Energy Prices, Growth, and the Channels in Between: Theory and Evidence

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Abstract

The paper is motivated by cross-country evidence on a negative relationship between energy use and growth. It develops a theoretical multisector framework to show how energy affects investments and the growth rate of economies. Empirical estimations using single equations and a system with five simultaneous equations for a sample of 37 developed countries with five-year average panel data over the period 1975-2009 are presented. The empirical results of the structural model do not indicate that higher energy prices harm the growth process. On the contrary, decreasing energy input induces investments in physical and knowledge capital, supporting growth and counteracting the negative static effects of higher energy prices.

Keywords: Energy Prices and Growth, Endogenous Capital Accumulation, Structural Change, Panel Data

JEL Classification: Q43, O47, Q56, O41

1 Introduction

The recent surge in fuel prices has given rise to concerns about the long-term growth prospects of the world economy. Developments in the last decades seem to show that high energy prices have a negative impact on economic dynamics. The oil price jumps of 1973-74, 1978-80, 1989-90 and 2004-08 were all followed by a worldwide recession. Thus, at first sight, high energy prices appear to be a curse, certainly not a blessing. In the same way, it is widely argued in public debate that lower energy input harms both output level and output growth. When we consider cross sections of countries, however, a rather different picture emerges. For the OECD countries, the simple correlation between energy use and growth is negative. Various countries with low energy use and high energy prices have performed well economically, while many low-energy price countries, especially less developed oil-producing economies, persistently show low growth rates. How can this be explained, what are the underlying mechanisms, how strong are the different effects? Finding the appropriate answers is not only important for understanding current development. As energy prices are expected to rise further in the future and with CO_2 emissions being closely connected to energy use, the findings are equally relevant for long-term growth and the formulation of efficient climate policies.

The present paper considers the impact of energy on long-run economic development, both theoretically and empirically. Contrary to common thinking, I find that higher energy prices do not hamper the growth process. The results of the regressions show that physical and knowledge capital accumulation are partially crowded out by abundant energy use. This result may be called a "scarcity paradox", which is due to three distinct effects: (i) lower energy use leads to a reallocation of inputs toward capital accumulation and (ii) higher capital accumulation entails higher growth, which (iii) may be associated with higher welfare. As growth is costly, it is not automatically related to higher welfare. But assuming positive externalities in capital accumulation (learning effects) and negative externalities of energy use (pollution of fossil fuels), the positive relationship is likely in this context. That high energy prices can be good for growth is somewhat counterintuitive. However, intuition may have been relying too much on the business cycle in the 1970s, and not necessarily on long-run growth experience. To track the different effects, the exploitation of cross-country information seems indispensable. The paper follows Hauk and Wacziarg (2009, p.103) who conclude that there is no good alternative to cross-country growth regression for addressing the fundamental question of what accounts for income differences across countries but takes into account recent empirical skepticism, see Durlauf (2009).

The paper shows that the level and growth have effects have to be carefully distinguished, which is often not the case in policy debates. It stresses that capital has to be treated as an endogenous variable in an energy-growth context. Energy does not affect growth directly but has an impact on capital investments, which is found to be crucial. Capital is disaggregated and includes non-physical components like human and knowledge capital, which allows to identify and explore distinct "channels" through which energy use affects the growth rate of the economy.

Different strands of economic theory are related to the present approach.[2] Most importantly, Hicks (Hicks 1932, p. 121) concludes that "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind - directed to economizing the use of a factor which has become relatively expensive." The prediction of "induced innovation" suggests that decreasing energy use (due to rising energy prices) fosters additional innovation improving energy efficiency, which has been corroborated empirically by Popp (2002). As not only innovations (i.e. knowledge capital) but all kinds of capital can raise energy efficiency, I use the term "induced investments" in this context. The purposeful use of capital, i.e. the shifting of consumption into the future in order to increase the productivity of the other factors like energy, is a main contribution of von Böhm-Bawerk (1921), who calls it "roundabout production." For open economies, the so-called "Porter Hypothesis" (Porter 1991) states that stringent environmental regulation can increase social welfare and net benefits of firms, assuming that high prices for the environment induce innovatory activities which increase the firms' competitiveness. As we regard distinct sectors, there is also a close relationship to trade theory. The so-called "Rybczynski theorem" analyses conditions under which a rise in the endowment of one factor leads to a (more than proportional) expansion of the output in one sector of the economy and an absolute decline of the output in the other sector.[3] Applied to the present problem it says that a decrease in energy may harm consumer goods production but benefit capital accumulation. However, it will be shown below that the Rybczynski forces need not dominate the result in a general dynamic framework. This is why an empirical study is warranted.

