income (relative to the world average).

Our results indicate that for the average developing country in our sample economic catch-up has been accompanied by converge towards the global average for the use of most primary energy carriers, the consumption of final energy in most sectors, and total CO_2 emissions. Therefore, countries that convergence towards similar income levels also converge towards similar patterns of energy use. We conclude that these energy use patterns can indeed be regarded as being characteristic for a certain stage of economic development. Furthermore, our estimates point to the fact that developing countries - instead of embarking on less energy and carbon-intensive development paths - closely follow the growth paths exemplified by wealthier countries in the past.

For OECD countries, we find that the relationship between growth of per capita income relative to the world average and growth of energy use relative to the world average is statistically insignificant for all primary energy carriers, energy consumption in most sectors and total CO_2 emissions. This is consistent with the hypothesis that economic growth in industrialized countries has partially decoupled from energy consumption, albeit at levels of energy use and carbon emissions not compatible with ambitious climate protection. Additional estimates suggest that OECD countries with above average rates of economic growth also experienced larger improvements in energy efficiency. This finding indicates a connection between gains in total factor productivity and energy efficiency improvements, emphasizing the need to identify the relevant engines of economic growth, their implications for energy use and possibilities to achieve low-carbon growth centered on productivity and efficiency improvements rather than capital accumulation.

Overall, we conclude that countries at the world income frontier can maintain economic growth without experiencing significant increases in energy consumption while catch-up growth by developing countries is much more energy intensive. Devising a paradigm of ‘low-carbon development’ which reconciles human development goals with environmental concerns could hence become one of the major future challenges for sustainability science.

This paper is structured as follows: In Section 2, the relevant literature to establish the link between economic convergence, energy transitions and convergence of energy use patterns is briefly reviewed. In Section 3, the data and estimation technique is described. In Section 4, the results are presented and discussed. In Section 5, a sensitivity analysis is performed. In Section 6, conclusions are drawn.

2. Economic Convergence and Energy Transitions

The question whether poorer countries catch up to the rich world has received widespread attention in growth theory and development economics. Barro and Sala-i-Martin (1991) and Mankiw et al. (1992) find ‘conditional convergence’ in growth regressions. That is among countries with identical steady states, the poorer ones can be expected to grow more quickly. However, as steady states across countries differ, there is no answer to the question if incomes per capita converge in absolute terms. Carlino and Mills (1993) introduce the concept of ‘stochastic convergence’ examining the stationarity properties of GDP relative to the group average for US regions. Jointly rejecting the null hypothesis of unit roots in all regional time series (which was the case for their sample) means that after a random shock, a region’s GDP tends to revert back to the group average in the long-term which can be interpreted as convergence behavior. Quah’s (1993) non-parametric estimates of the evolution of the world income distribution in the period 1962-1985 suggest that countries’ per capita GDPs tend towards two extremes (the so-called ‘twin-peaks’). Finally, in a study of long-run data sets, Pritchett (1997) points out that historical divergence was the prevalent phenomenon as the ratio between incomes in the richest and the poorest countries increased six-fold between 1870 and 1985.

More recently, many of the techniques mentioned above have been employed to examine the convergence behavior of CO_2 emissions. Strazicich and List (2003) use panel unit root tests and cross-sectional regressions, finding stochastic as well as conditional convergence of CO_2 emissions in 21 industrialized countries in the period 1960-1997. Romero-Ávila's (2008) stationarity test that allows for multiple structural breaks and cross-sectional dependence and Westerlund and Basher's (2008) panel unit root tests with factor models both confirm the finding of stochastic convergence of CO_2 emissions for samples of industrialized countries. Aldy (2006) finds convergence of CO_2 emissions for the OECD but divergence for a global sample of 88 countries (for the period 1960-2000). However, stationarity and unit root tests performed by Barassi et al. (2008) which allow for cross-sectional dependence and account for trend-stationary dependence reject the null hypothesis of a convergence of CO_2 emissions for OECD countries in 1950-2002. Lee and Chang (2008), implementing a test which takes into account cross-sectional effects and which are able to identify how many members contain unit roots, find stochastic divergence of CO_2 emissions for 14 out of 21 OECD countries. These results are informative but suffer from considerable limitations due to their focus on the statistical properties of time series without taking into account crucial socioeconomic variables. As we have argued, energy use and carbon emissions are intrinsically linked to economic activity and it should be expected that convergence or divergence of CO_2 emissions depends first and foremost on the convergence behavior of the underlying driving variables such as per capita income.

The literature on energy system transitions provides numerous examples on how energy use patterns vary between economies at different stages of maturity. Leach (1992) and Barnes and Floor (1996) exemplify how rising incomes in developing countries allow households to climb the 'energy ladder' and shift from traditional biomass and charcoal to more efficient and convenient energy carriers like petroleum products, liquefied or compressed natural gas and electricity. Marcotullio and Schulz (2007) as well as Grübler (2008) point out that for countries at early stages of industrialization the energy mix is dominated by solid fuels mainly in the form of fuel wood and coal and that with proceeding industrialization a large part of these fuels is replaced by grid-based, high-quality forms of energy such as natural gas and electricity. Burke (2010) presents empirical evidence supporting the hypothesis of national-level energy ladders in electricity generation. Schurr (1984) argues that energy transitions played a major role for continued economic growth in the US after the 1960s as more efficient and flexible energy use increased the productivity of all factors of production. Schäfer (2005) indicates that structural change in the economy is associated with shifts in final energy use: rising per capita incomes result in a smaller share of final energy use in the residential sector but larger ones for transportation and the service sector and a reversed U-shape pattern for industry. Hence, the cited studies provide a number of reasons to expect that economic convergence should be related to convergence of energy use patterns.

However, relatively few papers address this particular issue. Ravallion et al. (2000) and Heil and Wodon (2000) estimate an ‘Environmental Kuznets Curve’ (i.e. inverse U-shape) specification for the relationship between income per capita and CO_2 emissions and project future emissions for a range of plausible GDP scenarios. Their main result is that convergence in incomes indeed results in a convergence of CO_2 emissions. Padilla and Serrano (2006), performing non-parametric estimation using concentration indices and a decomposition of the Theil inequality index, demonstrate that rising inequality in world income is followed by greater inequality in global emissions. The paper that is closest to our analysis is Markandya et al. (2008). The authors employ panel regressions to examine the convergence of energy intensity of 12 countries of Eastern Europe to the EU average. They find that on average a 1% decrease in the income gap between the former and the EU average results in a decrease of the gap in energy intensity of 0.7%. While we use a similar estimation approach, our focus is clearly different: we employ a global sample and disaggregate energy use by primary energy carriers and energy use by sector in order to study the development of energy use patterns in the process of economic growth.

3. Data and Method

Data Sources and Aggregation

Our estimates are conducted using panel data for developing and industrialized countries for the period 1971-2005. We divide these 35 years of data into 7 observations per country with a length of 5 years each which leaves us with 6 time steps to estimate our equation in first differences (see below). Data on population as well as GDP measured in year 2005 $US at market exchange rates (and in PPP for a robustness check) were extracted from the World Development Indicators 2007 (WDI, 2007).

All data on energy use are measured in MJ per capita[2] per year and were drawn from the IEA (2007b,c). The IEA energy balances provide a detailed description of inputs of primary energy carriers into and output of secondary energy from transformation sectors (such as electricity generation or petroleum refineries) as well as consumption of primary and secondary energy in final use sectors (e.g. industry or transportation). To keep the analysis tractable, we clustered inputs of primary energy carriers into four broad aggregates: coal products, oil, natural gas and renewable energy (including hydro, wind, solar and biomass). We excluded nuclear energy from our analysis (a) because access to nuclear technologies is determined by political rather than economic forces and (b) because too few observations of countries employing these technologies are available to generate statistically sound results. However, nuclear energy is included in the aggregate 'total primary energy'. Sectoral use of final energy was grouped into the following five categories: industry, services, transport, residential and agriculture and fisheries[3]. Any of these sectors consumes primary as well as secondary energy (for example, industry uses coal and gas but also electricity generated from various primary energy carriers). In order to construct meaningful aggregates, we converted all secondary energy consumption to primary energy units by dividing secondary energy by the ratio between total input of primary energy into and total output of all transformation sectors[4] for each country and each year[5].

