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Economic growth, energy intensity and the energy mix☆

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ABSTRACT

This paper explores how changes in energy intensity and the switch to renewables can boost economic growth. To do so, we implement a dynamic panel data approach on a sample of 134 countries over the period 1960 to 2010. We incorporate a set of control variables, related to human and physical capital, socio-economic conditions, policies and institutions, which have been widely used in the literature on economic growth. Given the current state of technology, improving energy intensity is growth enhancing at the worldwide level. Moreover, conditional to energy intensity, moving from fossil fuels to frontier renewables (wind, solar, wave or geothermic) is also positively correlated with growth. Our results are robust to the specification of the dynamic panel with respect to alternative approaches (pooled OLS, within group or system GMM), and to alternative specifications (accounting for heterogeneity across countries, a set of institutional factors, and other technical aspects).

1. Introduction

Sustainability requires economic growth to be compatible with the social and environmental targets that are key for long term development (World Bank, 2012). Reducing energy intensity and switching to renewables have been proved to be viable options to reducing CO2 emissions for particular levels of development (Ang, 2007, 2008; Marrero, 2010; Apergis et al., 2010).[1] In this paper, we explore the links between economic growth and these two key energy dimensions at the worldwide level (see Ucan et al., 2014, and the references therein, for a recent survey about the links between energy and economic growth). We aim to quantify the extent to which a reduction in energy intensity paired with a movement to renewables can be reconciled with higher GDP per capita growth at the worldwide level. Therefore, could energy intensity reductions and the switch to renewables help curb down CO2 emissions and foster economic growth simultaneously?

A large body of research has analyzed the compatibility between economic growth and social targets, finding that the links between growth and social pillars are self-reinforcing in most cases. For instance, achievements such as reducing poverty (Ravallion, 2012), higher equality of opportunities (Marrero and Rodríguez, 2013), lower social conflict (Alesina et al., 1996), or higher political stability (Menegaki and Ozturk, 2013), are all factors that enhance growth. However, results are not that robust when the causal nexus between growth and the environment is taken into account. On the one hand, steady-state growth seems compatible with substantial reductions in local pollutants emissions (i.e., those pollutants related to local air quality and consequences on human health, such as CO, NOx, or sulfurs). On the other hand, for global pollutants such as CO2, the evidence that emissions first go up and later

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[1] More recently, Díaz and Puch (2018) analyze this relationship worldwide, Wang (2013) does for China and the US, and Álvarez Herranz et al. (2017) analyze OECD countries, emphasizing the role of energy innovation. Apergis et al. (2010) conclude that nuclear energy plays an important role in curbing CO2 emissions in the short run.

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go down in a growing economy, is not robust according to the literature related to the Environmental Kuznets Curve (EKC).[2]

A substantial body of existing literature has studied the link between the economy and CO2 emissions through the energy channel. For instance, Smiech and Papiez (2014) report evidence of different patterns of causality, depending on countries' degrees of compliance with the EU energy policy targets. These authors conclude that the higher the reduction in energy intensity and the higher the share of renewable energy consumption over total energy consumption, the greater the reduction of global emissions. In parallel, to understand the link between energy and the economy, several authors have emphasized the importance of the complementarity between capital and energy in the production technology. For instance, Atkeson and Kehoe (1999), and Díaz et al. (2004) made early attempts at understanding the mechanisms behind the short-term substitution between capital and energy and their consequences on production. Their results give theoretical support to the finding that big differences in energy prices across countries do not imply a substantial gap in macroeconomic performance though. The reason is that the production technology embodies channels that adjust energy price shocks in the medium run, fundamentally through investment in new, more energy efficient capital equipment. Yet, the capital replacement mechanism in Schumpeterian growth models helps to reconcile long-run growth with large movements in energy prices as in Ferraro and Peretto (2017). More recently, Díaz and Puch (2019) and Rausch and Schwerin (2017) have incorporated technological progress into various aggregate models with imperfect substitution between energy and capital. We take several pieces of these frameworks as a background for our empirical approach presented in Section 2, and to interpret our findings in Sections 5 and 6. We restrict our analysis to the energy factors-economic growth link.

While the positive effect on global emissions of reducing energy intensity and moving to renewables is a well-established result in the literature, the impact of both of these energy variables on economic growth deserves further exploration. For instance, while Inglesi-Lotz (2016), Bhattacharya et al. (2016, 2017) or Narayan and Doytch (2017), find a positive impact of renewables on growth, they do not account for energy intensity in their analysis. This omission could bias their results on the link between renewables and growth, because of the existing correlation between energy intensity and the energy mix (i.e., due to common environmental legislation or common technological progress).[3] At the same time, as each of these variables has its own inertia, it takes time for energy intensity and the mix to move alike, and consequently, simultaneity provides information on the quantitative importance of each channel as we show. Also, many of these studies produce results that differ significantly depending on the period, the set of countries, the variables included, or the method of analysis. These variations could be due to the state of the production technology in each setting. As technological progress makes renewable sources cheaper, the operating costs of these energy sources will actually decline, implying that their use become more appealing to boost growth.

Consequently, as stated above, our main goal is to analyze, on a global scale, the robustness of how changes in energy intensity, together with the changes in the share of renewables might affect growth. Our final purpose is to assess whether these energy factors are key drivers of growth, and therefore, suggesting that the link between growth and environmentally friendly energy might be self-reinforcing.

To achieve this goal, we construct a data set that combines economic, energy and other macroeconomic information for a total of 134 countries from 1960 through 2010. Then, we specify and estimate a reduced form growth model, in the spirit of Barro (2000) and Forbes (2000), but augmented with energy variables (Marrero, 2010). The energy variables are energy intensity, the primary energy mix (which distinguishes between fossil fuels, renewables sources and nuclear plants), and the final energy mix (which includes industry, transport, services, agriculture and the residential sector). In addition to the energy variables, we also include alternative macroeconomic variables widely used in the growth literature (the price of investment, educational attainment, fertility rates, government size, trade openness, inflation, etc.). We do so to explore the sensitivity of our growth-energy results to the specific choice of control variables.

We set-up a dynamic panel data (DPD) model over this dataset and estimate it using three alternative methods: i) pooled panel regression estimated by ordinary least squares; ii) fixed effect (within-group) approach; and iii) using system GMM approach (Blundell and Bond, 1998; Roodman, 2009) to try to overcome potential endogeneity issues, given the double-sense causality usually found between energy and GDP growth (Atems and Hotaling, 2018). In general, we find that our main results are robust to the econometric method and to the model specification considered.

The main findings of the paper are the following. First, improvements in energy intensity evolve alongside GDP per capita growth, regardless of the control variables included in the regressions and the econometric approach used. Conditional to the level of GDP and the energy mix, a 1% decrease in energy intensity is associated with a higher GDP per capita annual growth of between 0.5 and 1.0%, depending on the model specification.

Secondly, with respect to the primary energy consumption, the share of renewable energy sources negatively correlates with the growth rate. Given the level of GDP and energy intensity, an annual increase of 1 p.p. in the share of renewables (with respect to the share of fossil fuels) is associated, on average, with a lower per capita GDP growth of about −0.4 and −1.2 p.p., depending on the model. However, when we distinguish between "conventional" renewables (hydro and biomass) and "frontier" renewables (wind, solar, wave and geothermic), we find that moving from fossil fuels to conventional renewables is related to lower growth, but rather, if the switch goes towards "frontier" renewables, our results show a positive association with growth, with an elasticity ranging between 0.4 and 0.6.

Thirdly, with respect to the composition of the final energy mix, we find that only the share of the residential sector is negative correlated with growth, once variables such as energy intensity, the degree of development of the countries, and their primary energy mix, are controlled for in the regression analysis. Our estimates hover around −0.6 and −1.2, that is, those countries showing an annual increase of 1 p.p. of the share of the residential sector (relative to the primary sector) show, on average, a lower per capita GDP growth of about −0.6 and −1.2 p.p. This finding implies that neither the growing importance of energy consumption in services, mainly observed in developed countries, nor the increasing energy consumption in industry in countries such as China or India, are related to higher economic growth.

Our research is completed with a robustness study. We first explore whether the correlation between growth and the share of renewable energy sources is robust to alternative econometric methods and to the use of lagged energy intensity as an explanatory variable. We next explore the existence of possible heterogeneous patterns in the correlation between growth and the energy variables. We find heterogeneous patterns in the relation between growth and energy intensity concerning the period and the level of income. The sensitivity of economic growth with respect to energy intensity is higher after 1985 and for lower income per capita levels. We provide further evidence about the robustness of our estimates by including a rich set of alternative institutional factors.

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[2] For local pollutants with visible damage on health, the applicability of the policies at the local level has led policy makers to implement abatement policies very quickly (Álvarez et al., 2005; Brock and Taylor, 2010). On the other hand, the relationship between global emissions and economic growth has been extensively analyzed and the conclusions, in most cases, have found that the evidence of an EKC is weak (see Marrero, 2010, Kijima, 2010, and Bölük and Mert, 2014, and the references therein), especially when we look at the worldwide level.

[3] Another controversy in this literature is found in the direction of causality. For instance, Apergis and Payne (2010a, 2010b) report evidence for bidirectional Granger-causality between renewable energy consumption and economic growth in both the short-and long term in OECD countries over the period 1985–2005, and in Eurasian countries over the period 1992–2007, respectively. However, Ucan et al. (2014) provide empirical evidence in favor of the unidirectional causality of renewable energy consumption on GDP for 15 EU countries over the period 1990–2011. In this paper, we are interested in the causality of energy aspects on economic growth.

The rest of the paper is organized as follows. Section 2 discusses a general theoretical background. Section 3 describes the data set on growth and energy variables. Section 4 sets forth the reduced form equation that we finally work with, derived from the theoretical background in Section 2. Section 5 discusses the econometric approach implemented and shows the estimation results of the growth-energy model. Section 6 offers additional proofs of the robustness of our results. Finally, the last section concludes and introduces some possible energy policy prescriptions.

2. Theoretical background

This section presents a simple neoclassical framework that relates economic growth to energy intensity and differentiates the impact of renewable energy in the growth process (renewable as opposed to non-renewable energy). This framework will be used to motivate the empirical model presented in Section 4. We specify a sufficiently general aggregate production function where we make explicit the use of energy. This specification incorporates two key elements that account for differences in the energy technology across countries. First, we adopt a compact representation of *learning-by-doing* spillovers in the spirit of Aghion et al. (1999), which is incorporated through the lagged level of output. Secondly, we augment the production technology with J types of energy sources, which are imperfect substitutes, and aggregate them into a single energy input as in Hassler et al. (2018). We abstract, though, in our simple approach, from the sectoral composition of the economy and from the differential impact of renewable energy in the growth process. Rather, we adopt a reduced-form representation of the current state of energy efficiency, which we will assume it is embedded in the state of the technology through the inverse of the energy intensity in the economy.

We assume that aggregate output Y_t is produced from a bundle of resources, including energy usage, capital, and labor. We incorporate the existence of technological progress. For simplicity, let Z_t describe the energy input in the technology, and B_t synthetize all forms of other combined resources (i.e., capital and labor) along with the state of the technology. Thus, the production function can be written as:

$$Y_t = B_t Z_t^{\theta}, \tag{1}$$

where $0 < \theta < 1$. To simplify the exposition, we distinguish upfront among three primary sources: renewable sources ($j = 1$), nuclear plants ($j = 2$), and other sources including all type of fossil fuels ($j = 3$). We assume that Z_t is a homogeneous of degree one CES aggregator of the different primary energy sources $\{e_j\}_{j=1}^{3}$:

$$Z_t = \left[\lambda_1 e_{1,t}^{\rho} + \lambda_2 e_{2,t}^{\rho} + \lambda_3 e_{3,t}^{\rho}\right]^{1/\rho}, \tag{2}$$

with $\rho < 1$, and the elasticity of substitution between energy sources is $1/(1-\rho)$, and $\{\lambda_j\}_{j=1}^{3}$ denotes productivity parameters associated to each energy source. We further restrict to the case in which the three energy sources are relatively close substitutes, which requires $0 \le \rho \le 1$.

In addition, we specify the technological state B_t over the two key components stressed at the beginning of the section. First, a representation of *learning-by-doing* spillovers through the lagged level of aggregate income, Y_{t-1}. Secondly, a representation of the state of the energy technology in terms of energy efficiency through the inverse of the energy intensity, EI_t. Therefore, we consider the following parameterization:

$$B_t = \exp\{b_0\} \cdot Y_{t-1}^{\delta} \cdot EI_t^{-\pi} \cdot \overline{B}_t,$$

with $\delta > 0$, $\pi > 0$, and $b_0 > 0$ capturing the initial technological state, whereas $\overline{B}_t$ incorporates all other inputs (different from energy) used in production.

Let E_t denote aggregate primary energy demanded, that is $E_t = \sum_{j=1}^{3} e_{j,\ t}$, and let EI_t be the aforementioned energy intensity defined as primary energy usage relative to output, that is $EI_t = E_t/Y_t$. Furthermore, the primary energy shares are denoted by:

$$s_{j,t} = \frac{e_{j,t}}{E_t}, \text{where } \sum_{j=1}^{3} s_{j,t} = 1, \text{for all } t. \tag{3}$$

Thus, we can rewrite the production function in terms of these energy shares and the state of the technology, which depends on the lagged level of income and the energy intensity, that is:

$$Y_t = \ \exp\{b_0/(1-\theta)\} \cdot Y_{t-1}^{\frac{\delta}{1-\theta}} \cdot EI_t^{\frac{\theta-\pi}{1-\theta}} \cdot \overline{B}_t^{\frac{1}{1-\theta}} \cdot \left[\lambda_1 s_{1,t}^{\rho} + \lambda_2 s_{2,t}^{\rho} + \lambda_3 s_{3,t}^{\rho}\right]^{\frac{\theta}{(1-\theta)\rho}}. \tag{4}$$

There are three key elements in our representation of the technology. *First*, in order to induce stationarity, the power $\delta/(1-\theta)$ in the lagged term, Y_{t-1}, must be constrained below one. *Second*, the elasticity of output with respect to energy intensity EI_t can be either positive or negative, $(\theta-\pi)/(1-\theta)$. *Finally*, given that $\sum_{j=1}^{3} s_{j,\ t} = 1$, we can write (Álvarez Herranz et al., 2017) in terms of just the energy shares s_1 and s_2 (i.e., taking s_3, the share of fossil fuels, as the reference energy source).

It is straightforward to show that the signs of $\frac{\partial y_t}{\partial s_{1,t}}$ and $\frac{\partial y_t}{\partial s_{2,t}}$ depend on the signs of $(\lambda_1 s_{1,\ t}^{\rho-1} - \lambda_3 s_{3,\ t}^{\rho-1})$ and $(\lambda_2 s_{2,\ t}^{\rho-1} - \lambda_3 s_{3,\ t}^{\rho-1})$, respectively.[4] Hence, moving from fossil energy ($j = 3$) to renewables ($j = 1$) might have a negative impact on income (and growth) as long as $\lambda_1 s_{1,\ t}^{\rho-1} < \lambda_3 s_{3,\ t}^{\rho-1}$, i.e., when the aggregate productivity of renewables is lower than that of fossil fuels. In such a circumstance, a switch to cleaner energy technologies, that is more energy efficient technologies, will have a productivity cost as in Atkeson and Kehoe (1999), or Díaz and Puch (2019).

We will test and discuss on the sign of all these quasi-elasticities in our econometric exercise, i.e., whether $(\theta-\pi)/(1-\theta)$ is positive or negative on the one hand, and the signs of the coefficients associated to each primary energy source. With this representation, economies with similar energy intensities (due to either low energy or to high GDP) can differ in their energy mix. Also, both for the energy intensity and for the effect of changes in the share, either positive or negative signs are plausible cases. According to our theory, a negative correlation between energy intensity changes and economic growth corresponds to a situation in which the elasticity, π, of energy intensity in the state of the technology, B_t, is greater than the elasticity, θ, of the energy input in gross output.

Notice that our assumption on B_t, implies a direct productivity cost associated to lower energy efficiency (i.e., higher aggregate energy intensity). However, the choice of a particular energy mix $\{e_j\}_{j=1}^{3}$ has alternative implications for economic growth through the complementarity of energy with the production technology, and its impact on the energy efficiency of the energy sources. For instance, it is immediate to augment expression (4) to distinguish between different types of renewable energies, say frontier (i.e. wind, solar, wave or geothermic) versus conventional (hydro or biomass) renewables as we will do in the empirical

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[4] For the general expression, for$j = 1, 2,$in this case (j = 3 is fixed), these derivatives are given by:

$$\frac{\partial Y_t}{\partial s_{j,t}} = \frac{\theta Y_t}{(1-\theta)} \frac{\left(\lambda_j s_{j,t}^{\rho-1} - \lambda_3 s_{3,t}^{\rho-1}\right)}{\left[\lambda_1 s_{1,t}^{\rho} + \lambda_2 s_{2,t}^{\rho} + \lambda_3 s_{3,t}^{\rho}\right]} \gtrless 0,$$

and for the sake of simplicity, assuming $\rho = 1$ (i.e. perfect substitutes), these derivatives become:

$$\frac{\partial y_t}{\partial s_{j,t}} = \frac{\theta Y_t}{(1-\theta)} \frac{(\lambda_j - \lambda_3)}{[\lambda_1 s_{1,t} + \lambda_2 s_{2,t} + \lambda_3 s_{3,t}]} \gtrless 0,$$

So that the signs of the derivatives exclusively depend on $(\lambda_1 - \lambda_3)$ and $(\lambda_2 - \lambda_3)$ in our setting.

implementation of the model in Section 5. The adoption of renewables in the technological frontier may imply that energy use E_t is growing less than output, and thus, energy intensity will be decreasing while output is growing. This circumstance corresponds in the theoretical model to a negative coefficient for energy intensity, i.e. $(\theta - \pi)/(1 - \theta) < 0$. On the contrary, it might be the case that, a move towards not sufficiently efficient conventional renewables, turns out to be the result of an economy experiencing difficulties in its access to the international fossil fuels markets. We explore all these issues in Sections 5 and 6 below.

In particular, Rajbhandari and Zhang (2018) have recently provided evidence of long-run Granger causality from economic growth to lower energy intensity for a set of 56 economies analyzed from 1978 to 2012. They find, for middle-income economies, empirical support for long-run bidirectional causality between lower energy intensity and higher economic growth. These findings suggest that a positive effect of energy intensity and growth may occur solely at early stages of development. For instance, Voigt et al. (2014) find that reductions in energy intensity in most countries can be largely associated to technological change, whereas structural change plays a less important role. These authors only point to a less clear result for the cases of Japan, the United States, Australia, Taiwan, Mexico and Brazil.

3. Data description on economic growth and energy

To explore the link between energy and activity variables, we focus on the relationship between real GDP growth and energy intensity through the lenses of our theoretical framework. In doing so, we condition on both the primary and the final energy mix, and on a set of macroeconomic variables that have proven necessary for GDP growth. To organize the evidence, we comprehensively match energy and macroeconomic variables worldwide. Our database consists of an unbalanced panel of 134 countries spanning over the years 1960–2010.

Notwithstanding, in what follows, we will only refer to a final unbalanced panel of non-overlapping five-year periods of data, as it is standard in the recent empirical growth literature. Thus, we use a five-year frequency in our estimations, so the final panel contains 915 country-year observations for the aforementioned 134 countries over 1960–2010. As a consequence, lagged variables in the empirical model are denoted in five-year lag terms, while growth rates and other variables are annualized and measured over five-year periods. Our final sample extensively spans a broad time period, as well as it covers a highly heterogeneous sample of countries worldwide.[5]

This data set merges primary energy variables retrieved from the International Energy Agency, with series of population and real GDP (PPP adjusted in US$ 2005 prices) from the Penn World Tables (PWT 8.1). Additional controls considered in the econometric model described in Section 4 (such as educational attainment, investment prices, inflation, trade openness, government size, fertility rates or the quality of institutions) come from the PWT, the World Development Indicators of the World Bank, the Barro and Lee's (2013) educational attainment database, and the political risk module of the International Country Risk Database (ICRD) and the Polity 4 project (see Sections 4 and 6 for further details about the set of controls used).

Next, we briefly describe the information about energy and development we use. Our energy measure refers to primary energy consumption and it is defined in tons of oil equivalent (TOE)s. With respect to the energy inputs, renewable energy includes energy generated through hydro and biomass (we call these "conventional renewables"), plus wind, solar, geothermic and waves plants ("frontier renewables"). We also distinguish among final sectors of energy consumption: agriculture, industry, transport, residential, commerce and other services.

Table 1 reports the main descriptive statistics (mean and standard deviation) for our benchmark sample of 915 observations and restricted to the income and energy variables. We highlight the following aspects. Firstly, the average GDP per capita is $14,889 per year. The dispersion around the mean is huge (a standard deviation of $17,807 per year). In our sample, countries such as Mozambique, in 1995 or D.R. of the Congo in 2005 reached a GDP per capita of $422.30 and $502.26, respectively, while countries such as Norway and Singapore, reached $58,127 and $69,141, respectively, in 2010.

The range of the growth rates is also very wide, with a mean of 2.27% and a standard deviation of 5.44%. We have observations with highly negative growth rates (for example, −15% for Zimbabwe in 2005) and highly positive growth rates (for example, +21% for Yemen in 2005). In any case, on average, per capita GDP has grown worldwide except for the low-income countries group. It is worth noting that average growth rates in our sample are actually increasing with the level of income, so we can anticipate limited income convergence worldwide over the recent decades, at least unconditionally.

Regarding energy intensity, the mean of the sample is 202.1 TOE per 1M of US$, with a dispersion of 143.1. We observe strongly inefficient countries in terms of their use of energy, such as Luxembourg in 1975 or Turkmenistan in 2005, with energy intensities as high as 400 TOE, together with highly energy efficient countries, such as Switzerland in 1995 or Dominican Republic in 2010 with energy intensities clearly below 100 TOE.

With respect to the primary energy share, at the aggregate level, fossil fuel sources account for 70% of the production of energy, and renewable sources account for 27%. Moreover, the share of fossil fuel sources increases with the level of income, at the expense of lowering the share of (conventional) renewable sources. Clearly, the sharp differences in the level of GDP per capita across countries reflect different stages in development. On the other hand, the share of nuclear plants also increases with income, although this share barely represents a 1% in non-OECD high-income countries. With respect to the final consumption of energy, the residential sector is by far the most important one (32.5%), together with industry (26%), and transport services (23%). Actually, the residential sector accounts for the bulk in final energy consumption in low-income countries. The role of this residential share decreases with the income level. By contrast, the pattern is (more or less) one of increasing shares for industry, transport and services.

To illustrate the dispersion in the entire pool of data, Fig. 1 confronts the main economic and energy variables. The top panel depicts the scatter between GDP per capita and energy intensity for the levels (in logs, left picture) and the growth rates (right). The scatter between GDP per capita and energy intensity shows the enormous diversity of both variables in the sample. Indeed, we observe a wide range of country-year observations with small energy intensity and an enormous variation in their degree of development (almost 400% difference in the most extreme cases). Thus, although the correlation for the levels of these variables is negative, the observed dispersion is very large. However, when looking at their annual growth rates, the relationship between GDP and energy intensity turns out to be clearly negative and highly significant. That is, improvements in the use of energy (reductions of energy intensity) are associated with higher economic growth rates.

The bottom panel depicts the scatter between GDP per capita and the share of renewables (left picture) and the annual changes (right). When looking at the correlation between GDP per capita and the share of renewables (bottom panels of Fig. 1), the evidence is not that clear. While the correlation between the levels of GDP per capita and the share of renewables is negative (left picture), although weak, that of the GDP per capita growth and the change in the share of renewables is null (right picture). Actually, any descriptive evidence seems unclear, and therefore, in order to properly quantify the partial correlations between economic growth and the energy variables considered, we propose the empirical exercise in this paper, under alternative specifications.

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[5] Following the World Bank classification, our 915 observations can be classified according to their geographical location: 20 observations are from North America, 323 from Europe and Central Asia, 149 from Latin American and the Caribbean, 123 from the Middle East and North Africa, 143 from Sub-Saharan Africa, 42 from South Asia and 115 from East Asia and the Pacific.

Table 1
Descriptive statistics.

Variable	Unit	All countries		Low-income		Mid-low income		Mid-high income		High-income (OECD)		High-income (non-OECD)	
		Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Real GDP per capita	Level, US-2005$/(person x 1000)	14.9	17.8	1.5	0.8	3.4	1.9	8.6	4.0	25.1	11.8	36.6	34.2
Real GDP per capita	Growth rate (%)	2.27	5.44	−0.10	5.55	1.93	7.15	2.83	5.20	2.83	2.33	2.13	7.38
Energy Intensity	TOE (primary) per 1 M US$	202.1	143.1	316.1	200.8	227.6	181.6	171.5	100.2	175.1	77.7	201.8	167.9
Fossil share	% w.r.t. primary energy	70.1	28.5	20.6	17.9	51.7	28.4	77.4	17.2	80.9	17.2	97.5	5.9
Renewable share	% w.r.t. primary energy	27.3	29.5	79.3	17.6	49.7	34.3	21.0	17.6	12.3	15.4	1.2	3.9
Nuclear share	% w.r.t. primary energy	2.6	6.8	0.0	0.0	0.8	3.9	1.2	4.8	6.4	9.8	0.9	3.7
Agriculture share	% w.r.t. final energy	2.6	3.2	2.7	4.8	2.0	2.5	3.2	3.3	3.2	3.2	0.5	1.0
Industry share	% w.r.t. final energy	26.2	12.6	11.2	8.4	20.0	10.3	30.2	11.5	30.9	9.3	28.7	15.1
Transport share	% w.r.t. final energy	23.3	11.3	8.3	6.9	19.9	9.2	27.3	10.6	24.3	8.3	30.4	13.0
Residential share	% w.r.t. final energy	32.5	21.2	68.8	21.6	47.7	18.8	26.7	11.7	22.8	8.0	12.0	7.6
Services share	% w.r.t. final energy	6.2	5.7	2.6	3.6	5.2	6.6	4.8	3.5	9.1	4.8	7.1	7.8
Other sectors share	% w.r.t. final energy	9.2	10.5	6.4	12.6	5.1	6.2	7.7	7.5	9.8	6.9	21.3	18.1
	Sample size	915		90		194		253		276		102	

Notes. Source of data, list of countries, period considered, etc.
The shares for fossil fuels, renewable plants and nuclear plants energy have been calculated as the ratio corresponding to the consumption of primary energy relative to total primary energy. The sector shares have been calculated as final consumption of energy in sector s relative to total final consumption.

To sum up, the evidence described so far supports a negative relationship between economic growth and energy intensity growth. However, the energy mix profiles across countries seem to exhibit conflicting patterns. These two observations lead us to the specification of a model to properly identify the partial correlations between economic growth and the energy variables. For this purpose, it is important to test for common slopes worldwide, and to interpret the role of well-established technology and policy variables.

4. The empirical implementation: A growth-energy dynamic panel data model

Based on the model described in Section 2, we now introduce a reduced form specification model relating economic growth with energy variables (i.e., energy intensity and energy mix), as well as a set of macroeconomic control variables widely used in the growth literature. Our baseline reduced form is closely related with those specifications used in the economic growth literature (i.e., see Barro, 2000, and Forbes, 2000, among many others) and similar to the one used by Marrero (2010) in its application to CO2 emissions determinants in Europe. Thus, we start by estimating the following dynamic panel data model:

$$GY_{i,t} = \alpha + R_i + T_t + \beta \, \ln(\mathrm{Y}_{\mathrm{i,t-1}}) + \theta' XE_{i,t} + \lambda' X_{i,t} + \varepsilon_{i,t}, \tag{5}$$

where the dependent variable, $GY_{i,\ t}$, denotes per capita annual growth across the entire period (5 years, in our case) for country i and year t. That is, our dependent variable is expressed in growth rates rather than in levels, as considered in many papers in the related literature. We modify this assumption in Section 6.1, where we re-estimate our model using log-levels instead (see the discussion in that section and the references therein). In addition, R_i and T_t are country- and time-specific effects. In order to control for initial technology and conditional convergence, the per capita real GDP (in logs) at the beginning of the period, $\ln(\mathrm{Y}_{\mathrm{i,\ t-1}})$ is included.