Since energy use is the central topic of this paper, we limit our analysis of carbon emissions to emissions resulting from the combustion of fossil fuels. Carbon emissions from land use, land use change and forestry and neither non-energy CO_2 emissions from industrial processes nor non-CO_2 greenhouse gases are taken into account. The respective data (measured in metric

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[2] MJ = Megajoules. 1 MJ = 10^6 Joules. All values given are averages over a period of five years.

[3] A detailed description of primary energy carriers and sectors is provided in Appendix A.

[4] Prior to 1994, the IEA statistics lumped together all solid biomass in the category 'statistical differences'. This means that no information on solid biomass use by sectors is provided for years before 1994. To deal with this issue, we assume that the sectoral shares of solid biomass in 1971-1993 were the same as those observed in the period 1994-2000. As solid biomass use is largely dominated by the use of traditional biomass in the residential sector, this assumption seems to be rather unproblematic.

[5] Due to the way the data is structured, it is impossible to get exact estimates of sectoral energy use. The employed procedure, implicitly assuming identical conversion factors across sectors, understates primary energy equivalents corresponding to consumption of secondary energy in some sectors and overstates it in others. We argue that, as long as the energy mixes across countries in the sample are similar, the problem is primarily one of scale (i.e. estimated energy use in a certain sector deviates from its true value by a factor which is of similar magnitude for all countries). We run our estimates separately for OECD and developing countries, respectively. For both groupings, the latter condition is approximately satisfied. Hence, we do not expect any serious bias in our regression coefficients.

tons of CO_2 per capita per year) originate from the IEA's CO_2 Emissions from Fuel Combustion Database (IEA, 2007a).

Countries were classified into two groups (either 'OECD' or 'developing') according to OECD membership at the initial year of the observation period[6]. While this partition of countries is admittedly coarse, it is well suited for our purpose: as we explicitly adopt a perspective from which development is regarded as happening in discrete stages rather than being a smooth process, it seems reasonable to draw a distinction between countries that have industrialized successfully and those where this process is still in its infancy.

As this study focuses on interactions between the macro-economy and the energy system during long-run transitions, we employ panels with a length of five years per observation and take averages to smooth over cyclical fluctuations according to the following rule: if for any five-year-period three or more observations are available, the average value over this period will be used. Otherwise, the respective value is marked as 'missing'. In order to work exclusively with balanced panels and to ensure that results are comparable across primary energy carriers (sectors), our sample only includes countries for which observations for all primary energy carriers (sectors) and all periods are available[7]. This leaves us with three distinct sub-samples: one for consumption of primary energy carriers, one for sectoral energy use and one for CO_2 emissions. Sample sizes are shown in Table 1.

< Table 1 about here >

Data Description

Average per capita incomes between developing and OECD countries are marked by a huge gap: while in the period 1971-75 per capita GDP in the OECD was in the order of $US 15500, it was about 20 times lower in developing countries (around $US 730). Over the sample period, both groups of countries approximately doubled their per capita incomes, to $US28800 in the OECD and $US 1540 in developing countries. Therefore, the relative

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[6] A list of countries is provided in Appendix A. Note that for the purpose of this study, economies in transition are included in the category 'developing'.

[7] Due to a lack of data, only very few least developed countries are included in our sample.

distance between incomes in both country groups (and hence to the world average) remained relatively unchanged[8].

A quick glance at the energy data (Figure 1) reveals several interesting observations: first, OECD countries - despite their relatively small share in the world population - accounting for more than half of the global energy use. On average, in 2005, a person living in the industrialized world consumed more than three times more energy than someone living in a developing country (184 MJ/cap vs. 54 MJ/cap, respectively). It should be noted that there are large variations in energy use per capita, not only between developing and industrialized countries but also in countries with very similar per capita incomes[9].

Second, energy use in developing countries has grown significantly, rising almost threefold from 45 EJ per year[10] in the period 1971-1975 to 133 EJ per year in 2001-2005. For OECD countries, on the other hand, total energy consumption has increased much more slowly, from 128 EJ per year in the period 1971-1975 to 180 EJ per year in 2001-2005.

Third, developing and industrialized countries exhibit pronounced differences with regard to their energy mix and sectoral distribution of energy use: for developing countries, the largest part of primary energy consumption is met by coal and renewables (predominantly in the form of traditional biomass) while in industrialized countries oil and natural gas are the most widely employed energy carriers. On a sectoral level of detail, industry and the residential sector account for the largest shares of energy consumption in developing countries while in the OECD, transportation and the service sector are of a relatively higher importance.

In summary, the impression given by graphical inspection of our data is in line with the hypothesis derived earlier, namely that developing and industrialized countries do not only differ in their levels of total energy consumption but also in the implied patterns of energy use (i.e. total energy consumption disaggregated by primary energy carriers and sectoral energy use).

< Figure 1 about here >

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[8] This aggregate view, however, does not provide information about events of economic convergence or divergence in individual countries.

[9] In the period 2000-2005, for instance, the US consumed 309 MJ per capita per year while Japan managed to achieve a comparable level of income at 157 MJ.

[10] EJ = Exajoules. 1 EJ = 10^{18} Joules. All values given are averages over a period of five years.

Empirical Method

Our working hypothesis is that it is possible to identify characteristic patterns of energy use that correspond to an economy’s stage of development and that these patterns undergo transitions in the process of economic growth. Our estimator relates changes in per capita incomes relative to the world average from one time period to the next to changes in the structure of the energy system. For the purpose of this paper, the structure of an economy’s energy system is defined by the consumption of primary energy carriers (i.e. the energy mix) and the activities for which final energy is consumed (i.e. energy use by sector). The estimator can be derived from an underlying (ad-hoc) model that assumes that country *i*’s energy system variable v at time *t*, E_{vit}, relative to the world average[11] ($\overline{E}_{vt}$) is a function of country *i*’s GDP relative to the world average. We further allow for a country-specific deterministic trend, given by α_{vi} and a time-specific shift γ_{vt} that affects all countries identically in period *t* (such as a global recession or a price shock) and add an identically and independently distributed error term μ_{vit}:

$$\frac{E_{vit}}{\overline{E}_{vt}} = \left(\frac{GDP_{it}}{G\overline{D}P_t} \right)^{\beta_v} e^{\alpha_{vi} t} e^{\gamma_{vt}} e^{\mu_{vit}} \qquad (1)$$

Taking the logarithm and the first difference of this equation directly yields the equation to estimate:

$$\Delta(\ln E_{vit} - \ln \overline{E}_{vt}) = \alpha_{vi} + \delta_{vt} + \beta_v \cdot \Delta(\ln GDP_{it} - \ln G\overline{D}P_t) + \varepsilon_{vit} \qquad (2)$$

With $\varepsilon_{vit} = \mu_{vit} - \mu_{vit-1}$ and $\delta_{vt} = \gamma_{vt} - \gamma_{vt-1}$

The symbols are defined as follows:

Δ: first time difference

i: country index

t: time period index

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[11] Note that for the purpose of this paper, the world average is obtained by averaging over our sample which (due to limited availability of data) does not include all countries.

v: index designating energy system variable (either primary energy carrier, sectoral energy use, total energy use or CO_2 emissions)

α_{vi}: country-specific trend for energy system variable v, country i

δ_{vt}: time period-fixed effect for growth of energy system variable v, period t

GDP_{it}: per capita income in country i in period t

$G\overline{D}P_t$: average world income in period t

E_{vit}: value of energy system variable v in country i in period t

$\overline{E}_{vt}$: world average of energy system variable v in period t

β_v: relation between growth of energy system variable relative to the world average and growth of per capita income relative to the world average

ε_{vit}: error term for country i in period t for estimation equation v; $E(\varepsilon_{vit})=0$

We estimate this differences-in-differences equation using ordinary least squares (OLS) on panel data[12] assuming that the independent variables are exogenous. We include country-fixed effects to control unobserved country-specific characteristics which have an idiosyncratic time-invariant impact (such as geography or resource endowments). In our estimation tables, we report a single constant term equal to the average of all the country-fixed effects. We further include time-fixed effects (i.e. a dummy variable for each five-year period) to control shocks that have identical impacts on all cross-sectional units in the respective time period (such as oil price shocks). In order to allow for the possibility of heteroscedastic and/or autocorrelated error terms (which - if not controlled - would result in biased estimates of standard errors and could lead to erroneous conclusions with regards to statistical inference), we estimate robust standard errors using the Newey-West (1987) procedure which generates heteroscedasticity and autocorrelation consistent covariance matrices. As a measure of the goodness of fit, we report the within-R^2, which is obtained by running the regressions on demeaned data. Thus, it focuses on the explanatory power of the independent variables and deliberately excludes the fit provided by the country specific-fixed effects.

The economic interpretation of Eq. (2) is straightforward: $\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$ can be understood as the growth rate of energy system variable v for country i relative to the world average and $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ as the growth rate of its GDP relative to the world

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[12] Summary statistics for the dependent and independent variables are reported in Appendix B.

average[13]. Hence, the dependent and the independent variable capture by how much above or below the global average country *i*'s energy system variable v and its GDP, respectively, have grown and the coefficients β_v relates growth in energy system variable v relative to the world average to growth in GDP relative to the world average.

We estimate 11 separate equations (i.e. one equation for each of the four primary energy carriers, each of the five sectors as well as for total energy use and total CO_2 emissions) for each country group. For each equation, the dependent variable is the difference between period *t* and period *t+1* of (the log of) the respective energy system variable for country *i* relative to the world average. The independent (explanatory) variable is the same for all equations, namely the difference between period *t* and period *t+1* of (the log of) country *i*'s per capita income relative to the world average.

As an illustration, Figure 2 depicts the relationship between $\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$ and $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ in our pooled sample for total energy consumption and CO_2 emissions for developing as well as OECD countries. Negative (positive) signs on either axis indicate growth rates below (above) the world average for *GDP* or the energy system variable, respectively. Pooling the sample data means that each observation is simply treated as one data point. Furthermore, neither country nor time specific-fixed effects are taken into account and visual inspection of the data does not provide information about statistical significance. Keeping in mind these caveats, the scatter plots suggest different behaviors for both country groups: For developing countries, there appears to be a robust positive correlation and the trend line shows a slope in the order of one for both energy system variables. For OECD countries, on the other hand, both trend lines are rather flat and the slope of the regression line describing the relationship between relative GDP growth and relative growth of total energy use is slightly negative. This suggests that for developing countries, above average growth in per capita income is accompanied by above average growth in total energy use and carbon emissions while for industrialized countries the relationship is less clear. We will turn to a full analysis of these issues in the next section.

< Figure 2 about here >

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[13] This means that we can express the growth rate g_x of any variable *x* as: $g_x = \frac{dx}{dt}\frac{1}{x} = \frac{d}{dt}\ln(x)$.

4. Results

Developing countries

The results for developing countries are summarized in Table 2. The estimated coefficients are statistically significant at conventional levels for all energy system variables (the coefficient for the equations for coal use is significant at the 10% confidence level only) except for oil consumption, renewable energy and energy use in the residential sector.

Remarkably, all of the statistically significant coefficients except the one for total primary energy use have values close to one. This means that for countries in this group, movements of their relative incomes relative to the global average have their correspondence in very similar changes in coal and gas use as well as energy use in industry, the service sector, transportation and agriculture and fisheries, i.e. countries whose economies grow faster than the global average also exhibit above average growth of the aforementioned energy system variables. Thus, economic convergence, i.e. closing the gap to the global average by a certain percentage, is associated with changes of similar magnitudes in the energy system for the average developing country in our sample and countries that converge towards similar per capita incomes also converge towards very similar patterns of energy use. This finding lends support to the hypothesis that energy systems do not evolve independently from the economic system and that a certain energy use pattern is typical for a given level of economic development. However, most estimates show relatively low R-squares indicating that country-specific effects besides per capita income are important explanatory factors and that there is a considerable variation in individual countries' development paths. From the above arguments, it also follows that our results do not support the leapfrogging hypothesis: poor countries which experience increases in per capita incomes and catch-up to the world average also undergo transformations of their energy use patterns that bring them closer to the global average and on average economic growth in newly industrializing countries results in energy use patterns that are not significantly less energy or carbon-intensive than those prevailing in richer countries.

As already mentioned, the estimated constant term c_v (computed by averaging the country-fixed effects α_{vi}) can be interpreted as a deterministic trend in (the level of) the respective energy system variable. The statistically significant constant terms on oil and gas consumption as well as total energy consumption hence suggest secular increases which affect developing countries as a group beyond what is explained by the trend of per capita income. Plausible candidates might be transformations taking place on a global scale such as increasing urbanization, ever greater integration into world trade or lifestyle changes. However, the trends for oil and gas are not continuous over the entire sample period: for oil, it is offset by statistically significant period-fixed effects with coefficients that are of comparable magnitude to the constant c_v for the periods 1986-1990 and 1996-2005 (reported in Appendix C). Likewise, the upward trend for gas is interrupted for the period 1986-1995 due to period-fixed effects of similar size as the constant term. Finally, the time specific-fixed effects also suggest above average growth rates of energy use in the industry sector during the period 1991-2000.

A plausible explanation for the insignificant coefficients found for renewables and residential energy use could be that these are largely determined by important non-economic factors which are constant over time and hence captured by the country specific-fixed effects. The use of commercial renewable energy on the global scale (i.e. excluding traditional biomass use) is for instance dominated by hydropower which accounts for almost 80% of renewables other than biomass (IEA, 2009) and constitutes an important source of low-cost energy for many countries at different stages of economic development. Therefore, it is not unreasonable to expect that natural endowments are the most important factor explaining the use of renewable energies, at least if policies to explicitly further their use are lacking. Likewise, energy use in the residential sector could well be influenced by country-specific factors which are constant over time (such as climatic factors or habits), with development of disposable household income playing only a lesser role.

< Table 2 about here >

Industrialized countries

Results for OECD countries are shown in Table 3. Obviously, there are significant differences compared to the results found for developing countries. Most notably, none of the coefficients for the equations describing the growth of consumption of primary energy carriers relative to the global average is statistically significant, neither are the coefficients on total primary energy use, CO_2 emissions and energy use in the residential sector, agriculture and fisheries or the service sector (albeit the coefficient on energy use in services is on the fringe of significance at the 10% level). Only the coefficients for energy use in industry and transportation are statistically significant.

Finding a large number of insignificant coefficients with regards to changes in consumption of primary energy carriers and sectoral use of final energy relative to the world average is consistent with the presumption that at more advanced stages of economic development, ‘dematerialization’ plays an important role (Herman et al., 1990). This means that a larger rate of economic growth is (at least partially) counterbalanced by efficiency improvements and structural shifts in demand which result in increased shares of services (which can be assumed to consume less energy than industry per unit of GDP) in economic activity. Our results do not lend support to the hypothesis that decreasing consumption of physical units of energy per unit of GDP is mainly a result of switching to higher quality forms of energy (e.g. from coal to oil and gas) instead of real improvements in end-use efficiency as suggested by Cleveland et al. (2000) and Kaufmann (2004). Confirmation of this hypothesis would require a negative coefficient for coal consumption but positive ones for the consumption of oil and gas relative to the world average[14].