The term $\theta\,' XE_{i,\ t}$ encompasses the effect of a set of energy variables with the following structure (Marrero, 2010):

$$\theta' XE_{i,t} \equiv \theta_0 \Delta EI_{i,t} + \sum_{j=1}^{J-1} \theta_j^m \Delta m_{j,i,t} + \sum_{k=1}^{K-1} \theta_k^s \Delta s_{k,i,t}. \tag{6}$$

The first key term $\Delta EI_{i,\ t}$ denotes the annual growth rate of the energy intensity, defined as the ratio between total primary energy consumption and real GDP (in TOE per 1 M US$). The second term, $\Delta m_{j,\ i,\ t}$, denotes the annual changes (in percentage points, p.p.) in the share of consumption of primary energy from the source j over total primary energy. We classify primary energy from source j following the IEA criterion: renewable, nuclear, and fossil fuels (coal, oil and gas). The final term in expression (6), $\Delta s_{k,\ i,\ t}$, denotes the annual changes (in p.p.) in the share of final consumption of energy in sector k over total final consumption. Sectors k are grouped into industry, transport, residential, service and agriculture. This set of variables attempts to control for the changes in the final use of energy in economic sectors. In this way, we consider the differential effects that a *primary* energy source, such as renewable, may have depending on the *final* sector, such as transport, in which it is employed. In Section 6.1, we will also relax the assumption that energy variables are expressed as growth rates or first differences.

In order to avoid multicollinearity in the estimation of (Ang, 2007), we omit fossil fuels from primary energy, and agriculture from the final energy mix. Thus, the estimated coefficients should be understood with respect to these omitted categories. In this sense, θ_j^m accounts for the quasi-elasticity of economic growth with respect to a change of the share in the primary mix from source j (i.e., renewables and nuclear) relative to the fossil fuels, while θ_k^s accounts for the growth due to a change in the share of final energy consumption in the sector k (industry, transport, residential, service) from the agriculture sector.

The last component in Eq. (5), $X_{i,\ t}$, comprises a set of control variables influencing the heterogeneous pattern of economic growth across countries. It includes technology and policy factors (details are shown

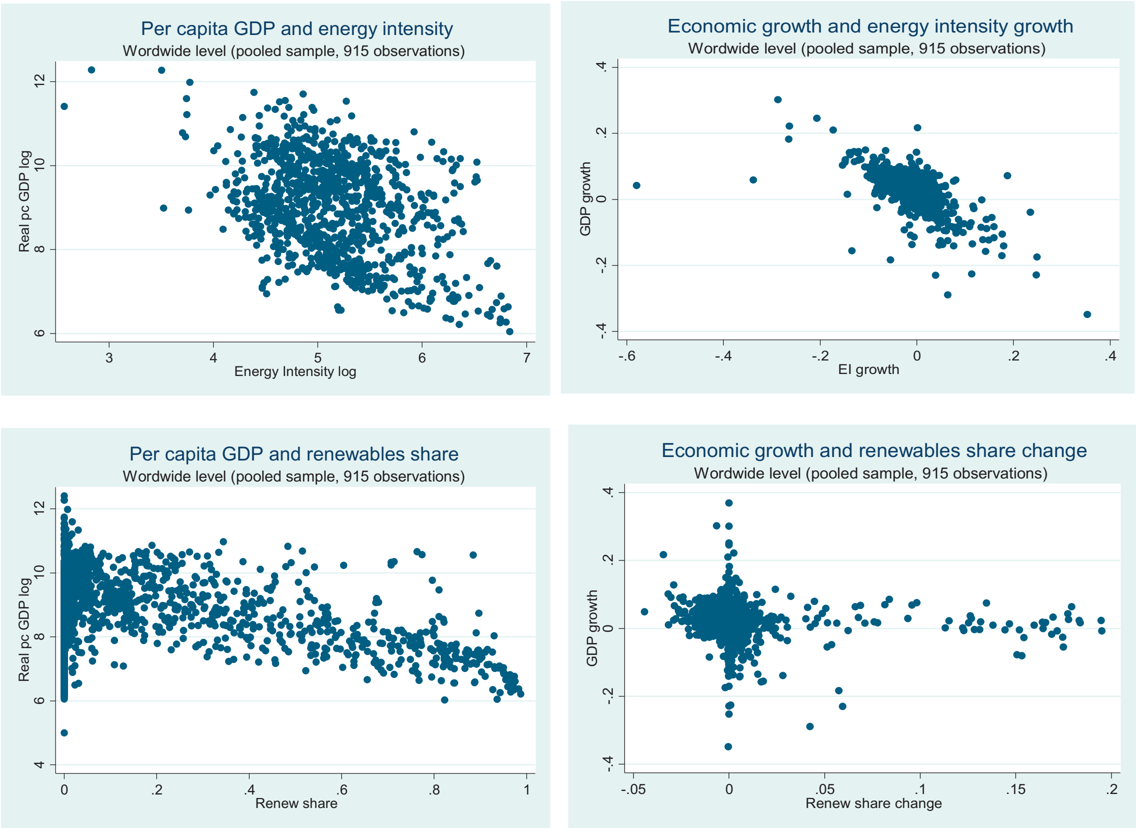

Fig. 1. Facts on income, energy intensity, and renewable sources.

below). We opt for considering alternative specifications to explore the sensitivity of the growth-energy results to the choice of macroeconomic factors. In all cases, energy variables are introduced sequentially, in order to analyze their direct impact on growth alongside the indirect effects produced by other energy variables.

For all specifications of (5), the set of variables $(R_i, T_t, \ln(Y_{i,\,t-1}), \Delta EI_{i,\,t})$ is always included, i.e., regional and time dummies, the lagged per capita income, and the change in energy intensity that is part of expression (6). In addition, the rest of the energy variables in (Ang, 2008), are sequentially incorporated to the structure: first the primary shares $\{\Delta m_{j,\,i,\,t}\}_{j=1}^{J-1}$, and then the sector shares $\{\Delta s_{k,\,i,\,t}\}_{k=1}^{K-1}$. Bearing this sequential strategy in mind, we define three specifications, labeled as M1, M2 and M3.

In specification M1, also referred to as the *skeleton* model, no additional control is considered, i.e., $X_{i,\,t} = 0$ in (5). The second specification M2 adds controls from the empirical growth literature, as in Perotti (1996), Forbes (2000), and Knowles (2005). In particular, the price of investment goods relative to those of the U.S. is considered as a measure of market distortions.[6] Additionally, as a measure of human capital, we use the rate of primary and secondary attained education (as a percentage of the population).[7] Finally, the third specification M3 considers standard policy indicators as control variables (in line with Barro, 2000): the inflation rate (GDP deflator) as an indicator of macroeconomic stability, the adjusted ratio of the country's volume of trade to the country's GDP as an indicator of the degree of openness of the economy, the ratio of public consumption to GDP as an indicator of the burden imposed by the government on the economy, and the fertility rate (number of births over population).[8] In Section 6.4, we consider controls for institutional quality, such as the degree of democracy, political stability, control of corruption, etc., variables taken from the political risk module of the International Country Risk Database (ICRD).[9]

5. Estimation results

We now analyze our estimates. First, we comment on the econometric strategy to estimate (5)-(Ang, 2008). This consists of implementing three alternative methods: pooled-OLS, within-group (WG) and system GMM. We do so by choosing alternative specifications for the three sets of variables we use: energy, technology and policy variables. Finally, we discuss the main findings.

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[6] In the growth literature, the price of investment goods relative to those of the U.S. has been considered as an indicator of market distortions. Thus, we take as negative its impact on growth (Forbes, 2000; López and Servén, 2009). This variable captures a different aspect than gross fixed capital formation (as a share of GDP), as a proxy for physical capital, which is another widely used variable in growth models (we will consider this in Appendix E, as a robustness check).

[7] Human capital is generally assumed to be beneficial for growth. However, recent studies have raised some caveats about the validity of average years of schooling or the percentage of the population with primary or secondary education, to proxy the role human capital on growth (see Sianesi and Van Reenen, 2003, among many others), as they do not account for the "quality" of education (Hanushek, 2017). Nevertheless, the main results in the paper (i.e., those estimations related with energy variables) remain valid when using alternative proxies of human capital, such as the average years of secondary education of the male population, or the average years of secondary education of the female population. Results are available upon request.

[8] Although the Inflation rate is associated with economic fluctuations, it is also related with economic uncertainty and, for that reason, it is a widely used factor in the growth literature (see Barro, 2000, or more recently, Marrero and Servén, 2018, among many others). Thus, we hypothesize that the inflation rate is harmful for growth. Government size is a measure of aggregate public distortions and should be viewed as harmful for growth and the steady state level of output (Barro, 2000). Finally, the existing empirical evidence reveals that a rise in net fertility rate has a negative impact on growth (Galor and Zang, 1997; Barro, 2000), through its negative effect on inequality and labor productivity in developing countries.

[9] It is worth mentioning that, in general, institutional quality variables are strongly correlated with other macroeconomic variables already included in the different models, such as the per capita GDP or the inflation rate.

5.1. Econometric issues

Each specification of Eq. (6), namely M1, M2 and M3, is firstly estimated through robust pooled-OLS including controls for both regional and time dummies (Table 2.a). Next, we compute WG estimates (Table 2.b). With respect to pooled-OLS, the WG has the advantage of dealing with the existence of country-specific (and time-invariant) effects possibly correlated with regressors. However, several authors such as Banerjee and Duflo (2003), Barro (2000) or Partridge (2005), raise some caveats as regards to the WG approach. This is because it may produce inaccurate results for controls that mostly vary in the cross-section, such as growth and energy usage in our case, as the method takes into account within-state variability. Additionally, in dynamic models, pooled-OLS and WG estimates are affected by an endogeneity bias, at least due to the lagged GDP term included in (5)-(6) as a regressor. For that reason, the lagged dependent variable is dropped from models in Tables 2.a and 2.b, as in static models. Nevertheless, it is worth mentioning that the estimated results for all other variables remains basically unchanged when a dynamic term is included under pooled-OLS and WG estimates (results are available upon request).

To address the endogeneity problem in a dynamic panel data framework in the absence of suitable external instruments (a standard limitation of growth models) a GMM based approach is a natural alternative in a dynamic context (Arellano and Bond, 1991; Arellano and Bover, 1995). The basic idea is to first-differentiate Eqs. (5)–(6), and then employ the levels of the explanatory variables - lagged two or more periods - as internal instruments (i.e., in Eqs. (5)–(6): $\ln(\mathrm{Y}_{\mathrm{i},\,t-s})$, $XE_{i,\,t-s}$, $X_{i,\,t-s}$, for $s \geq 2$), resulting in a first-difference GMM estimator (Arellano and Bond, 1991).

However, using the model only in the first-differences form may lead to important finite sample bias when variables are highly persistent (Blundell and Bond, 1998), which is the case of variables like per capita GDP or energy intensity. An alternative to the first-difference GMM estimator is the system-GMM approach (Arellano and Bover, 1995; Blundell and Bond, 1998). This consists of estimating a system of equations in both first-differences and levels, where now the instruments of the level equations are suitable lags of the first differences variables (i.e., $\Delta \ln \mathrm{Y}_{\mathrm{i},\,t-1}$, $\Delta XE_{i,\,t-1}$ and $\Delta X_{i,\,t-1}$).[10] We consider robust standard errors with a variance-covariance matrix corrected by small sample properties (Windmeijer, 2005; Roodman, 2009). Table 2.c reports the results for the system GMM strategy.

The validity of the GMM instruments is tested using an over identifying Hansen J-test (Table 2.c). It is worth mentioning, though, that the proliferation of instruments, relative to the number of cross-sectional units (a common issue in system-GMM macroeconomic model estimation), biases downward the estimated standard errors and weakens the power of the overidentification tests (Roodman, 2009). Under this over identifying situation, the p-value of the Hansen J-test tends to be close to one, and we must apply the Windmeijer (2005) correction to the variance-covariance matrix and call for an instrument's reduction (Roodman, 2009). Bearing this in mind, in our baseline system GMM specification (three first columns from each panel in Table 2.c), we limit the number of instruments in the instruments matrix to one.[11] However, when all energy variables are included in the model (the third column from each panel in Table 2.c), this

Table 2.a
Pooled-OLS estimation (static panel).

Dependent variable: GDP per capita growth (5-year average)	Model 1: Skeleton model			Model 2: Model with human capital & investment prices			Model 3: Model with policy variables		
Energy Intensity, % change	−0.645***	−0.651***	−0.644***	−0.597***	−0.598***	−0.595***	−0.705***	−0.702***	−0.702***
	(−7.19)	(−7.62)	(−7.51)	(−5.14)	(−5.25)	(−5.18)	(−17.44)	(−17.95)	(−17.75)
Renew. Mix, % change		−1.192***	−0.830***		−0.667***	−0.439***		−0.721***	−0.545***
		(−4.31)	(−3.34)		(−3.56)	(−2.78)		(−3.59)	(−2.98)
Nuclear. Mix, % change		−0.0385	−0.0105		0.0914	0.0940		0.0641	0.0113
		(−0.17)	(−0.05)		(0.57)	(0.55)		(0.35)	(0.06)
Industrial Mix, % change			0.118			0.0597			0.191
			(0.77)			(0.43)			(1.29)
Transport Mix, % change			−0.0330			−0.0157			−0.0796
			(−0.16)			(−0.09)			(−0.46)
Residential Mix, % change			−1.093***			−0.852***			−0.712***
			(−5.77)			(−5.37)			(−5.06)
Service Mix, % change			−0.382			−0.211			−0.351
			(−1.07)			(−0.79)			(−1.40)
log(Invest. Price), lagged				−0.00497***	−0.00439***	−0.00318***			
				(−4.61)	(−4.17)	(−3.21)			
Attained primary ed., % over Pop., lagged				0.0147	0.0181	0.0171			
				(0.99)	(1.27)	(1.21)			
Attained secondary ed., % over Pop., lagged				−0.0114	−0.00352	0.0000249			
				(−1.06)	(−0.33)	(0.00)			
Fertility rate, lagged							−0.00211*	−0.00222*	−0.00250**
							(−1.75)	(−1.90)	(−2.07)
Inflation, 5-year average							−0.00766*	−0.00671	−0.00412

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[10] Huang et al. (2008) and Marrero (2010), among many others, have emphasized the relevance of using system GMM when working with dynamic panel data growth models. Recently, see Atems and Hotaling (2018) for a similar exercise using the GMM approach.