The fact that we find a positive, statistically significant coefficient that is smaller than one for industrial energy use can be seen as a sign that economic growth is not completely decoupled from energy, i.e. that industry continues to be an important driver of energy consumption, albeit with a β_v of 0.415 its growth rate relative to the global average is significantly lower than that of the overall economy (most likely due to structural changes and efficiency gains). The coefficient β_v for energy use in transport, which is statistically significant and very close to one, suggests that the demand for transportation has not (yet) reached the point of

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[14] Our results should however not be interpreted as rejecting the aforesaid hypothesis: the cited studies present time series evidence whose results will only be reproduced in panel estimates if a sufficient degree of parameter heterogeneity among countries obtains.

saturation and that it suffers from a kind of 'rebound effect' in the sense that technical improvements in energy efficiency are set off by either higher demand or demand for more energy-intensive modes of transportation.

The statistically significant and positive constant term for renewable energy use indicates that over the observation period renewables on average experienced an upward trend beyond what can be explained by the dynamics of GDP. This is consistent with the small negative coefficient on total CO_2 emissions which corresponds to a trend towards decarbonisation. Likewise, the negative constant term on industrial energy use in combination with the positive values for services and transport (which are statistically significant at the 10% level) suggest that secular shifts of energy use from the former sector to the latter ones took place (such as changes in the international division of labor and individual mobility patterns) regardless of the behavior of per capita income. We also find statistically significant time specific-fixed effects for every interval covered by the period 1991-2005 for natural gas (reported in Appendix C) which are large and negative (ranging from -0.236 to -0.277).

In summary, during the observation period, industrialized country growth relative to the global average is found to be unrelated to increasing consumption of primary energy carriers and to energy use in most sectors (relative to the world average). Our estimates suggest a stabilization of energy use at high levels[15]. In particular, no mechanism through which increased incomes result in declining energy use or carbon emissions is detected. In this sense, the observed behavior is probably best described as a decoupling of economic growth from energy use.

< Table 3 about here >

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[15] One further concern is that analyzing national energy use and carbon emissions fails to take into account energy used for the production of imported products. From this point of view, more developed countries become cleaner by 'off-shoring' part of their energy intensive production to third countries (see e.g. Davis and Caldeira, 2010). However, several studies point out that the amount of carbon embedded in developing countries' exports is very similar to the emissions that are avoided by imports (i.e .the emissions that would have been generated if imported goods had been produced in these countries instead) and that hence the composition of developing countries' export portfolios does not significantly influence their emissions (cf. Peters et al., 2008 and Dietzenbacher and Mukhopadhayay, 2007).

Energy use and the engine of growth

So far, the results of this paper point to fundamental structural differences with regard to the role of energy use in economic activity between developing and industrialized countries. As we have argued, structural change is one of the defining features of economic development. Our findings emphasize the importance of taking into account different growth drivers and their interplay instead of simply regarding economic growth as a continuous expansion of a stylized one-sector economy[16]. This is done in e.g. Ayres and van der Bergh (2005) whose model is based on (1) the 'resource use (fossil fuel) growth engine', (2) the 'scale cum learning growth engine' and (3) the 'value creation ('dematerialization') growth engine' and generates predictions which - broadly speaking - are in accordance with our estimates. More stylized models built around a neo-classical framework, as e.g. the "Green Solow Model" (Brock and Taylor, 2004), can also explain some of the observed trends by postulating exogenous improvements in energy efficiency: for wealthy countries, which are close to their steady state, growth is largely driven by gains in total factor productivity and increases in economic activity can be counterbalanced by energy efficiency. This can result in slowly increasing, constant or even decreasing total energy use depending on the growth rates of total factor productivity and energy efficiency, respectively. By contrast, countries which are farther away from their steady state (i.e. poorer) grow more quickly and accumulation of physical capital plays a more important role for catching-up. For these countries, economic growth is more energy-intensive as it outpaces the rate of energy efficiency improvement and leads to growing energy consumption.

In order to gain further insight into the role of growth drivers, we modify our estimation equation to distinguish between economic convergence and divergence. Thus, we can identify countries which experienced more rapid or slower growth compared to the global average. For this reason, we define two dummy variables: the variable 'div_{it}' will have the value one if country i experiences economic divergence in period t, i.e. if the gap between its per capita income and the world average widens from period $t-1$ to period t, and zero otherwise. The variable '$above_{it}$' will equal one if country i's per capita income in period $t-1$ is higher than the world average, otherwise it is zero. div_{it} takes on the value of one for 57 out of the 84 observations contained in our sample of OECD countries (18 countries times 6 time steps) and $above_{it}$ for 55 of them. For 22 observations both div_{it} and $above_{it}$ are one (i.e. in this case

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[16] This means that structural and technological change play crucial roles for economic development.

a country that displayed per capita GDP above world average experienced above average growth).

In our set of regression equations, we include two additional explanatory variables: the original explanatory variable $\Delta(GDP_{it} - \overline{GDP}_t)$ interacted with the divergence dummy variable div_{it}, and, the same variable interacted with both div_{it} and $above_{it}$. Our estimation equation becomes:

$$\begin{aligned} &\Delta(\ln E_{vit} - \ln \overline{E}_{vt}) = \\ &\alpha_{vi} + \delta_{vt} + (\beta_{v,1} + \beta_{v,2} \cdot div_{it} + \beta_{v,3} \cdot div_{it} \cdot above_{it}) \cdot \Delta(\ln GDP_{it} - \ln \overline{GDP}_t) + \varepsilon_{vit} \end{aligned} \tag{3}$$

This allows us to estimate different slopes for three kinds of qualitatively different patterns of per capita income growth relative to the world average: (a) convergence to the group average (div_{it} = 0, $above_{it}$ = 0 or 1) is described by $\beta_{v,1}$, (b) divergence downward (div_{it} = 1, $above_{it}$ = 0) by $\beta_{v,1} + \beta_{v,2}$ and (c) divergence upwards (div_{it} = 1, $above_{it}$ = 1) by $\beta_{v,1} + \beta_{v,2} + \beta_{v,3}$.

The results are shown in Table 4. Compared to the estimates we performed without interaction terms, none of the significant coefficients $\beta_{v,1}$ (i.e. the ones for industry and transportation) changes its sign or its level of statistical significance and their values change only slightly. For the interaction variables, two observations deserve attention:

First, for the consumption of oil and total energy, we find (on the 5% or 1% level of significance, respectively) a quite large negative coefficient for the term $\Delta(\ln GDP_{it} - \ln \overline{GDP}_t)$ interacted with the divergence dummy ($\beta_{v,2}$) and values that are positive and of comparable magnitude for $\Delta(\ln GDP_{it} - \ln \overline{GDP}_t)$ interacted with both the *div* and the *above* dummy variables ($\beta_{v,3}$). This suggests (a) that in countries that diverged downwards (i.e. that were initially poorer and grew less quickly than the average; $above_{it}$ = 0, and div_{it} = 1), oil and total primary energy consumption increased at higher rates than the global average and (b) that countries for which per capita GDP diverged upwards (i.e. that were initially richer and grew more rapidly than the average; $above_{it}$ = 1, and div_{it} = 1), consumption of oil and total primary energy relative to the world average remained practically unchanged[17]. Hence, the latter countries experienced above average improvements in energy efficiency which allowed them to keep their consumption of oil and total energy relative to the group average unchanged but grow more rapidly. Vice versa, energy efficiency growth for the former countries lagged behind.