[11] Following Blundell and Bond (1998), for the set of equations in first-differences, we use the levels of the regressors lagged two periods ($\ln(\mathrm{Y}_{\mathrm{i},\,t-2})$, $XE_{i,\,t-2}$, $X_{i,\,t-2}$) as instruments, while for the set of level equations, we use the first difference of the regressors lagged one period ($\Delta \ln (\mathrm{Y}_{\mathrm{i},\,t-1})$, $\Delta XE_{i,\,t-1}$, $\Delta X_{i,\,t-1}$). In all GMM specification, we use R_i and T_t as exogenous instrument (Baltagi, 2005).

							(−1.76)	(−1.59)	(−1.07)
Gov. Size, 5-year average							−0.00406*	−0.00398*	−0.00240
							(−1.72)	(−1.74)	(−1.09)
Openness trade, 5-years average							0.00322	0.00357	0.00391*
							(1.31)	(1.57)	(1.82)
Num. Obs	915	915	915	814	814	814	744	744	744
R2-adj	0.528	0.577	0.617	0.533	0.554	0.585	0.593	0.622	0.650
Num. Countries	134	134	134	120	120	120	128	128	128

Notes: Regressions above are pooled-OLS results, with constant, regional and time dummies, and robust variance-covariance. Fossil fuel mix is omitted for the primary energy mix (i.e. fossil fuel mix plus renewable mix plus nuclear plants mix amount to one). Agriculture, Cattle and Fishing sector is omitted from the final energy mix (i.e. the final mix for agriculture together with industrial, transport sector, services and residential sector must sum up to one). Figures into parenthesis represent t-statistics. Starred values denote significance at $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

strategy still leads to a problem of too many instruments, i.e., the number of instruments clearly exceeds the number of cross-sections and the *p*-values of the Hansen test still hover around one. In this case, we also show the results when collapsing the matrix of instruments, which further reduces the number of instruments (fourth column from each panel in Table 2.c).[12]

Noticing these situations, the Hansen's J-test suggests that the null hypothesis of joint validity of all instruments cannot be rejected in most cases. Moreover, we also compute a difference-in-Hansen test, which compares the efficiency of system GMM over first-difference GMM in each model (their *p*-values are always >0.10, see Table 2.c).

As a final caveat, it should be mentioned that the system-GMM performs better when the number of cross-sectional observations (N) is large (i.e., consistency is obtained as N tends to infinite). This is an advantage in our case given the worldwide sample. However, when data exhibit a high degree of persistence (which may lead to problems of weak instruments even in system GMM), as in our case, the system GMM estimators can also behave poorly (Binder et al., 2005; Bun and Sarafidis, 2015). Thus, under this situation, as in many macroeconomic applications, it is not evident that a GMM based approach is preferred over robust pooled-OLS (with regional and time dummies) or vice versa. In this situation, it is a good practice to report both estimation results (as we do) and verify robustness.

5.2. Main findings

We next show our estimation results of models M1, M2 and M3 using robust pooled-OLS (Table 2.a), within-group estimates (Table 2.b) and system GMM (Table 2.c). As we shall see, a key estimation result is the composition effect towards renewable energy between “conventional” and “frontier” technologies, as defined earlier. Thus, Table 3 reports estimates of models M1 through M3 using system-GMM, and where the trade-off between incentives to switch to either technology is explored. Our initial panel contains 915 country-year observations (Section 3), but the final number of observations used in the estimation of each model could be reduced due to limited availability of data for several control variables in the empirical specifications (i.e. the $X_{i,\,t}$ component in (6).

Indeed, given that the income level of a country can affect its energy intensity and energy consumption structure, throughout the paper, we use the system GMM estimator to address this potential endogeneity issue. Nevertheless, we also consider the alternative of a *simultaneous equation system* where our baseline equation is complemented with another equation for the change in energy intensity in which income growth is the explanatory variable. Such a system is estimated as a seemingly unrelated equation system (SURE) by maximum likelihood, and results are included in Appendix A. We next discuss the main findings.

5.2.1. The role of energy intensity

We provide strong evidence of a robust negative correlation between energy intensity and economic growth at the worldwide level. The coefficients of energy intensity are always negative and highly significant, consistent with the unconditional evidence provided in Fig. 1. This means that the reductions in energy intensity are found to be associated with higher GDP growth. This qualitative result is robust to a change in the econometric method used. For the static panel estimated by pooled-OLS in Table 2.a, we find that, on average, a 1% reduction in energy intensity is associated with an increase in the per capita growth

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[12] Following Roodman (2009), when collapsing the matrix of instruments, we create one instrument for each variable and lag distance, rather than one instrument for each lag distance, time period and variable. Notice that this strategy does not mean to collapse the cross-section dimension of the panel (i.e., to average observations across countries). On the contrary, the panel dimension of the sample remains unchanged. Indeed, we consider all lags (t-2 and further) to collapse the matrix of instruments.

Table 2.b
Within group estimation (static panel).

Dependent variable: GDP per capita growth (5-year average)									
	Model 1: Skeleton Model (M1)			Model 2: Model with human capital & investment prices (M2)			Model 3: Model with policy variables (M3)		
Energy Intensity, % change	−0.652***	−0.662***	−0.648***	−0.589***	−0.593***	−0.587***	−0.719***	−0.720***	−0.715***
	(−6.40)	(−7.01)	(−6.84)	(−4.73)	(−4.91)	(−4.79)	(−14.43)	(−15.39)	(−15.49)
Renew. Mix, % change		−1.224***	−0.832***		−0.689***	−0.433**		−0.669***	−0.482**
		(−3.64)	(−2.70)		(−3.47)	(−2.53)		(−3.22)	(−2.52)
Nuclear. Mix, % change		−0.0846	−0.0984		0.0815	0.00964		0.101	−0.00692
		(−0.47)	(−0.53)		(0.46)	(0.04)		(0.48)	(−0.03)
Industrial Mix, % change			0.139			0.0569			0.157
			(0.78)			(0.40)			(0.95)
Transport Mix, % change			0.145			0.137			0.0280
			(0.66)			(0.85)			(0.16)
Residential Mix, % change			−1.009***			−0.780***			−0.650***
			(−4.28)			(−4.44)			(−3.66)
Service Mix, % change			−0.493*			−0.392			−0.362
			(−1.70)			(−1.32)			(−1.26)
log(Invest. Price), lagged				−0.00516***	−0.00465***	−0.00349**			
				(−4.24)	(−3.54)	(−2.54)			
Attained primary ed., % over Pop., lagged				0.00751	0.00825	0.0116			
				(0.35)	(0.43)	(0.59)			
Attained secondary ed., % over Pop., lagged				0.00791	0.0112	0.00836			
				(0.32)	(0.47)	(0.35)			
Fertility rate, lagged							−0.00727***	−0.00671***	−0.00652***
							(−3.41)	(−3.43)	(−3.32)
Inflation, 5-year average							−0.00939*	−0.00785	−0.00551
							(−1.74)	(−1.51)	(−1.02)
Gov. Size, 5-year average							−0.0149**	−0.0134**	−0.0118*
							(−2.19)	(−2.01)	(−1.83)
Openness trade, 5-years average							0.00669	0.00787	0.00828
							(1.05)	(1.23)	(1.24)
Num. Obs	915	915	915	814	814	814	744	744	744
R2-adj	0.547	0.596	0.630	0.526	0.549	0.576	0.617	0.642	0.665
Num. Countries	134	134	134	120	120	120	128	128	128

Notes: Regressions above are fixed effects estimation results (WG estimates), with time dummies and robust variance-covariance. Fossil fuel mix is omitted for the primary energy mix (i.e. fossil fuel mix plus renewable mix plus nuclear plants mix amount to one). Agriculture, Cattle and Fishing sector is omitted from the final energy mix (i.e. the final mix for agriculture together with industrial, transport sector, services and residential sector must sum up to one). Figures into parenthesis represent t-statistics. Starred values denote significance at $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 2.c
GMM estimation (dynamic panel).

Dependent variable: GDP per capita growth (5-year average)												
	M1: Skeleton Model				M2: Model with human capital & investment prices				M3: Model with policy variables			
log(income), lagged	−0.0108	−0.0148	−0.00221	−0.0136	−0.00130	−0.000410	0.000242	0.00709	−0.00921*	−0.00662	−0.00489	−0.00345
	(−0.84)	(−1.51)	(−0.49)	(−0.04)	(−0.26)	(−0.11)	(0.08)	(1.08)	(−1.90)	(−1.59)	(−1.32)	(−0.64)
Energy Intensity, % change	−0.945***	−0.978***	−0.802***	−0.844	−0.687***	−0.663***	−0.629***	−0.701***	−0.871***	−0.778***	−0.734***	−0.821***
	(−11.90)	(−13.30)	(−13.03)	(−0.51)	(−4.68)	(−5.20)	(−5.82)	(−6.65)	(−11.61)	(−10.44)	(−11.69)	(−11.27)
Renew. Mix, % change		−2.171***	−1.126***	−1.377		−0.723**	−0.640**	−1.076***		−0.882***	−0.422*	−1.007**
		(−2.63)	(−2.61)	(−0.28)		(−2.38)	(−2.12)	(−2.80)		(−2.80)	(−1.80)	(−2.55)
Nuclear. Mix, % change		0.194	0.143	−0.275		0.0164	0.0531	−0.249		0.0136	−0.252	0.142
		(0.83)	(0.52)	(−0.04)		(0.11)	(0.15)	(−0.84)		(0.06)	(−0.64)	(0.48)
Industrial Sector, % change			−0.0451	−0.242			0.248	0.278			0.0524	0.00182
			(−0.12)	(−0.04)			(0.89)	(0.84)			(0.21)	(0.01)
Transport Sector, % change			−0.172	−0.322			0.104	0.128			−0.220	−0.428
			(−0.55)	(−0.11)			(0.45)	(0.72)			(−0.92)	(−1.31)
Residential Sector, % change			−1.188***	−0.789			−0.793***	−0.533*			−1.009***	−0.668***
			(−3.71)	(−0.23)			(−3.97)	(−1.76)			(−3.59)	(−2.60)
Service Sector, % change			−0.286	−0.736			0.0355	−0.133			−0.402	−0.412
			(−0.77)	(−0.09)			(0.07)	(−0.40)			(−1.05)	(−1.23)
log(Invest. Price), lagged					−0.00361***	−0.00335***	−0.00250***	−0.00240***				
					(−3.03)	(−3.11)	(−2.71)	(−3.20)				
Attained primary ed., % over Pop., lagged					0.0100	0.0106	0.0157	0.0379				
					(0.22)	(0.32)	(0.53)	(1.23)				
Attained secondary ed., % over Pop., lagged					−0.0458	−0.0371	−0.0137	0.0147				
					(−0.99)	(−1.11)	(−0.55)	(0.18)				
Fertility rate, lagged									−0.0106***	−0.00846***	−0.00650**	−0.00656*
									(−2.68)	(−2.97)	(−2.41)	(−1.74)
Inflation, 5-year average									−0.000238	−0.000426	−0.000454	−0.000734***
									(−0.98)	(−1.32)	(−1.36)	(−2.97)
Gov. Size, 5-year average									−0.0176**	−0.0181***	−0.0132**	−0.0290**
									(−2.32)	(−3.13)	(−2.25)	(−2.32)
Openness trade, 5-years average									−0.00276	0.00437	0.00110	0.0148
									(−0.27)	(0.60)	(0.15)	(1.01)
Num. Observations	915	915	915	915	814	814	814	814	744	744	744	744
Hansen test (*p*-val)	0.003	0.084	0.773	0.069	0.036	0.413	1.000	0.360	0.084	0.455	1.000	0.179
Hansen-diff-test (*p*-val)	0.021	0.419	0.998	0.234	0.693	0.984	1.000	0.777	0.469	0.970	1.000	0.461
m1-test (*p*-val)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
m2-test (*p*-val)	0.873	0.633	0.906	0.790	0.643	0.709	0.605	0.969	0.490	0.792	0.284	0.837
Number of countries	134	134	134	134	120	120	120	120	128	128	128	128
Number of Instruments	44	78	148	87	98	132	202	117	109	142	209	125

Notes: Regressions above are system GMM, 2-step, robust estimates, including one lag in the matrix for instruments. Fossil fuel mix is omitted for the primary energy mix (i.e. fossil fuel mix plus renewable mix plus nuclear plants mix amount to one). *Agriculture, Cattle and Fishing* sector is omitted from the final energy mix (i.e. the final mix for agriculture together with industrial, transport sector, services and residential sector must sum up to one). Figures into parenthesis represent t-statistics. Starred values denote significance at $^{*}p < 0.10$, $^{**}p < 0.05$, $^{**}p < 0.01$.

Table 3

Growth and the role of Energy Intensity (system-GMM estimation).