This finding indicates that there are intrinsic links between the underlying drivers of economic growth and the efficiency of energy use. It seems reasonable to assume that countries that economically diverged upwards experienced above average total factor productivity (TFP) growth while TFP growth was below average for countries that diverged downwards (Easterly and Levine, 2001). This suggests that TFP and energy efficiency have very likely developed in the same direction and we expect technological progress to be the main source for driving growth of both TFP and energy efficiency. This explanation would also be consistent with the view that more efficient and flexible energy use also increases the productivity of the other factors of production (cf. Schurr, 1984). This finding emphasizes the need to gain a more detailed understanding of growth engines, their relation to energy use and possibilities to achieve low-carbon growth centered on productivity and efficiency improvements rather than capital accumulation.

Second, for industrial energy use as well as CO_2 emissions, only the coefficient of $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ interacted with both the divergence and the above dummy variables ($\beta_{v,3}$) is statistically significant (at the 1% and 5% level, respectively) and in the vicinity of one. F-tests confirm that for both energy system characteristics, $\beta_{v,1} + \beta_{v,2} + \beta_{v,3}$ is positive and statistically significant. Hence, countries that experienced growth rates above the world average also experienced above average increases in industrial energy use and CO_2 emissions. For these countries, the over-proportional economic expansion was not matched by similar increases in total energy use suggesting that (a) the industry sector increased its share in total energy consumption during growth spells and (b) that energy systems tend to become more carbon-intensive in periods of accelerated economic expansion. The former observation

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[17] For (a) the coefficient is $\beta_{v,1} + \beta_{v,2}$. F-tests confirm that for both oil and total primary energy use, $\beta_{v,1} + \beta_{v,2}$ is statistically significant and negative. Hence, if economic growth lags behind the world average $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t) < 0$ and $\Delta(\ln E_{vit} - \ln \overline{E}_{vt}) > 0$. For (b) the coefficient is $\beta_{v,1} + \beta_{v,2} + \beta_{v,3}$ and, according to our F-tests, statistically insignificant for oil as well as gas use. This implies that for countries that diverged upwards (i.e. $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t) > 0$) $\Delta \ln E_{vit}$ was not higher than the world average (i.e. $\Delta \ln E_{vit} = \Delta \ln \overline{E}_{vt}$).

suggests that industry played an important role in accelerating economic growth; a possible explanation for the latter one could be that growth spells are accompanied by higher real interest rates which divert resources away from investments in capital-intensive energy investments and tilt the balance in favor of less capital-intensive but dirtier energy carriers such as coal.

< Table 4 about here >

5. Sensitivity analysis

To assess the robustness of our results, we perform a sensitivity analysis. For brevity, we only report the general findings; detailed results of these sensitivity checks are available as supplementary online material.

First, our observation period includes the 1970s which experienced two major oil price shocks and triggered substantial changes in energy use (Popp, 2002). To ensure that our results are not driven by these somehow extreme events, we repeat all estimates with a restricted sample starting in 1981. For developing countries, the coefficients for coal and natural gas consumption become insignificant, while the coefficient for renewable energy use becomes significant at the 10%-level. The coefficient for energy use in individual sectors, as well as the coefficients for total primary energy use change little compared to the estimates performed with the sample starting in 1971. It seems likely that these observations can best be explained by adjustments in response to rising oil prices that resulted in less pronounced use of all fossil fuels. For OECD countries, the major finding is that energy use in the service and the residential sectors (with values of 1.02 and 0.66, respectively, and significance levels of 1%) display statistically significant coefficients. This suggests that at least some part of the observed decoupling of economic growth and energy use indeed took place in the 1970s but was not upheld in later periods.

Second, to investigate the effect of smoothing our data, we employ annual data instead of five year averages. For developing countries, the coefficient for oil consumption becomes statistically significant (at the 1%-level), while the coefficients for natural gas use, energy use in the service sector and energy use in agriculture and fisheries become statistically insignificant. The coefficients for energy use in industry and transport are smaller than those that were obtained with observation averaged over 5 years. While in the former case they are 0.78 and 0.79, respectively, in the latter they are 1.01 and 1.08. This finding suggests that energy systems display some inertia as movements in GDP are accompanied by changes in energy use patterns that are more pronounced in the long run than in the short run. For OECD countries, the coefficient for coal consumption becomes statistically significant, taking on a value of 1.32. The coefficient for total energy consumption becomes significant at the 10% level with a value of 0.23 and the coefficient for CO_2-emissions becomes significant at the 1%-level with a value of 0.43. This can be regarded as a sign that short-term fluctuations due to shocks in per capita income which result in higher/lower growth of energy demand relative to the global average are met by corresponding changes in the growth of energy use relative to the world average but that these adjustments do not persist in the long-term.

Third, we analyze the effect of measuring GDP in terms of units adjusted by power-purchasing parity (PPP) instead of market exchange rates (MERs) to take into account differences in price levels across countries. Valid arguments exist for and against each of these two measures[18]. For the purpose of this paper, we decided to focus on GDP in MERs first to circumvent issues related to the construction of price indices for the cost of living and, second, due to reasons of data availability. For the full sample of countries, data for GDP measured in PPP is only available from 1975 on which reduces the length of our sample by five years. Most coefficients obtained with the PPP measure lie very close to those estimated with MERs. For developing countries, the coefficients for coal and natural gas use become insignificant. None of the coefficients for sectoral energy use, total primary energy consumption, or total CO_2-emissions becomes statistically insignificant or changes its sign. For OECD countries, however, the coefficient on energy use in the service sector is now significant with a value of 1.00 as is the one on residential energy consumption with a value of 0.66 (both at the 1%-level). The results for OECD countries seem to be intuitive if we keep in mind that richer countries generally exhibit higher price levels (Balassa-Samuelson effect) due to higher prices of non-traded goods. For this reason, as countries get richer, their price level also increases and GDP measured in terms of PPP increases proportionally less than GDP measured in MERs. As energy consumption is not affected by our choice of GDP measures, employing GDP in PPP can be expected to result in larger absolute values for

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[18] See e.g. Nordhaus (2007) for a discussion.

coefficient estimates. Therefore, the general conclusion remains that developing countries' economic convergence is associated with converging energy use patterns while in industrialized countries economic growth is partially decoupled from energy use, independent of the employed GDP measure. However, with GDP measured in PPP units, the evidence for decoupling industrialized countries' economic growth from energy use rests on somehow less solid foundations compared to the estimates undertaken with MER units, an issue that might deserve further attention in future research.

Finally, we also apply a random effects (RE) estimator to exclude the possibility that insignificant coefficients are mainly due to a lack of efficiency of our estimation technique. In contrast to the RE estimator, the fixed effects (FE) estimator is the only estimator that produces unbiased estimates in the face of country-specific unobserved effects that are correlated with one of the independent variables. However, as the fixed effect for each cross-sectional unit absorbs one degree of freedom, the FE estimator suffers from low efficiency in samples that contain relatively few observations on the time dimension. Therefore, employing the RE estimator - which has higher power but produces potentially biased estimates - can help to identify whether insignificant coefficients are a result of small sample size[19]. The random effects estimates produce coefficients remarkably close to those obtained with fixed effects. The most important difference is a statistically significant coefficient (at the 1% level) of 0.62 for oil consumption in developing countries and a statistically significant coefficient (at the 5% level) of 1.24 for energy use in agriculture and fisheries in OECD countries. These findings strengthen our conviction that the insignificant coefficient estimated for OECD countries does indeed suggest a partial decoupling of energy use from economic activity instead of being just an artifact of limited sample size.

6. Conclusions

More than a quarter of a century ago, Goldemberg et al. (1985) pointed out that considerable improvements in poor countries' living standards can be accomplished with energy use of as little as 1 kilowatt per capita provided that highly efficient end-use technologies are adopted on a broad scale. More recently, Birdsall et al. (2009) have outlined a related proposal to

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[19] Note that carrying out estimates with annual data instead of five year panels (described above) greatly reduces problems related to sample size, too.

break the gridlock in climate negotiations by putting basic energy needs and equal access to energy services in the centre of the debate.

The results presented in this paper show the magnitude of this challenge: for developing countries, we find an almost one-to-one relationship between economic convergence and convergence of energy use patterns. This means that developing countries that recently have caught up economically to the world average have undergone changes in their energy systems that resulted in energy use patterns and carbon emissions that also approached the global average. Only for countries with high per capita incomes, we find a partial de-coupling, i.e. continued economic growth without increasing use of primary energy carriers or energy consumption in most sectors.

These findings are clearly worrisome from a sustainability point of view. To keep global warming below 2°C compared to pre-industrial levels, reductions of CO_2 emissions in industrialized countries will prove insufficient unless developing countries also start transforming their energy systems (IPCC, 2007). According to our results, developing countries are currently following development pathways that bring them ever closer towards the unsustainable patterns of energy consumption in wealthier countries. For instance, CO_2 emissions for the average country in our sample are about 4.4 tons per capita globally and about 2.5 tons for developing countries. If countries that catch up economically to the world average also attain corresponding emission levels, providing an income close to the world average to all people in developing countries will imply an increase of global energy-related carbon emissions by more than 10 $GtCO_2$ in total (from currently 27 $GtCO_2$).

In order to provide incentives to developing countries to keep their carbon emissions below a critical threshold without hampering their development prospects, any future global climate agreement will have to be evaluated by what it can do to promote development. As we have demonstrated in this article, the transformation of growth patterns in developing countries towards ‘low-carbon growth’ is unlikely to happen by itself. Rather, an appropriate institutional arrangement that defines widely accepted and shared responsibilities for the climate as well as human development will be required to stimulate the transfer of technologies and financial resources from industrialized to developing countries and put ‘low-carbon development’ into practice.

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Appendix A: Aggregation of energy carriers and sectors

Primary Energy Carriers

Category used in this paper	**IEA classifications included**
Coal	HARDCOAL, BROWN, PEAT
Oil	CRUDEOIL, CRNGFEED, NGL
Gas	NATGAS
Renewables	HYDRO, GEOTHERM, SOLARPV, SOLARTH, TIDE, WIND, OTHER, INDWASTE, MUNWASTER, MUNWASTEN, SBIOMASS, RENEWNS

Sectors

Category used in this paper	**IEA classifications included**
Industry	TOTIND
Services	COMMPUB
Transport	TOTTRANS
Residential	RESIDENT
Agriculture and Fisheries	AGRICULT, FISHING

List of countries

Primary Energy Carriers Sample	Developing Countries	Algeria, Argentina, Bangladesh, Brazil, Chile, China, Colombia, Egypt, Hungary, India, Indonesia, Iran, Malaysia, Mexico, Morocco, Nigeria, Pakistan, Peru, Venezuela
	OECD	Australia, Austria, Belgium, Canada, Denmark, France, Germany, Italy, Japan, New Zealand, Spain, Switzerland, UK, USA
Sectors Sample	Developing Countries	Argentina, Bangladesh, Brazil, Chile, China, Colombia, Cote d'Ivoire, Ecuador, Ghana, Guatemala, Hungary, India, Indonesia, Kenya, Korea, Mexico, Morocco, Nepal, Nicaragua, Pakistan, Peru, South Africa, Sudan, Thailand, Tunisia, Turkey, Uruguay, Venezuela, Zambia, Zimbabwe
	OECD	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, The Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK, USA
CO_2 Emissions Sample	Developing Countries	Algeria, Argentina, Bangladesh, Bolivia, Brazil, Cameroon, Chile, China, Colombia, Costa Rica, Cote d'Ivoire, Dominican Republic, Ecuador, Egypt, El Salvador, Gabon, Ghana, Guatemala, Haiti, Honduras, Hungary, India, Indonesia, Israel, Jamaica, Kenya, Korea, Malaysia, Mexico, Morocco, Nepal, Nicaragua, Nigeria, Pakistan, Panama, Paraguay, Peru, Philippines, Saudi Arabia, Senegal, Singapore, South Africa, Sri Lanka, Sudan, Syria, Thailand, Togo, Tunisia, Turkey, Uruguay, Venezuela, Zambia, Zimbabwe

	OECD	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, The Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK, USA

Appendix B: Summary Statistics

Developing Countries

Variable		Obs	Mean	Std. Dev.	Min	Max
$\Delta(\ln GDP_{it} - \ln \overline{GDP}_t)$		318	-.0112574	.129422	-.4008747	.4091505
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Coal)	108	.1173839	.6295505	-2.022027	2.448736
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Oil)	108	.0899562	198262	-.4286912	.9182542
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Natural Gas)	108	.1783573	.4441855	-1.280106	2.118199
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Renewables)	108	-.001688	.1386114	-.5216306	.5659307
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Transport)	180	-.0396693	.3306098	-1.65539	2.469683
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Industry)	180	.0221006	.3140105	-1.030114	2.402532
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Services)	180	-.0101361	.4885146	-1.513225	2.738359
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(AgFish)	180	.044537	.5817607	-2.489336	2.785594
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Residential)	180	-.0149455	.1598764	-.4185912	1.313983
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(PE total)	108	.05072	.1402223	-.3533883	.7451087
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(CO_2)	318	.0139367	.202659	-.6818457	.5786324

OECD

Variable		Obs	Mean	Std. Dev.	Min	Max
$\Delta(\ln GDP_{it} - \ln \overline{GDP}_t)$		126	.0016222	.0515991	-.1249773	.2477313
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Coal)	84	.0007355	.2302915	-620154	1.094191
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Oil)	84	.000168	.1002331	-.2307934	.3905244
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Natural Gas)	84	.1985175	.7246808	-.3156953	6.083865
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Renewables)	84	.0771991	.2286973	-.2931615	9788129
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Transport)	126	.0150056	091201	-.2782761	.273298
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Industry)	126	.0021843	.096495	-3276298	2660823
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Services)	126	.0705971	.2587065	-.5204809	1.315602
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(AgFish)	126	.0234924	3526242	-.7576253	2.200555
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(Residential)	126	.032735	.1586562	-.3469217	1.138372
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(PE total)	84	.0083154	.0710868	-.1531306	.2618958
$\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$	(CO_2)	126	.0121113	.0804804	-.2042449	.2676824

Appendix C: Time specific-fixed effects[20]

Developing Countries (time specific effects for the period centered on t, e.g. δ_{1983} is the fixed effect for the period 1981-1985)

Energy System Variable ν	δ_{1983}	δ_{1988}	δ_{1993}	δ_{1998}	δ_{2003}
Coal	0.0490 (0.139)	0.219 (0.169)	0.041 (0.155)	0.118 (0.200)	-.0216 (0.137)
Oil	-0.0270 (0.073)	-0.128** (0.060)	-0.052 (0.051)	-0.171** (0.066)	-0.148** (0.062)
Natural Gas	-0.261 (0.171)	-0.351** (0.164)	-0.385** (0.160)	-0.304 (0.181)	-0.238 (0.209)
Renewables	0.014 (0.056)	-0.014 (0.035)	0.038 (0.068)	-0.030 (0.049)	0.015 (0.060)
Industry	0.024 (0.055)	-0.016 (0.042)	0.231*** (0.069)	0.203*** (0.070)	0.014 (0.104)
Services	-0.090 (0.111)	-0.163 (0.105)	-0.040 (0.157)	0.034 (0.127)	-0.194 (0.144)
Transport	-0.013 (0.053)	-0.080 (0.060)	0.013 (0.077)	0.030 (0.068)	-0.300*** (0.102)
Residential	-0.033 (0.025)	-0.028 (0.034)	0.003 (0.032)	-0.015 (0.029)	-0.065 (0.047)
Agriculture and Fisheries	0.035 (0.103)	-0.109 (0.158)	0.105 (0.173	0.154 (0.141)	0.013 (0.152)
Total Primary Energy	-0.019 (0.038)	-0.066 (0.039)	0.030 (0.035)	-0.063 (0.042)	-0.055 (0.025)
CO_2 Emissions	-0.088*** (0.026)	-0.017 (0.027)	0.021 (0.030)	0.068* (0.034)	-0.008 (0.018)

Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

OECD Countries (time specific effects for the period centered on t, i.e. δ_{1983} is the fixed effect for the period 1981-1985)

Energy System Variable ν	δ_{1983}	δ_{1988}	δ_{1993}	δ_{1998}	δ_{2003}
Coal	0.109 (0.118)	-0.024 (0.064)	-0.044 (0.067)	-0.043 (0.090)	0.046 (0.113)
Oil	0.040 (0.045)	0.025 (0.064)	0.038 (0.054)	0.021 (0.040)	0.011 (0.038)
Natural Gas	0.252 (0.456)	-0.115 (0.173)	-0.236** (0.107)	-0.277* (0.131)	-0.275** (0.119)
Renewables	-0.023 (0.056)	0.013 (0.047)	0.027 (0.065)	-0.019 (0.072)	-0.001 (0.067)
Industry	-0.017 (0.023)	-0.024 (0.029)	0.003 (0.027)	-0.019 (0.022)	-0.014 (0.025)
Services	-0.112 (0.098)	-0.112 (0.117)	-0.102 (0.114)	-0.130 (0.109)	-0.143 (0.107)
Transport	0.007 (0.016)	-0.008 (0.028)	0.004 (0.024)	-0.020 (0.021)	-0.021 (-0.025)
Residential	-0.000 (0.048)	-0.025 (0.066)	-0.025 (0.069)	-0.039 (0.066)	-0.038 (0.065)
Agriculture and Fisheries	-0.018	-0.007	-0.075	-0.071	-0.101

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[20] Note that time specific-fixed effects account for idiosyncratic changes to the growth rate of the respective energy system variable relative to the global average that have identical impacts on all countries in the respective time period (cf. Eq.(1))

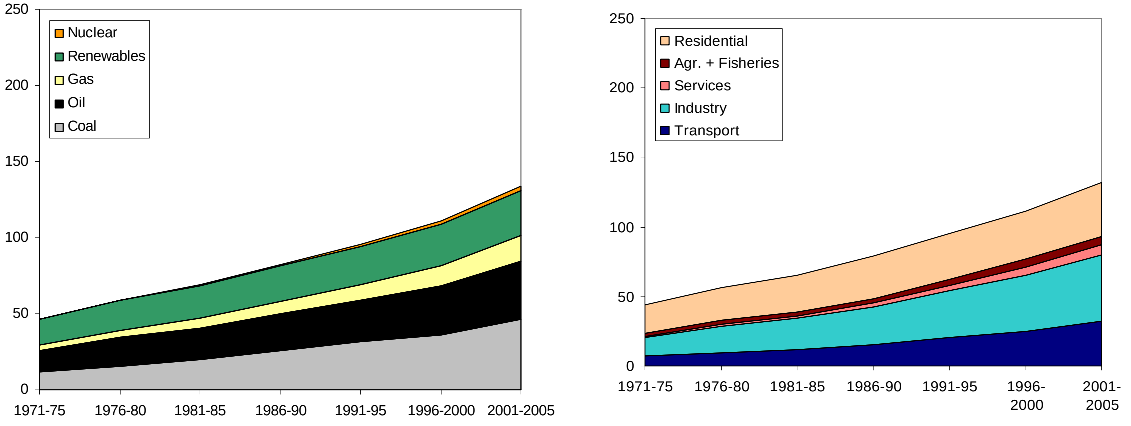
	(0.111)	(0.134)	(0102)	(0.092)	(0.100)
Total Primary Energy	0.025 (0.029)	0.017 (0.032)	0.017 (0.029)	0.005 (0.018)	0.007 (0.018)
CO_2 Emissions	0.007 (0.019)	-0.002 (0015)	0.000 (0.018)	-0.013 (0.014)	-0.008 (0.015)

Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

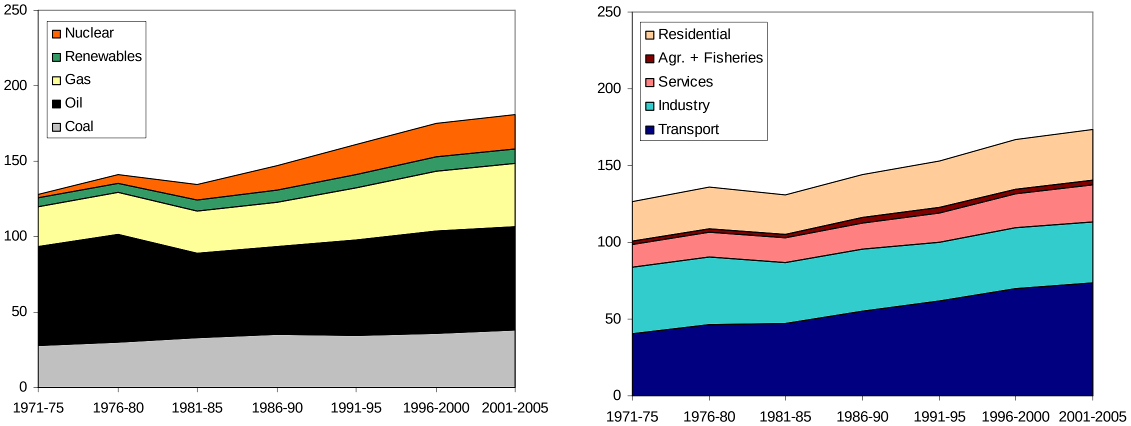
Figures and Tables

		Observations DCs	Observations OECD
Primary Energy Carriers	Coal, Oil, Gas, Renewables, Total Primary Energy	18	14
Sectors	Industry, Services, Transport, Residential, Agriculture and Fisheries	30	21
	CO_2 emissions	50	21

Table 1: Overview of data availability for the respective disaggregation of energy by primary energy carriers and sectors

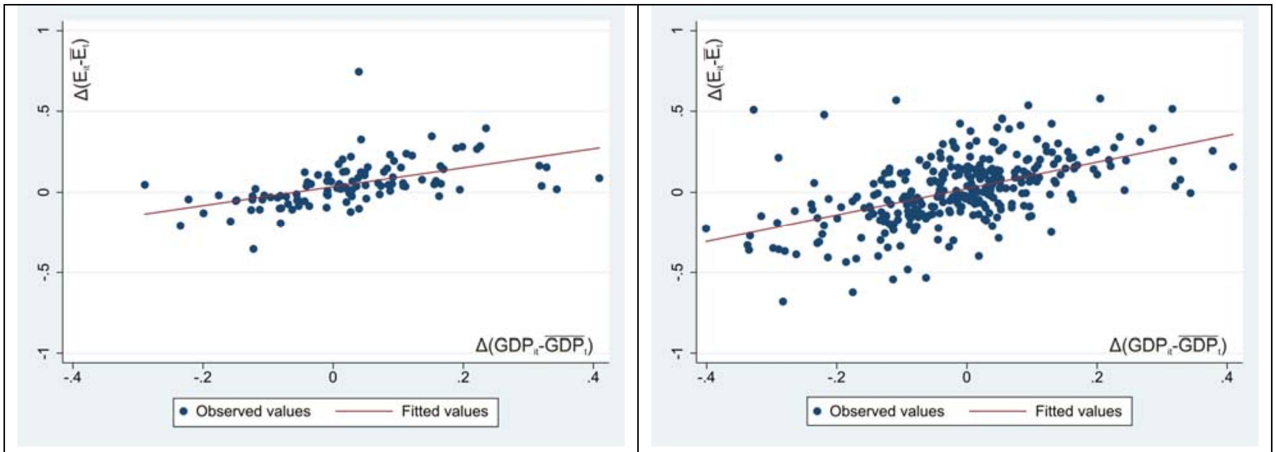


(a) Energy mix, developing countries **(b) Energy use by sector, developing countries**