Dependent variable: GDP per capita growth (5-year average)						
	M1	M2	M3	M1	M2	M3
log(income), lagged	−0.00842	−0.00624	−0.0121***	−0.0477***	−0.0305***	−0.011
	(−1.40)	(−1.32)	(−3.33)	(−4.53)	(−4.15)	(−1.36)
Energy Intensity, % change	−0.675***	−0.650***	−0.745***			
	(−6.48)	(−5.17)	(−12.58)			
Renew. Mix, % change				−0.344	−0.145	−0.824
				(−0.89)	(−0.47)	(−1.60)
Renew. Mix (Conventional), % change	−1.209***	−0.540*	−0.687**			
	(−2.88)	(−1.80)	(−2.45)			
Renew. Mix (Frontier), % change	0.587*	0.598*	0.388			
	(1,74)	(1,77)	(0,76)			
Nuclear. Mix, % change	−0.217	−0.36	−0.554*	−0.424	−0.860**	−0.773*
	(−0.48)	(−1.05)	(−1.68)	(−0.74)	(−2.08)	(−1.68)
Industrial Sector, % change	0.0871	0.16	0.14	0.339	0.386	0.0007
	(0,42)	(0,87)	(0,89)	(1,07)	(1,54)	(0,0)
Transport Sector, % change	0.162	0.165	0.0439	0.483	0.536	0.687
	(0,69)	(1,0)	(0,25)	(1,15)	(1,45)	(1,46)
Residential Sector, % change	−1.217***	−0.915***	−0.677***	−1.489***	−0.959***	−0.903**
	(−4.28)	(−3.89)	(−3.68)	(−4.27)	(−2.88)	(−2.08)
Service Sector, % change	−0.396	−0.0718	−0.559**	−0.546	0.0862	−0.465
	(−1.25)	(−0.21)	(−2.17)	(−1.17)	−0.22	(−1.16)
log(Invest. Price), lagged		−0.00309**			−0.00741***	
		(−2.09)			(−3.88)	
Attained primary ed., % over Pop., lagged		0.0711***			0.182***	
		(3,03)			(4,63)	
Attained secondary ed., % over Pop., lagged		0.000387			0.0873**	
		(0,02)			(2,24)	
Fertility rate, lagged			−0.0158***			−0.0132**
			(−3.93)			(−2.19)
Inflation, 5-year average			−0.000453*			−0.000334
			(−1.74)			(−0.56)
Gov. Size, 5-year average			−0.0183**			−0.0335*
			(−2.12)			(−1.66)
Openness trade, 5-years average			0.00309			−0.0044
			(0,42)			(−0.27)
Num. Observations	915	814	744	915	814	744
Hansen test (p-val)	0.0205	0.506	0.845	0.00873	0.148	0.146
m2-test (p-val)	0.862	0.718	0.682	0.943	0.398	0.0172
Number of countries	134	120	128	134	120	128
Number of Instruments	110	142	151	91	123	121

Notes: Regressions above are system GMM, 2-step, robust estimates, including one lag in the matrix for instruments. Fossil fuel mix is omitted for the primary energy mix (i.e. fossil fuel mix plus renewable mix plus nuclear plants mix amount to one). *Agriculture, Cattle and Fishing* sector is omitted from the final energy mix (i.e. the final mix for agriculture together with industrial, transport sector, services and residential sector must sum up to one). Figures into parenthesis represent t-statistics. Starred values denote significance at $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

rate between 0.60% and 0.70%, depending on the model used. This elasticity estimates a range between 0.59% and 0.72% for the WG approach, and between 0.63% and 0.98% for system GMM (dynamic panel). Indeed, the main differences in point estimates are due to the econometric method used rather than to the effect of the alternative controls included in model (Ang, 2008).

Therefore, the observed correlation between energy intensity and economic growth at the worldwide level seems to be driven either by a direct effect, or by indirect channels not observed or not considered in the model (for instance, the quality of institutions). This is important because the direct effect has implications in terms of our assumptions on the technology. In the context of the model discussed in Section 2, a negative impact between energy intensity changes and economic growth arises when $\pi > \theta$, which indicates that the efficiency channel of energy intensity in B_t (the state of the production technology) through parameter π dominates the input intensity channel in Z_t/E_t^{ρ} (the energy use) through parameter θ. This result is in line with the theory of energy-saving technical change developed in Díaz and Puch (2019). Indeed, Rajbhandari and Zhang (2018) have recently found a negative correlation between energy intensity changes and economic growth. They also provide evidence that higher levels of energy intensity imply lower levels of economic productivity which is also growth deterred.

The negative relationship between energy intensity and economic growth among developed countries has been extensively studied. Here we show that this negative relationship is not specific of developed countries. That is, declining energy intensity is also a feature of emerging/developing countries where capital deepening is still a significant source of growth, not only technical progress, as in developed countries.[13] This fact can be rationalized with the existing macro literature (cf. Atkeson and Kehoe, 1999; Díaz et al., 2004, Díaz and Puch, 2019) where capital deepening entails lower energy intensity in a world with increasing energy prices.

Finally, as indicated above, when we estimate the alternative two-equation system as a SURE the results are similar to those obtained under the system GMM approach. We interpret this finding as a confirmation that both approaches are properly handling the endogeneity issue for the purpose in this paper (see Appendixes A and C).[14]

5.2.2. The role of the primary energy mix

The second key empirical result relates to the relationship between growth and changes in the primary energy mix from fossil fuels towards renewables (θ_1^m in expression (6)), given the share of the nuclear, the degree of development and the energy intensity.

In Tables 2.a–2.c, we consider renewable technologies as a homogenous block, while in Table 3 we distinguish between two types of renewable choices: the aforementioned conventional class (hydro and biomass) versus what we call frontier renewables (wind, solar, geothermic or wave). When renewables are taken as a whole (Tables 2.a–2.c), or for the part concerning conventional renewables (Table 3), the estimated coefficient is always negative and significant, going from −0.42 to −2.2. This indicates that the switch from fossil fuels to renewables (neglecting the type of them), albeit environmentally friendly, may not be a free lunch and it can be driven by factors undermining GDP growth. In terms of our theoretical framework, it is that the aggregate productivity of renewables is lower than that of fossil fuels (i.e., $\lambda_1 s_{1,t}^{\rho-1} < \lambda_3 s_{3,t}^{\rho-1}$ in the model described in Section 2).

However, according to the results in Table 3, if the move is oriented towards "frontier" renewables, the association with economic growth turns positive although weakly significant, between 0.4 and 0.6. In other words, this switch from fossil fuels to "frontier" renewables (all other shares, energy intensity, and the state of technology given) might help reconcile CO2 emission curbing policies with economic growth. Therefore, our interpretation is that while moving resources from dirty- to clean-energy technologies generally produces adjustment costs that may erode growth capacity, it turns out that the quality of the move matters. Our estimates in Table 3 suggest that the sign of the correlation, between renewables and growth rate, is modified when the economy moves to "frontier" rather than "conventional" renewable sources.[15] This might be taken as an evidence of slow growth when the driver for a switch to renewables is a country's difficulties in the fossil-fuels market.

It is also worth mentioning that when removing energy intensity from the equation, the change in the renewables' share is no longer statistically significant for growth. This result might arise due to a significant relationship between changes in energy intensity and the energy mix (i.e., due to common technological progress or environmental legislation).[16] It also emphasizes the importance of considering simultaneously energy aspects (primary and final energy mix and energy intensity) to understand growth differences between countries, which is a contribution with respect to other papers in the related literature (Inglesi-Lotz, 2016, Bhattacharya et al., 2016, 2017, or Narayan and Doytch, 2017), as commented in the Introduction.

Finally, moving from fossil fuels towards nuclear plants is not significant for GDP per capita growth whatsoever. In almost all cases, the coefficients θ_2^m in expression (6) are not significant (estimates under fixed-effects for the skeleton model M1 is an exception). In terms of aggregate productivity at the worldwide level, the aggregate productivity of nuclear plants is similar to the corresponding to fossil fuels.

5.2.3. Convergence in income per capita

In Table 2.c, our system-GMM estimations do not provide evidence of conditional convergence: the coefficient of the lagged log-level of income is not significant in almost all cases (just in model M3, the convergence rate is nearly 1%). By contrast, the system-GMM of Table 3 presents an important finding. When the change in energy intensity is included in the model together with a disaggregation of the renewables share into "conventional" and "frontier" (left panel in Table 3), as in Table 2.c, the GDP convergence speed is not significant (M1 and M2) or very small (1.2% in M3). Notwithstanding, in the right panel of Table 3, removing energy intensity changes makes the lagged income term in (6) more negative and more significant. The speed of convergence increases from 1.2% to 4.7% under system GMM. The implications from this result are twofold. First, the omission of a (highly) relevant variable induces a bias in the remaining parameters, including an upward bias in the speed of convergence. Second, it reveals a latent relation between the speed of convergence in real GDP per capita and the change in energy

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[13] Filipovic et al. (2015) scrutinize which are the determinants of energy intensity in 28 EU member countries. They find that energy prices (mainly), energy taxes and GDP per capita are likely behind the degree of energy intensity. This result is corroborated by experiences in Denmark, Germany and Italy.

[14] Although the other way of the causality goes beyond the scope of this paper, it is worth mentioning that the estimated energy intensity equations reveal several important growth-related aspects, namely: (i) a 1% income growth reduces energy intensity by 1% (this result is robust across specifications); and (ii) the share of renewables and the residential sector are significantly and negatively related with energy intensity.

[15] Inglesi-Lotz (2016), Bhattacharya et al. (2016), Bhattacharya et al. (2017) or Narayan and Doytch (2017) find a positive impact of renewables on growth. See Section 6.1 for more details about this issue.

[16] For the entire sample, the correlation between energy intensity and the share of renewables is 0.121, albeit significant. However, this low correlation is far from generating collinearity problems. Moreover, additional indirect cross-correlations through a third variable, such as the lagged level of per capita GDP (i.e., its cross-correlations with the share of renewables and the energy intensity are −0.64 and −0.34, respectively) or other energy shares (i.e., the correlation between the energy share in the industry and the share of renewables is −0.43 and almost zero for energy intensity), could also affect the significance of renewables to explain growth. The complexity of the aforementioned cross-correlations makes it very important to estimate models in which all energy variables are included simultaneously (Marrero, 2010). Otherwise, the estimates of any energy parameter could be biased.

Table 4
Alternative system-GMM estimation.

Dependent variable: GDP per capita (logged)	M1	M2	M3
log(income), lagged	0.969***	0.969***	0.947***
	(31.67)	(45.84)	(51.85)
log(Energy Intensity), lagged	−3.510***	−3.213***	−3.766***
	(−6.74)	(−4.91)	(−13.83)
Renew. Mix, % change	−7.164***	−2.713**	−3.549***
	(−3.15)	(−2.04)	(−2.64)
Nuclear. Mix, % change	−0.344	−0.924	−0.883
	(−0.30)	(−0.62)	(−0.59)
Industrial Sector, % change	0.0845	0.546	0.944
	(0.08)	(0.60)	(1.02)
Transport Sector, % change	0.177	0.661	−0.0497
	(0.15)	(0.86)	(−0.06)
Residential Sector, % change	−6.245***	−4.437***	−3.415***
	(−4.24)	(−3.67)	(−3.66)
Service Sector, % change	−2430	−0.899	−2.242*
	(−1.43)	(−0.56)	(−1.65)
log(Invest. Price), lagged		−0.0148***	
		(−3.04)	
Attained primary ed., % over Pop., lagged		0.284***	
		(2.75)	
Attained secondary ed., % over Pop., lagged		−0.0591	
		(−0.55)	
Fertility rate, lagged			−0.0532***
			(−2.78)
Inflation, 5-year average			−0.00254*
			(−1.80)
Gov. Size, 5-year average			−0.0958**
			(−2.22)
Openness trade, 5-years average			0.0550
			(1.36)
Num. Observations	915	814	744
Hansenp	0.0122	0.311	0.622
ar1p	0.000202	6.86e−09	1.90e−08
ar2p	0.834	0.672	0.594
N_g	134	120	128
J	101	134	143

Notes: Regressions above are system GMM, 2-step, robust estimates, including one lag in the matrix for instruments. Fossil fuel mix is omitted for the primary energy mix (i.e. fossil fuel mix plus renewable mix plus nuclear plants mix amount to one). *Agriculture, Cattle and Fishing* sector is omitted from the final energy mix (i.e. the final mix for agriculture together with industrial, transport sector, services and residential sector must sum up to one). Figures into parenthesis represent t-statistics. Starred values denote significance at $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

intensity worldwide. Therefore, the inclusion of energy intensity growth (alongside with changes in the use of renewables) matters to explain growth and its process of (conditional) convergence. We interpret this finding as an evidence of the key role that improvements in energy intensity play on income convergence along the transition to sustained growth path and, moreover, their key importance as a transmission channel for economic development.

In the last three columns of Table 3, the changes in the share of nuclear energy become significant and negative. Compared with the first three columns of Table 3, the finding is that changes in the primary energy mix affect growth through changes in the share of renewable energies. However, the result here implies that the transmission channel is particularly evident when we abstract from the role of changes in energy intensity. A rationale for this result is that some countries are possibly constrained in the growth process, either by rising prices of fossil energy or by adopting new energy technologies, or possibly both. As a consequence, they might be switching to inefficient conventional renewables as a response to any obstacles during their decision-making process of the optimal energy technology. If this is so, it is not surprising that once we control for changes in the primary energy mix in those countries, the neoclassical growth mechanisms show up, and conditional convergence cannot be rejected. According to the system GMM approach, we normally find non-significant rates of convergence, although for some specification the rate hovers below 2.0%, a common finding in the related research (1.21% in Table 2.c).[17] This discussion is extended in Appendix B.

As an alternative approximation to analyze the speed of convergence term (and all the remaining terms in Eq. (5)), we estimate a dynamic panel where the endogenous variable is the log-level of GDP per capita, instead of its growth rate. In dynamic models, this implies an adjustment in the dynamic term and a re-scaling in the rest of coefficients. Note that the growth term in expression (5) is defined as $GY_{i,\,t} = [\ln(\mathrm{Y}_{\mathrm{i,\,t}}) - \ln(\mathrm{Y}_{\mathrm{i,\,t-1}})]/5$, so that the new specification to estimate takes the following form:

$$\ln(\mathrm{Y}_{\mathrm{i,t}}) = \alpha_0 + R_i + T_t + \beta_0 \ln(\mathrm{Y}_{\mathrm{i,t-1}}) + \theta_0' XE_{i,t} + \lambda_0' X_{i,t} + \varepsilon_{i,t}, \quad (5\ \text{bis})$$

where β_0 in (5 bis) and β in (5) are related as $\beta = (\beta_0 - 1)/5$. Table 4 presents the results for some selected specifications under system-GMM (by collapsing the set of instruments as an alternative to overcome the problem of overfitting). Consistently with previous

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[17] In the related growth literature, pooled-OLS estimations offer convergence coefficients biased downward, while those given by the fixed-effects approach tend to be biased upward. Our estimated coefficient under system GMM is between those conventional estimates (although non-significant in many occasions). Estimated results for a dynamic panel under pooled-OLS and WG approaches are available upon request. This finding was earlier confirmed by papers such as Islam (1995), and Caselli et al. (1996), among others.

specifications in Tables 2.c and 3, the rates of convergence change little, going from 0.2% to 1.06%. Moreover, the main results concerning the relation between energy related variables and economic growth hold robust after this specification, which is the main contribution of the paper.

5.2.4. Sectoral composition

Finally, the inclusion of sectoral variables (final consumption of energy in sector s relative to total final consumption, i.e. $\Delta s_{k,\ i,\ t}$ in (6)) has little effect over GDP per capita growth worldwide. The only remarkable exception is the share of energy demanded by the residential sector. The estimated contribution to growth of this variable ranges within the interval −0.68 to −1.49, depending on the specification and method. On average, for 1% deviation in the residential sector energy share, relative to the share of agriculture, it can be associated with a change of −1.12% in GDP per capita growth rate. This is worth highlighting, given the secular downward trend in agriculture, almost certainly caused by structural change and huge migration from rural areas to the cities in emerging countries, which brings about the upward trend in the residential share of energy along the development path towards steady growth.

6. Robustness of results

This section analyzes the robustness of our results to alternative specifications of our baseline empirical model (i.e., results in Tables 2.c and 3). Precisely, we assess first the effect of switching to a higher share of renewable energy in the mix. Secondly, we evaluate the consequences of using lagged energy intensity as a control variable instead of using their growth rates. Thirdly, we present an overall analysis of heterogeneity in the sample across regions, income levels and periods. Finally, we evaluate the potential role of additional controls, notably through measures of institutional quality and private investment. Further details of these alternative checks are given in Appendixes B, C, D and E corresponding to Sections 6.1, 6.2, 6.3 and 6.4, respectively.

6.1. The correlation with renewables

One of our most important results is the negative correlation found between economic growth and the changes in the share of renewables relative to the share of fossil fuels.

Following the existing literature on empirical growth (see Barro, 2000, and Marrero, 2010, and the references therein), we have considered per capita GDP growth rates and dynamic terms in our empirical reduced form specification. Alternatively, it has been often considered a departure from the empirical growth literature according to which the relationship in (log-) levels between per capita real GDP and renewables is considered (cf. Inglesi-Lotz, 2016; Bhattacharya et al., 2016, 2017; or Narayan and Doytch, 2017, among others). Such a specification abstracts from variability in economic growth rates and occasionally omits the dynamic aspect. This circumstance implies to assume that economies stay along a balanced growth path, which can be more or less justified depending on the sample. In most of these empirical exercises, the finding is a positive correlation between GDP per capita and consumption of renewables. Table B.1 in Appendix B summarizes the estimated elasticities for some of these representative papers. The differences between the results in those papers and our results could be attributed to the use of different samples (countries and time periods) or the econometric methods used. See also Appendix B for further details of this discussion.

We further analyze this issue in our sample. Thus, Table B.2 in Appendix B reports our estimates where the dependent variable and all other variables in the regression are expressed in log-levels for different specifications and methods. The main finding is that the observed positive correlation (as some previous research have found) between per capita GDP and consumption of total renewables could be due to the omission of country and time fixed effects, together with the omission of a measure of overall energy efficiency (proxy by energy intensity in our case). Moreover, in all cases, the energy intensity coefficient is negative and highly significant, as we reported in Tables 2.a to 2.c.

More importantly, when we make the distinction between conventional and frontier renewables (columns (v) through (viii) in Table B.2), we obtain the same result we reported in Table 3. While conventional renewables maintain the negative sign (and significant), the correlation between frontier renewables and real per capita GDP becomes positive. The (long-run) elasticity of the conventional renewable sources ranges between −13% and −19%, while that of the frontier renewables ranges between 1.4% and 4.6%. Consequently, this assessment based on long-run analysis reinforces the conclusions of Section 5 above, which in turn are consistent with the theoretical framework we presented in Section 2.

This robustness analysis reconciles, at least in part, our results with those previously mentioned in the literature. The finding that "aggregate" renewables are negatively or positively correlated with per capita real GDP could be sensitive to the sample and to the model and econometric method used. However, when we distinguish between conventional and frontier renewables, it is quite robust that the former is negatively correlated, while the latter is positively correlated.

6.2. Lagged energy intensity as explanatory variable

Another important result is the negative correlation found between economic growth and the changes in energy intensity, given the energy mix and the state of the technology. In Tables 2.a to 2.c and 3, we have used energy intensity growth as the explanatory variable. However, one may wonder what the results would look like if instead, the energy intensity level at the beginning year of the five-year period is used as explanatory variable.

Table C.1 in Appendix C shows the estimated results of this analysis. We find that the sign of the estimated coefficient of the lagged level of energy intensity varies depending on the inclusion of the growth rate of energy intensity. The intuition of this result is the following. The omission of the change in energy intensity as explanatory variable (first three columns in Table C.1) makes that the lagged level of energy intensity would be capturing the convergence process of energy intensity and, therefore, its estimations would be strongly biased and could even change its sign. Precisely, the reason of the bias is that higher levels of *past* energy intensity are correlated with low changes in *current* energy intensity, which in turn is correlated with higher income per capita growth. Hence, when the change in energy intensity is omitted in the regression, the coefficient of the lagged level of energy intensity is positive, while it turns negative when the convergence process for energy intensity is explicitly controlled.

As a final remark, note that the change in renewable is no longer significant after omitting the change in energy intensity. Again, this is likely due to a biased effect of omitting relevant variables. Once the change in energy intensity is included, the lagged value $\ln(EI_{i,\ t-1})$ does not show up much relevant, so the results shown in Tables 2.a to 2.c can be seen as robust.

6.3. Analysis of heterogeneity: Regions, income levels and time periods

Our previous results have been obtained at the worldwide level. However, there could be heterogeneity across several dimensions. Thus, we explore next whether our main results (from Table 2.c and 3) vary across regions, time period and income levels. Estimated results are shown in Tables D.1, D.2 and D.3 in Appendix D. In all cases, we use system GMM estimation, as in Tables 2.c and 3.

First, in Table D.1, we differentiate the following regions: Europe (we include dummies for East EU countries), America, Asia-Pacific, and Sub-

Saharan Africa (SSA).[18] We find that the coefficient of energy intensity is negative and statistically significant in all cases, ranging from −0.436 (Europe) to −0.982 (SSA, Sub-Saharan Africa). In Europe, the changes in the share of renewable energy sources (particularly conventional sources) and the shares of the residential sector and the service sector appear negatively and statistically significant, in line with our aggregate results in Tables 2.a–2.c. For the remaining regions, the share of renewables is not significant. Thus, the negative correlation observed between the renewables share and economic growth at the worldwide level (Tables 2.a–2.c) is mainly due to the between-region comparison.

Second, in Table D.2, we differentiate between time periods and explore whether the energy-growth correlation has been affected by the oil price crisis of mid 80s (i.e., we distinguish between before and after 1985). We select the 80's, rather than mid 70's, to allow for a sufficiently large number of observations before and after that period. Interestingly, the sensitivity of growth with respect to energy intensity increases (in absolute terms) from −0.36 to −0.84 after 1985. This change in this coefficient is robust to the differentiation between renewable sources (i.e. conventional versus frontier). The coefficient of the conventional renewable share also increases from −0.66 to −1.04, while that of the frontier renewable sources does not seem to affect economic growth when we differentiate between both periods. Finally, the share of nuclear sources was positively correlated and significant before 1985 and turned out non-significant after that date.

Finally, in Table D.3, we complete this analysis accounting for country degree of development according with the Word Bank classification: low and lower-middle income countries, upper-middle income and high-income countries (for these latter, we also distinguish between OECD countries). The estimates in Table D.3 indicate that the lower the income, the lower the speed of convergence (from 4% to 10%), and the higher the sensitivity of growth with respect to energy intensity (from −0.77 to −0.16). Notice that this is consistent with our previous regional analysis (Table D.1).

The decay in these coefficients is robust to the differentiation between conventional versus frontier renewable sources. The coefficient of the conventional renewable share is negative and significant for upper-middle income countries and high-income countries, from −0.79 to −1.03, while that of the frontier renewable sources is significant and positively correlated with growth, but only for upper-middle income countries, +1.62. Notice that these latter countries have experienced a greater shift in their development and energy use pattern, which could explain this highly positive sign for frontier renewables.

Overall, the main result in this exercise is that we find heterogeneous patterns in the relation between growth and energy intensity concerning the period and the level of income. The sensitivity of economic growth with respect to energy intensity is higher after 1985, and the lower the level of income per capita. It is also evident that a more detailed analysis looking inside each region (and even inside the countries) would reveal relevant information on the relationship between energy and growth. However, the goal here is to describe the average pattern worldwide, and the detailed heterogeneity analysis goes beyond the scope of this paper and is left for future extensions.

6.4. Alternative controls: The role of institutional quality and private investment

To finish this section of robustness analysis, we consider alternative controls in regression Eq. (5), mainly related to institutional quality and private investment in the different countries.

Table E.1 in Appendix E reports the results when this new set of institutional variables is included in the regression. These variables are the following: the quality of democracy, Government stability, private investment and political stability (see the Appendix for the detail of the source). All coefficients have the expected sign. The coefficients of both the quality of democracy and Government stability are positive and significant, meaning that quality of institutions has a positive impact on growth. Yet, investment, as a share of GDP, and *Polity2* also affect positively growth.

Notice that the results of energy intensity and the total share of renewables are robust to the inclusion of these controls. Moreover, when we make the distinction between frontier and conventional renewables, the sign of the move towards conventional renewables remains negative, while the sign of the move to frontier turns positive (although non-significant). Then, what is relevant here is that moving to frontier renewables (from non-renewables), at least, does not harm growth. The fact that the coefficient of frontier renewables is non-significant could be indicating that institutional quality is a relevant aspect to explain how renewables and economic growth are correlated. However, this is an aspect that deserves a much more detailed analysis and goes beyond the scope of this paper.

7. Concluding remarks

The relationship between economic growth and energy use is intricate, as it involves aspects related to institutions and policy, the state of the technology, and the sectoral composition of an economy. This paper contributes to this issue in that it proposes an empirical specification to provide evidence on the relative importance of all these aspects. Our specification incorporates, in a dynamic panel data model, an indicator of energy intensity, the shares in the primary energy mix (where we distinguish between renewable sources and fossil fuels), and the shares for the sectors where energy is finally consumed. As we use a dataset that includes a sample of 134 countries over the period 1960–2010, we also need to control for country specific features. This heterogeneity enriches our analysis, contrary to existing studies that typically restrict to a reduced set of countries. In addition, our unique dataset allows gauging the influence of institutions and policy together with the level of economic development. Furthermore, our reduced energy-growth empirical regression form is motivated from a neoclassical framework that relates economic growth with energy intensity and differentiates the impact of renewable energy (as oppose to non-renewable) in the growth process.

Our results confirm a negative correlation between energy intensity and growth at the worldwide level: the higher the energy intensity, the lower the GDP per capita growth. Depending on the model specification and the econometric method, we find, on average, an elasticity of GDP p.c. growth with respect to energy intensity ranging between −0.5 and −1.0%. Existing literature has widely reported evidence about this negative correlation for developed countries. We find that this correlation also holds for emerging and developing countries. Moreover, by excluding energy intensity from the regressions, we find significant evidence of conditional convergence, and of the role of technological variables even at the expense of policy variables. These findings suggest that improvements in the energy technology are also a developmental force.

We further report evidence that those countries that switch from fossil to conventional renewables, rather than to frontier renewables, might be experiencing difficulties in their path of development (the coefficients of renewable mix changes are always negative and significant). Related to the share of energy in final sectors, only the share of energy demanded by the residential sector shows a robust and significant negative effect on GDP per capita growth. The inclusion of the rest of the sectoral variables is negligible in its effect over GDP per capita growth worldwide.

We contribute to the existing literature in that we have scrutinized certain relations between energy intensity, the energy mix, sectoral composition and economic growth. Our results appear to be fairly robust to alternative specifications and estimation procedures. Further questions about the energy-growth relationship, such as the optimal composition of energy sources, surely requires a dynamic general equilibrium model. The empirical evidence found in this paper will help us to discipline the construction of such a model that will relate alternative energy technologies with technological progress and the growth process.

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[18] Sample sizes widely differ across regions. Given that system-GMM estimation can be affected by small samples, we aggregate those regions with smaller sample size. Thus, we aggregate American region with Asia-Pacific countries (labeled as ASP).

Appendix A. Simultaneous equation system

We next estimate a *seemingly unrelated equation* system (SURE) by maximum likelihood:

$$GY_{i,t} = \alpha + R_i + T_t + \beta_1 \ln\left(\mathrm{Y}_{\mathrm{i,t-1}}\right) + \delta_1 \Delta EI_{i,t} + \theta_1' XE_{i,t} + \lambda_1' X_{i,t} + \varepsilon_{i,t}, \tag{A.1}$$

$$\Delta EI_{i,t} = \alpha + R_i + T_t + \beta_2 \ln\left(\mathrm{Y}_{\mathrm{i,t-1}}\right) + \delta_2 GY_{i,t} + \theta_2' XE_{i,t} + \lambda_2' X_{i,t} + \eta_{i,t}, \tag{A.2}$$

where:

$$\theta_{\ell}' XE_{i,t} \equiv \sum_{j=1}^{J-1} \theta_{\ell,j}^{m} \Delta m_{j,i,t} + \sum_{k=1}^{K-1} \theta_{\ell,k}^{s} \Delta s_{k,i,t}, \tag{A.3}$$

and $\ell = 1, 2$, i.e. growth and energy intensity, respectively. Eq. (A.1) is identically written as Eq. (5) in Section 4. The second Eq. (A.2) encompasses almost the same explanatory variables as Eq. (A.1), except the change in energy intensity $\Delta EI_{i,\,t}$, but including the growth rate of income, $GY_{i,\,t}$. The energy shares $\{\Delta m_{j,\,i,\,t}\}_{j=1}^{J-1}$ and $\{\Delta s_{k,\,i,\,t}\}_{k=1}^{K-1}$, and the set of control variables $X_{i,\,t}$, are also incorporated, without imposing further restrictions on the set of parameters.

Table A.1 presents a summary of these new results under five alternative specifications. For each specification, we provide a regression (A.1) for growth and a regression (A.2) for the change in energy intensity. We compare these results with those already reported in Table 2.a (Pool-OLS) and Table 2.c (system GMM). We highlight the following aspects.

First, when we estimate the two-equation system (A.1) and (A.2), growth and energy intensity change, respectively, the results approach those reached under the system GMM case. For instance, in the basic "skeleton" model (labeled as (Aghion et al., 1999)), the energy intensity coefficient becomes −0.88, while the lagged log-level of income (i.e. the convergence coefficient) keeps insignificant. When the share of renewable energy sources and (especially) the share of energy consumed by the residential sector are added (model specifications (Alesina et al., 1996) and (Álvarez et al., 2005)), the SUR estimation provides coefficient closer to the GMM case (Table 2.c) than those under the pooling estimate (Table 2.a). Something similar happens when the control variables are incorporated into the equations. As already discussed in the paper, the pool-OLS estimates appears biased with respect to the system GMM table, likely due to the endogeneity issue among key variables. This is always the case for the *energy intensity* coefficient in the growth equation: while it is around 0.6 in the pooling estimation, it is 0.9 under the system-GMM. The SUR system partially straightens this bias. Second, the energy intensity equations reveal several important growth-related aspects, namely: (i) a 1% income growth reduces energy intensity by 1% (this result is robust across specifications); and (ii) the share of renewables and the residential sector are significantly and negatively related with energy intensity.