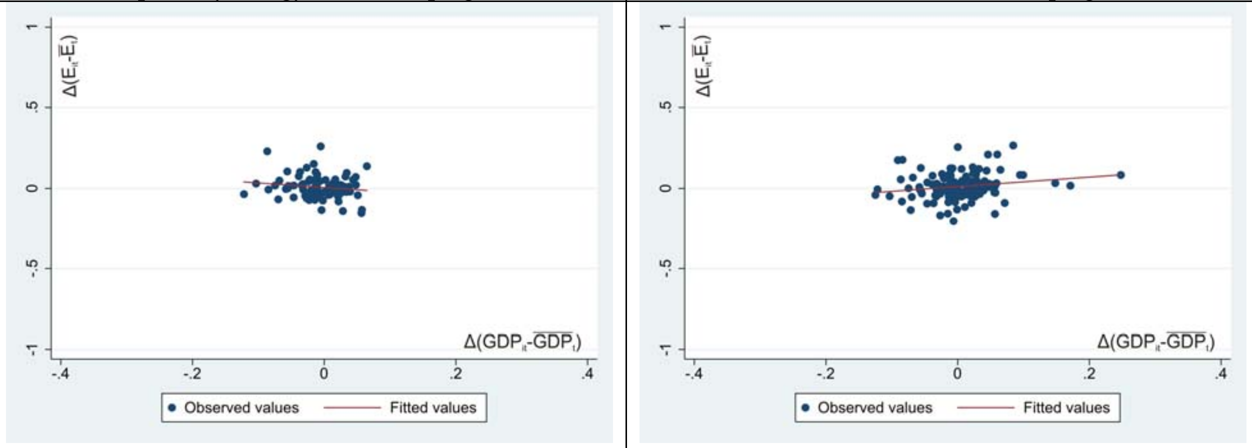


(c) Energy mix, OECD countries **(d) Energy use by sector, OECD countries**

Figure 1: Energy consumption (in exajoules) disaggregated by primary energy carrier and sectors for developing countries (panels (a) and (b)) and OECD countries (panels (c) and (d)). All sectoral energy use is in primary energy units. Note that due to statistical differences and the conversion of final energy to primary energy units, the sum over primary energy carriers does not match the sum over energy consumption by sector. Uses IEA (2007b,c)



(a) Total primary energy use, developing countries **(b) Total carbon emissions, developing countries**



(c) Total primary energy use, OECD **(d) Total carbon emissions, OECD**

Figure 2: Scatterplots showing the correlation between $\Delta(\ln E_{vit} - \ln \overline{E}_{vt})$ **on the y-axis and** $\Delta(\ln GDP_{it} - \ln G\overline{D}P_t)$ **on the x-axis for total primary energy use and total carbon emissions. Correlations for developing countries are depicted in panels (a) and (b), for industrialized countries in panels (c) and (d). Uses IEA (2007b,c) and WDI (2007)**

Energy System Variable ν	β_v	c_v	R^2
Coal	1.116* (0.561)	0.0197 (0.067)	0.064
Oil	0.441 (0.318)	0.166*** (0.0425)	0.162
Natural Gas	1.267** (0.548)	0.401*** (0.131)	0.161
Renewables	0.135 (0.177)	-0.0913 (0.0358)	0.039
Industry	1.014*** (0.143)	-0.0522 (0.0446)	0.067
Services	1.048*** (0.339)	0.0670 (0.0900)	0.074
Transport	1.081*** (0.211)	-0.0205 (0.0492)	0.239
Residential	0.084 (0.126)	-0.0081 (0.0173)	0.029
Agriculture and Fisheries	1.402** (0.654)	-0.0137 (0.102)	0.072
Total Primary Energy	0.631*** (0.167)	0.0625** (0.0248)	0.290
CO_2 Emissions	0.935*** (0.0964)	0.0285 (0.0182)	0.325

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 2: Relationship between growth (relative to the world average) of energy system variable ν and growth (relative to the world average) of per capita income for developing countries (β_v). Estimates were performed with 5-year-panels for the period 1971-2005, including country and period-specific fixed effects (period-specific fixed effects are reported in Appendix C).

Energy System Variable ν	β_v	c_v	R^2
Coal	0.772 (1.157)	-0.00601 (0.0594)	0.082
Oil	0.152 (0.485)	-0.0257 (0.0375)	0.025
Natural Gas	-1.741 (1.593)	0.236 (0.140)	0.101
Renewables	0.302 (0.651)	0.123*** (0.0397)	0.020
Industry	0.415** (0.171)	-0.0351** (0.0146)	0.062
Services	0.716 (0.424)	0.174* (0.0861)	0.060
Transport	1.021*** (0.141)	0.0291* (0.0154)	0.288
Residential	0.378 (0.261)	0.0681 (0.0501)	0.029
Agriculture and Fisheries	0.321 (0.882)	0.0634 (0.0699)	0.016
Total Primary Energy	-0.181 (0.343)	-0.0105 (0.0183)	0.024
CO_2 Emissions	0.129 (0.0914)	-0.0240** (0.0100)	0.027

Robust standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 3: Relationship between growth (relative to the world average) of energy system variable ν and growth (relative to the world average) of per capita income for OECD countries (β_v). Estimates were performed with 5-year-panels for the period 1971-2005, including country and period-specific fixed effects (period specific-fixed effects are reported in Appendix C).

Energy System Variable ν	$\beta_{v,1}$	$\beta_{v,2}$	$\beta_{v,3}$	c_v	R^2
Coal	2.878 (3.213)	-3.756 (3.881)	-0.0323 (1.882)	-0.0202 (0.0723)	0.120
Oil	1.087 (0.672)	-2.645** (0.941)	2.849** (1.232)	-0.0498 (0.0351)	0.148
Natural Gas	-1.985 (3.151)	-0.723 (4.196)	3.399 (3.739)	0.272* (0.127)	0.104
Renewables	0.231 (0.648)	-0.578 (1.114)	2.066 (2.053)	0.0662 (0.0524)	0.036
Industry	0.408** (0.178)	-0.567 (0.362)	1.334*** (0.467)	0.00250 (0.0171)	0.105
Services	0.677 (0.711)	-0.527 (0.822)	1.394 (1.249)	0.158* (0.0893)	0.066
Transport	1.137*** (0.224)	-0.111 (0.204)	-0.312 (0.436)	0.0216 (0.0167)	0.292
Residential	0.0758 (0.448)	0.392 (0.524)	0.566 (0.674)	0.0507 (0.0524)	0.039
Agric.+ Fishery	-0.550 (1.125)	-0.174 (1.261)	4.628* (2.254)	0.0367 (0.0564)	0.052
Total Prim. Energy	0.490 (0.498)	-1.945** (0.701)	2.185*** (0.627)	-0.0265 (0.0165)	0.182
CO_2 Emissions	0.143 (0.179)	-0.408 (0.261)	0.867** (0.310)	0.00726 (0.0100)	0.079

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Relationship between growth (relative to the world average) of energy system variable ν and growth (relative to the world average) of per capita income for OECD countries ($\beta_{v,1}$). To distinguish between different growth patterns, we included two additional interaction terms: one between our original explanatory variable $\Delta(GDP_{it} - G\overline{D}P_t)$ and a dummy variable denoting divergence ($\beta_{v,2}$) and a second between $\Delta(GDP_{it} - G\overline{D}P_t)$, the divergence dummy, and a dummy variable indicating if country i's per-capita income had been above the group average in period t-1 ($\beta_{v,3}$). Estimates were performed with 5-year-panels for the period 1971-2005, including country and period-specific-fixed effects (not reported).