Table A.1
SURE system.

Model:	(1)		(2)		(3)		(4)		(5)	
Dependent variable:	Growth	ΔEI	Growth	ΔEI	Growth	ΔEI	Growth	ΔEI	Growth	ΔEI
log(income), lagged	0.000199	0.00231	0.00118	0.00298**	0.000915	0.00258*	−0.00136	−0.000164	−0.00344***	−0.00218
	(0.14)	(1.56)	(0.87)	(2.07)	(0.71)	(1.82)	(−1.06)	(−0.11)	(−2.60)	(−1.52)
Income growth		−0.958***		−0.994***		−1.028***		−1.092***		−1.021***
		(−44.34)		(−46.98)		(−48.22)		(−44.24)		(−46.47)
Energy Intensity, % change	−0.882***		−0.875***		−0.856***		−0.796***		−0.885***	
	(−44.34)		(−46.98)		(−48.22)		(−44.24)		(−46.47)	
Renew. Mix, % change			−1.227***	−1.247***	−0.907***	−0.982***	−0.461***	−0.531***	−0.554***	−0.591***
			(−10.76)	(−10.11)	(−7.73)	(−7.63)	(−4.31)	(−4.24)	(−5.78)	(−5.74)
Nuclear. Mix, % change			0.0337	0.0719	0.0762	0.122	0.233	0.348	0.132	0.213
			(0.12)	(0.24)	(0.29)	(0.42)	(1.04)	(1.32)	(0.62)	(0.93)
Industrial Sector, % change					0.0969	0.0978	0.00446	−0.0113	0.201*	0.210*
					(0.81)	(0.75)	(0.04)	(−0.08)	(1.79)	(1.74)
Transport Sector, % change					−0.228	−0.334*	−0.198	−0.314*	−0.328**	−0.433***
					(−1.46)	(−1.95)	(−1.35)	(−1.83)	(−2.39)	(−2.96)
Residential Sector, % change					−1.066***	−1.074***	−0.864***	−0.945***	−0.676***	−0.684***
					(−8.27)	(−7.48)	(−6.92)	(−6.39)	(−6.12)	(−5.72)
Service Sector, % change					−0.387	−0.410	−0.271	−0.353	−0.373*	−0.421*
					(−1.64)	(−1.58)	(−1.08)	(−1.21)	(−1.68)	(−1.76)
log(Invest. Price), lagged							−0.00212**	−0.00168		
							(−2.02)	(−1.36)		
Attained primary ed., % over Pop., lagged							0.0150	0.0103		
							(1.54)	(0.90)		
Attained secondary ed., % over Pop., lagged							0.000804	−0.00583		
							(0.07)	(−0.41)		
Fertility rate, lagged									−0.00336***	−0.00265**
									(−3.16)	(−2.29)
Inflation, 5-year average									−0.00524	−0.00521
									(−1.37)	(−1.27)
Gov. Size, 5-year average									−0.00320	−0.00299
									(−1.51)	(−1.31)
Openness trade, 5-years average									0.00351	0.00346
									(1.54)	(1.42)
Num. Observations	915	915	915	915	915	915	814	814	744	744

Robust t-statistics in parentheses: *** denotes significance at 1%, ** at 5%, * at 10%.

Appendix B. On the correlation between growth and renewables

Table B.1 reports the estimated elasticities between economic growth and renewable energy consumption reported in some representative papers in the literature. Except for the six cases presented by Bhattacharya et al. (2016), these studies show positive *long-run* elasticities within a wide range of values.[19]

Table B.2 summarizes the assessment of this issue in our sample. Columns (i) through (v) in the table report the results using pooled-OLS under different specifications. The final two columns show results for the Within-Group (WG) and the GMM system approaches. We present the results sequentially in order to explore the causes behind the potential change of sign in the coefficient of the energy variables. For ease of exposition, we do not include here the set of controls used along Tables 2.a–2.c, but we do distinguish between *conventional* and *frontier* renewables sources.

First, unconditionally, the correlation between per capita GDP (in logs) and consumption of renewables (in logs) is positive. Moreover, its elasticity is 4.5%, somewhat lower than the average found in previous papers (Table B.1). Moreover, when regional fixed effects are included in the regression, this positive correlation is maintained, although the elasticity lowers to just 0.74%. Conditional on both time and regional fixed effects (column (iii)), the coefficient of renewables becomes negative and significant, in line with our results in Tables 2.a–2.c (the elasticity is −1%).

Secondly, when energy intensity is included in the regression (now in log levels, column (iv)), the coefficient of renewables becomes more negative and more significant. Thus, part of the positive correlation initially observed between the consumption of renewables and GDP per capita owes to a hidden correlation due to fixed effects (time and country-specific) and to the energy intensity of each country. Once these factors are controlled for, the partial correlation between total renewables and GDP per capita (in logarithms) becomes negative. Thus, we attribute the changing result to the omission of country and time fixed effects, and also of energy intensity.

Indeed, the differences could also be attributed to the use of different samples (countries and time periods) or the econometric methods used. For example, Bhattacharya et al. (2016) use top 38 countries according with the Renewable Energy Country Attractive Index and estimate the long-run output elasticities. Thus, the model is not dynamic and use pooled data and annual observations. Inglesi-Lotz (2016) uses annual data for 34 OECD countries from 1990 to 2010 and performs a long-run cointegration analysis with pooled-OLS and fixed effects techniques. Bhattacharya et al. (2017) use annual data from 85 developed and developing economies from 1991 to 2012, using pooled-OLS and system GMM. In this paper, system GMM clearly suffers overfitting problem (too-many instruments are used), as the *p*-value of the Hansen test show a value of 1.00. Narayan and Doytch (2017) use a panel of 89 countries from 1971 to 2011, split into low-income, upper-middle income and high income. They analyze short- and long-run effects and distinguish between residential and industrial users of renewable. Thus, their results are not fully comparable to our case.

Table B.1

Long run output elasticities wrt renewable energy consumption.

Article	Elasticity	Countries	Sample
Apergis and Payne (2010a)	0.760	34 OECD countries	1985–2005
Apergis and Payne (2010b)	0.195	13 Eurasian countries	1992–2007
	0.074	(Russia excluded)	
Inglesi-Lotz (2016)	0.100	34 OECD countries	1990–2010
	0.080		
Bhattacharya et al. (2016)	0.101	38 countries	1991–2012
	−0.162	Ukraine	
	−0.118	India	
	−0.072	United States	
	−0.061	Israel	
	0.066	Spain	
	0.117	France	
	0.150	Germany	
	0.160	United Kingdom	
	0.260	China	
Bhattacharya et al. (2017)	0.219	85 countries	1991–2012
	0.152	High income countries	
	0.277	Middle and low income countries	
	0.132	Middle East and North Africa	
	0.367	Sub-Saharan Africa	
	0.141	Europe & Central Asia	
Narayan and Doytch (2017)	1.008	89 countries	1971–2011
	1.002	Middle and low income countries	
	1.006	Upper middle income	
	1.003	High income countries	

Table B.2

Pooled-OLS, Fixed Effects WG and system-GMM estimation.

Endogenous variable: Real GDP per capita (PPP-adjusted, log-level)								
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
Energy Intensity log-level				−0.690***	−0.603***	−0.622***	−0.719***	−1.390***
				(−14.57)	(−12.58)	(−8.44)	(−5.43)	(−7.25)
Renew. Mix, log-level	0.0453***	0.00745**	−0.0101***	−0.104***				
	(10.95)	(2.11)	(−2.62)	(−14.17)				
Renew. Mix (Conventional), log-level					−0.128***	−0.0125	−0.197***	−0.186***
					(−16.70)	(−0.85)	(−5.41)	(−5.12)
Renew. Mix (Frontier), log-level					0.0442***	0.0146***	0.0458**	0.0290**
					(8.84)	(3.34)	(2.49)	(2.48)

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[19] The four exceptions are India (−0.118), Ukraine (−0.162), the United States (−0.072) and Israel (−0.061).

Table B.2 (*continued*)

Endogenous variable: Real GDP per capita (PPP-adjusted, log-level)

	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
Method	Pool-OLS	Pool-OLS	Pool-OLS	Pool-OLS	Pool-OLS	WG	System GMM	System GMM
Time dummies	No	No	Yes	Yes	Yes	Yes	Yes	
Regional dummies	No	Yes	Yes	Yes	Yes	No	Yes	
Fixed effects	No	No	No	No	No	Yes	Yes	
Matrix of Instruments	–	–	–	–	–	–	Reduce: 1 lag, starting at t-2	Collapse (all lags, starting at t-2)
Num. Observations	1676	1676	1676	1049	1049	1049	1049	1049
R2-adjusted	0.071	0.439	0.488	0.612	0.648	0.717		
Hansen (*p*-val)							0.0212	0.0688
m1-test (*p*-val)							0.0991	0.0439
m2-test (*p*-val)							0.385	0.131
Num. of countries						134	134	134
Num. of instruments							71	47

Robust t-statistics in parentheses: *** denotes significance at 1%, ** at 5%, * at 10%.

Appendix C. On the use of lagged energy intensity as explanatory variable

To save space, we only show the results using system-GMM under specifications M1, M2, M3 and using all energy variables.[20] In the first three columns, when only the lagged level of energy intensity is included (and its growth rate is excluded), the coefficient is positive and statistically significant in all cases. However, in the last three columns, when both the lagged level and the growth rate of energy intensity are jointly incorporated into the regression, both coefficients are negative and statistically significant. This raises the caveat that the exclusion of a relevant variable, such as the growth rate of energy intensity, could strongly bias the estimation of the lagged energy intensity variable.

In our sample, we find strong evidence of energy intensity β-convergence (both absolute and conditional). That is, the relationship between energy intensity growth and its lagged level is negative and highly significant.[21] The key implications of this result are summarized in the main text, Section 6.2.

Table C.1
Robustness analysis: lagged log-level and growth rates of Energy Intensity under system GMM estimation.

Dependent variable: GDP per capita growth rate

	M1	M2	M3	M1	M2	M3
log(income), lagged	−0.0186*	−0.0160	−0.0161*	−0.0334***	−0.0180**	−0.0188***
	(−1.68)	(−1.63)	(−1.68)	(−3.49)	(−2.51)	(−4.25)
log(Energy Intensity), lagged	0.0298**	0.0378***	0.0550***	−0.0867***	−0.0434***	−0.0291***
	(2.06)	(2.75)	(3.46)	(−5.52)	(−2.94)	(−3.09)
Energy Intensity, % change				−0.871***	−0.727***	−0.790***
				(−13.61)	(−8.59)	(−12.57)
Renew. Mix, % change	−0.614	−0.202	−0.485	−0.941***	−0.393*	−0.560**
	(−1.27)	(−0.68)	(−1.36)	(−2.61)	(−1.75)	(−2.30)
Nuclear. Mix, % change	−0.394	−0.832**	−0.836	0.277	0.118	−0.0438
	(−0.79)	(−1.97)	(−1.35)	(1.34)	(0.43)	(−0.16)
Industrial Sector, % change	0.291	0.304	0.0584	0.111	0.176	0.152
	(0.93)	(1.19)	(0.22)	(0.68)	(0.98)	(0.90)
Transport Sector, % change	0.446	0.544	0.625**	−0.156	−0.0145	−0.102
	(1.09)	(1.47)	(2.05)	(−0.71)	(−0.09)	(−0.51)
Residential Sector, % change	−1.632***	−1.024***	−0.852***	−0.912***	−0.722***	−0.660***
	(−4.74)	(−3.29)	(−3.34)	(−3.90)	(−3.47)	(−3.41)
Service Sector, % change	−0.557	0.0550	−0.469	−0.423	−0.170	−0.589**
	(−1.33)	(0.13)	(−1.34)	(−1.31)	(−0.57)	(−2.10)
log(Invest. Price), lagged		−0.00737***			−0.00189**	
		(−6.18)			(−2.57)	
Attained primary ed., % over Pop., lagged		0.134***			0.0836***	
		(3.22)			(3.86)	
Attained secondary ed., % over Pop., lagged		0.0322			0.0373	
		(0.83)			(1.39)	
Fertility rate, lagged			−0.0214***			−0.00975***
			(−4.06)			(−2.58)
Inflation, 5-year average			−0.000363			−0.000558**
			(−0.67)			(−2.21)

(*continued on next page*)

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[20] In order to overcome the problem of too-many instruments, we use the "collapse" version to limit the number of instruments (as in the fourth column in Table 2.c.).

[21] We consider time dummies in both cases. Results do not change significantly when time fixed effects are excluded. Using pool-OLS (absolute convergence), the β-convergence result is:

$$\Delta EI_{i,t} = \alpha - \underset{(0.0029)}{0.0343} \ln(EI_{i,t-1}) + \varepsilon_{i,t},$$

and for Within-Group estimates (conditional convergence):

$$EI_{i,t} = \alpha_i - \underset{(0.0049)}{0.0945} \ln(EI_{i,t-1}) + v_{i,t}.$$

Figures into parenthesis represent standard deviations, thus both coefficients are statistically significant at the 1% significance level. These two regressions imply yearly rates of convergence for energy intensity of 3.4% (absolute) and 9.5% (conditional), larger than those often obtained for real GDP. For instance, in our sample, the regression for absolute convergence for GDP produces a coefficient of −0.0009, which is not significant, while under fixed effects the coefficient is −0.0443, significant at the 1% level. Thus, the evidence of convergence is stronger for energy intensity than for per capita GDP.

Table C.1 (*continued*)

Dependent variable: GDP per capita growth rate						
	M1	M2	M3	M1	M2	M3
Gov. Size, 5-year average			−0.0596***			−0.0126
			(−3.50)			(−1.22)
Openness trade, 5-years average			0.0176			0.0128*
			(1.43)			(1.87)
Num. Observations	915	814	744	915	814	744
Hansen (*p*-val)	0.00786	0.360	0.410	0.0563	0.629	0.763
m1-test (*p*-val)	0.000357	0.00224	0.0000285	0.00163	2.71e-09	7.46e-09
m2-test (*p*-val)	0.994	0.324	0.0198	0.840	0.836	0.508
Num. of countries	134	120	128	134	120	128
Num. of instruments	101	134	143	111	144	153

Notes: Regressions above are system GMM, 2-step, robust estimates, including one lag in the matrix for instruments. Fossil fuel mix is omitted for the primary energy mix (i.e. fossil fuel mix plus renewable mix plus nuclear plants mix amount to one). *Agriculture, Cattle and Fishing* sector is omitted from the final energy mix (i.e. the final mix for agriculture together with industrial, transport sector, services and residential sector must sum up to one). Figures into parenthesis represent t-statistics. Starred values denote significance at $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Appendix D. On heterogeneity across regions, income and time

First, in Table D.1, we differentiate the following regions: Europe (we include dummies for Eastern EU countries), America, Asia-Pacific, and sub-Saharan Africa.[22] Second, in Table D.2, we differentiate between time periods and explore whether the energy-growth correlation has been affected by the oil price crisis of mid 80s (i.e., we distinguish between before and after 1985). Finally, in Table D.3, we complete this analysis trying to account for the degree of development of countries according to the Word Bank classification: low and lower-middle income countries, upper-middle income and high-income countries (both OECD and non-OECD); we show also results for OECD countries. In all cases, we use system GMM estimation, as we did in Tables 2.c and 3.[23]

Table D.1
GMM estimation by region.

Dependent variable: GDP per capita growth rate								
	Europe	America	Asia&Pacific	SSA	Europe	America	Asia&Pacific	SSA
log(income), lagged	−0.0190	−0.0236	−0.0474***	0.0134***	−0.0189	−0.0343*	−0.0486***	0.0131***
	(−1.37)	(−1.41)	(−3.07)	(2.86)	(−1.56)	(−1.74)	(−2.93)	(2.85)
Energy Intensity, % change	−0.436**	−0.716***	−0.542***	−0.982***	−0.443**	−0.681***	−0.525***	−0.980***
	(−2.33)	(−6.26)	(−5.43)	(−27.38)	(−2.36)	(−6.33)	(−4.71)	(−25.94)
Renew. Mix, % change	−2.009***	−0.0575	0.817	−0.208				
	(−4.31)	(−0.22)	(1.21)	(−0.47)				
Renew. Mix (Conventional), % change					−1.948***	−0.0748	1.072	−0.213
					(−3.84)	(−0.26)	(1.12)	(−0.51)
Renew. Mix (Frontier), % change					−0.0496	0.392	−0.0977	−0.598
					(−0.07)	(0.46)	(−0.16)	(−0.66)
Nuclear. Mix, % change	−0.704	0.0145	0.462	0	−0.680	0.0548	0.550	0
	(−1.50)	(0.02)	(0.68)	(.)	(−1.50)	(0.07)	(0.74)	(.)
Industrial Sector, % change	0.133	−0.527*	−0.412*	0.247	0.104	−0.669**	−0.414*	0.231
	(0.36)	(−1.82)	(−1.66)	(0.56)	(0.28)	(−2.03)	(−1.68)	(0.48)
Transport Sector, % change	0.472	−0.657	−0.246	0.00514	0.477	−0.601	−0.288	0.0105
	(1.12)	(−1.37)	(−0.67)	(0.01)	(1.14)	(−1.28)	(−0.76)	(0.02)
Residential Sector, % change	−0.791***	−1.129**	−1.377*	−0.725***	−0.832***	−1.267***	−1.437*	−0.739***
	(−3.14)	(−2.31)	(−1.79)	(−2.88)	(−3.30)	(−2.64)	(−1.81)	(−2.80)
Service Sector, % change	−0.625*	−0.632	−1.291***	0.425	−0.584*	−0.797	−1.226***	0.415
	(−1.91)	(−1.10)	(−3.12)	(0.40)	(−1.71)	(−1.29)	(−2.91)	(0.39)
Num. Observations	323	169	280	143	323	169	280	143
hansenp	0.203	0.533	0.262	0.204	0.516	0.723	0.255	0.404
ar1p	0.0130	0.00148	0.0264	0.0152	0.0153	0.00320	0.0247	0.0146
ar2p	0.847	0.200	0.858	0.470	0.879	0.373	0.851	0.479
N_g	48	24	40	22	48	24	40	22
j	51	35	44	28	56	38	48	31

Note: Sample sizes widely differ across regions. Given that system-GMM estimation can be affected in small samples, we aggregate those regions with smaller sample size. Thus, we aggregate American region with Asia-Pacific countries (labeled as AAP).
Robust t-statistics in parentheses: *** denotes significance at 1%, ** at 5%, * at 10%.

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[22] Sample sizes widely differ across regions. Given that system-GMM estimation can be affected by small samples, we aggregate those regions with smaller sample size. Thus, we aggregate American region with Asia-Pacific countries (labeled as ASP).

[23] When we differentiate by region or income levels, system-GMM estimate usually present an overfitting (too many instruments), which reduces the power of the hypothesis testing (for instance, the *p*-value in the Hansen test tends to be very close to one in all cases). For this purpose, we limit our instruments to no >2–3 lags and, simultaneously, we need to collapse the matrix of instruments.

Table D.2
GMM estimation by period.

Dependent variable: GDP per capita growth rate				
	Year <1985	Year ≥1985	Year <1985	Year ≥1985
log(income), lagged	−0.0285***	0.000409	−0.0296***	0.000931
	(−2.76)	(0.11)	(−2.96)	(0.28)
Energy Intensity, % change	−0.367*	−0.839***	−0.358*	−0.841***
	(−1.82)	(−16.16)	(−1.86)	(−16.28)
Renew. Mix, % change	−0.468	−1.056**		
	(−1.57)	(−2.14)		
Renew. Mix (Conventional), % change			−0.658*	−1.043**
			(−1.88)	(−2.14)
Renew. Mix (Frontier), % change			−0.404	0.122
			(−0.56)	(0.20)
Nuclear. Mix, % change	0.983***	−0.147	0.946***	−0.104
	(2.95)	(−0.53)	(3.00)	(−0.38)
Industrial Sector, % change	0.156	0.0883	0.217	0.0919
	(0.49)	(0.35)	(0.65)	(0.36)
Transport Sector, % change	−0.203	0.222	−0.114	0.207
	(−0.46)	(0.79)	(−0.26)	(0.72)
Residential Sector, % change	−0.905***	−1.397***	−0.896***	−1.407***
	(−2.75)	(−4.25)	(−2.81)	(−4.35)
Service Sector, % change	0.819	−0.532	0.494	−0.488
	(1.52)	(−1.60)	(0.89)	(−1.45)
Num. Observations	282	633	282	633
Hansen (*p*-val)	0.268	0.106	0.662	0.365
m1-test (*p*-val)	0.0663	0.0000474	0.0947	0.0000641
m2-test (*p*-val)	0.505	0.395	0.483	0.412
Num. of countries	104	134	104	134
Num. of instruments	80	132	89	147

Robust t-statistics in parentheses: *** denotes significance at 1%, ** at 5%, * at 10%.

Table D.3
GMM estimation by income levels.

Dependent variable: GDP per capita growth rate								
	Low & Lower-middle	Upper-middle	High-income (all)	High-income (OECD)	Low & Lower-middle	Upper-middle	High-income (all)	High-income (OECD)
log(income), lagged	−0.0402***	−0.1000***	−0.100***	−0.0641***	−0.0416***	−0.0838***	−0.0975***	−0.0658***
	(−3.05)	(−4.79)	(−3.71)	(−4.44)	(−3.21)	(−4.13)	(−3.76)	(−4.45)
Energy Intensity, % change	−0.776***	−0.423***	−0.137	−0.109	−0.773***	−0.488***	−0.159*	−0.133*
	(−10.11)	(−3.61)	(−1.55)	(−1.52)	(−10.06)	(−3.87)	(−1.79)	(−1.68)
Renew. Mix, % change	−0.504	−1.097**	−0.447	−0.658				
	(−1.19)	(−2.12)	(−1.12)	(−1.27)				
Renew. Mix (Conventional), % change					−0.445	−1.030**	−0.791*	−1.236**
					(−1.13)	(−2.44)	(−1.85)	(−2.03)
Renew. Mix (Frontier), % change					0.412	1.617**	0.0967	−0.220
					(1.13)	(2.39)	(0.30)	(−0.71)
Nuclear. Mix, % change	−0.252	−0.476	−0.251	−0.373	−0.320	−0.318	−0.224	−0.364
	(−0.39)	(−1.60)	(−0.91)	(−1.58)	(−0.51)	(−1.11)	(−0.82)	(−1.43)
Industrial Sector, % change	0.230	0.528**	−0.0449	0.830***	0.313	0.491**	−0.0827	0.686**
	(0.48)	(2.24)	(−0.16)	(2.68)	(0.66)	(2.21)	(−0.30)	(2.24)
Transport Sector, % change	0.466	−0.110	0.123	0.153	0.513	−0.230	0.0968	0.135
	(0.81)	(−0.29)	(0.34)	(0.66)	(0.93)	(−0.59)	(0.26)	(0.52)
Residential Sector, % change	−0.677**	−0.727*	−1.003***	−0.507**	−0.701**	−0.871**	−0.986***	−0.448**
	(−2.02)	(−1.80)	(−2.67)	(−2.30)	(−2.16)	(−2.18)	(−2.67)	(−2.13)
Service Sector, % change	0.0464	−0.311	−0.541*	0.329	0.0549	0.103	−0.541*	0.312
	(0.09)	(−0.55)	(−1.75)	(1.26)	(0.11)	(0.18)	(−1.80)	(1.20)
Num. Observations	284	253	378	304	284	253	378	304
Hansen (*p*-val)	0.170	0.684	0.439	0.288	0.592	0.826	0.557	0.583
m1-test (*p*-val)	0.0144	0.0418	0.0950	0.000784	0.0134	0.0214	0.0882	0.000949
m2-test (*p*-val)	0.190	0.721	0.271	0.462	0.258	0.853	0.252	0.211
Num. of countries	46	42	46	35	46	42	46	35
Num. of instruments	52	55	54	46	57	60	59	50

Robust t-statistics in parentheses: *** denotes significance at 1%, ** at 5%, * at 10%.

Appendix E. On the use of alternative control variables

We consider a set of variables taken from the political risk module of the *International Country Risk Database* (ICRD). An index of control of corruption (corruption); in this case, the higher the index value is, the lower corruption is. An index of democratic accountability (democracy); that is, whether there are free and fair elections and the degree of government's accountability. Finally, an index of government stability (stability); which measures both of the government's ability to carry out its declared program(s) and its ability to stay in office.[24] We also consider the *Polity2* variable (from the *Polity IV project*), whose *score* captures the regime authority spectrum ranging from −10 (hereditary monarchy) to +10 (consolidated democracy). For the model with *Polity2*, we also consider private investment (gross fixed capital formation) as a share of GDP (as in Barro, 2000). Table E.1 presents results concerning additional institutional indicators as control variables in the regression.

Table E.1
System GMM estimation: institutional quality and investment controls.

Dependent variable: GDP per capita growth rate					
	(i)	(ii)	(iii)	(iv)	(v)
log(income), lagged	−0.0162**	−0.00495	0.00104	−0.00606	−0.00109
	(−2.55)	(−1.05)	(0.28)	(−1.29)	(−0.26)
Energy Intensity, % change	−0.790***	−0.714***	−0.657***	−0.819***	−0.667***
	(−14.33)	(−6.52)	(−6.39)	(−15.35)	(−5.36)
Renew. Mix (Conventional), % change	−0.313	−1.025**	−1.061***	−0.288	−0.896**
	(−1.21)	(−2.46)	(−2.93)	(−1.36)	(−2.26)
Renew. Mix (Frontier), % change	0.425	0.262	0.313	0.505	0.0167
	(0.75)	(0.67)	(0.84)	(1.12)	(0.04)
Nuclear. Mix, % change	−0.102	−0.0253	0.0465	0.101	0.0132
	(−0.32)	(−0.09)	(0.28)	(0.50)	(0.05)
Industrial Sector, % change	0.0291	0.0648	0.197	−0.0400	0.146
	(0.13)	(0.31)	(0.95)	(−0.18)	(0.63)
Transport Sector, % change	−0.151	0.160	−0.0258	−0.282	−0.000584
	(−0.80)	(0.61)	(−0.10)	(−1.34)	(−0.00)
Residential Sector, % change	−1.085***	−1.142***	−1.156***	−1.087***	−1.143***
	(−3.32)	(−4.16)	(−4.09)	(−3.15)	(−4.04)
Service Sector, % change	−0.486	−0.377	−0.157	−0.472	−0.0903
	(−1.25)	(−1.08)	(−0.56)	(−1.36)	(−0.24)
Quality of democracy	0.00575***			0.00237	
	(2.67)			(1.27)	
Corruption	0.00229			0.000437	
	(0.81)			(0.21)	
Government stability	0.00327***			0.00168*	
	(2.86)			(1.70)	
Polity2		0.00191***			0.00145**
		(2.73)			(2.35)
GFFC over GDP			0.219***	0.144***	0.190***
			(4.58)	(3.78)	(4.61)
Num. Observations	673	845	835	624	775
Hansen (*p*-val)	0.209	0.200	0.224	0.666	0.360
m1-test (*p*-val)	0.000570	0.00192	0.000329	0.00191	0.00236
m2-test (*p*-val)	0.832	0.920	0.964	0.926	0.535
Num. of countries	122	126	130	118	122
Num. of instruments	129	124	124	141	136

Notes: Regressions above are system GMM, 2-step, robust estimates, including one lag in the matrix for instruments. Fossil fuel mix is omitted for the primary energy mix (i.e. fossil fuel mix plus renewable mix plus nuclear plants mix amount to one). *Agriculture, Cattle and Fishing* sector is omitted from the final energy mix (i.e. the final mix for agriculture together with industrial, transport sector, services and residential sector must sum up to one). The institutional variables have been retrieved from the *Political Risk Module* of the *International Country Risk Database* (ICRD): https://www.prsgroup.com/explore-our-products/countrydata-online/.
Figures into parenthesis represent t-statistics. Starred values denote significance at $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Appendix F. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2019.05.022.

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[24] https://www.prsgroup.com/explore-our-products/countrydata-online/.

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