By using cross-country data and five-year averages for the empirical estimations, the study exploits long-run and cross-section information, which is crucial for the topic. The paper finds that increasing energy prices have the (expected) negative effect on energy use and that decreasing energy use has a positive impact on capital accumulation and growth. Specifically, a decrease of energy input raises the accumulation of physical and knowledge capital; the two channel effects turn out to be of similar size, while the effect via human capital is not significant. These results can be used for the evaluation of current energy and climate policies. Building on the empirical results of the present paper, Peretto (2009) argues that (higher) energy taxes are predicted to increase welfare.

Results from recent contributions using time series analysis differ from our conclusions. Specifically, Yuan et al. (2008), Lee and Chang (2008), and Soytas and Sari (2007) find a positive impact of energy on growth.[4] Time series models are very detailed in estimation

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[2] For the foundations of recent growth theory see the seminal contributions of Romer (1990) and Grossman and Helpman (1991); the combination with natural resources is treated in Bovenberg and Smulders (1995), Bretschger (1998), Barbier (1999), Scholz and Ziemes (1999), Grimaud and Rougé (2003), Brock and Taylor (2005), Xepapadeas (2006), Bretschger and Smulders (2006), and López, Anriquez and Gulati (2007).

[3] Rybczynski (1955, p. 337) writes: ".. the maintenance of the same rates of substitution in production after the quantity of one factor has increased must lead to an absolute expansion in production of the commodity using relatively much of that factor, and to an absolute curtailment of production of the commodity using relatively little of the same factor."

[4] Further literature with similar conclusions includes Stern (1993, 2000), Glasure and Lee (1997), Lee (2005, 2006) and Chontanawat et al. (2008), while Huang et al. (2008) find no evidence indicating that

techniques but not closely connected to modern growth theory. Key constraints for growth regressions are the limited number of observations and the fact that some key growth determinants display little time variation. The distinction between business cycles and growth effects is more difficult than in cross-country growth regressions. But the difference is important, as business cycle and growth effects may be exactly opposite. When looking at the long-run growth effects of energy use, the main interest concerns potential output, not the short- or medium-run deviations from potential output. Vector autoregressive regressions tracking impulse-response effects deal with transitory shocks, see e.g. Kilian (2009). On the contrary, the structural approach of this paper is concerned with energy-driven *permanent* shifts in *long-run* growth rates.

Having a first look at a cross-section of countries I do not find an indication of energy being good for growth but rather see a motivation to elaborate on a model where a negative impact can be derived as a possible outcome. The empirical estimation of the issues in cross-country regressions have to be done and interpreted with care, however. There has recently been a clear objection against a too mechanic application of cross-country growth empirics and too far-reaching policy conclusions, see Durlauf (2009). The present paper also suggests that the estimation of single substitution elasticities[5] is not useful in the energy-growth context, which supports Solow (1987) who argues that elasticities are concepts of partial equilibrium models, disregarding general equilibrium responses and differences in energy intensities.[6] The paper explains the role of the elasticities when capital is endogenous and shows how equilibrium effects can be included in an energy-growth model. The dataset includes 37 higher-income countries, where knowledge accumulation and innovative activities as used in the model are important issues, while geography and institutions are not a predominant topic (as in poorer countries). In the political debate, energy and carbon reduction policies are especially considered in the richer economies, so that a study about the effects of energy prices is especially rewarding for this country group.

The remainder of the paper is organized as follows. In section 2, empirical observation are presented to motivate the theoretical model. In section 3, the theoretical model is developed. Section 4 presents the estimation method and the data. In section 5 the results of the empirical estimations are presented. Section 6 concludes.

2 Cross-country Evidence

To further motivate the study and to get a first impression about the energy-growth nexus I present empirical evidence on energy use and growth for a cross-section of countries. For each of the five-year growth periods of our data sample of 37 developed countries, Figure 1 shows the result of a cross-section OLS regression with per capita income growth as endogenous variable and (the log of) energy use per capita and country fixed effects as

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energy consumption leads economic growth and the seminal paper in this area, Kraft and Kraft (1978), finds evidence of unidirectional causality running from GDP to energy consumption.

[5] See e.g. Berndt and Wood (1979)

[6] He states that direct estimates of factor substitutability based on aggregate data are "misleading" and the capital-energy complementarity debate "has been misfocused," see Solow (1987, p. 606).

right-hand variables. It emerges that in six of the seven periods the effect of energy is negative and in five periods it is statistically significant.[7] This does indeed not correspond to the intuition one gets when looking at time series.

Of course, one has to look at the mechanism transmitting the effect of energy in detail which will be done below. I will follow growth theory in arguing that investments are important for growth so that, with regard to transmission, the impact of energy use on investments becomes crucial. Table 1 looks at investments in four selected countries. For the USA, UK, Sweden, and China we see that energy use per GDP has decreased over the whole time period while the investment share has increased. Hence, the negative relationship between energy per GDP and investment can also be seen on a country level, but this actually does not hold for all the countries in the sample. For the case of the USA and Sweden we also see a decrease in energy use per capita, while for the UK and especially China the opposite holds. This suggests that energy use per capita and per GDP have to be treated separately which is done below.

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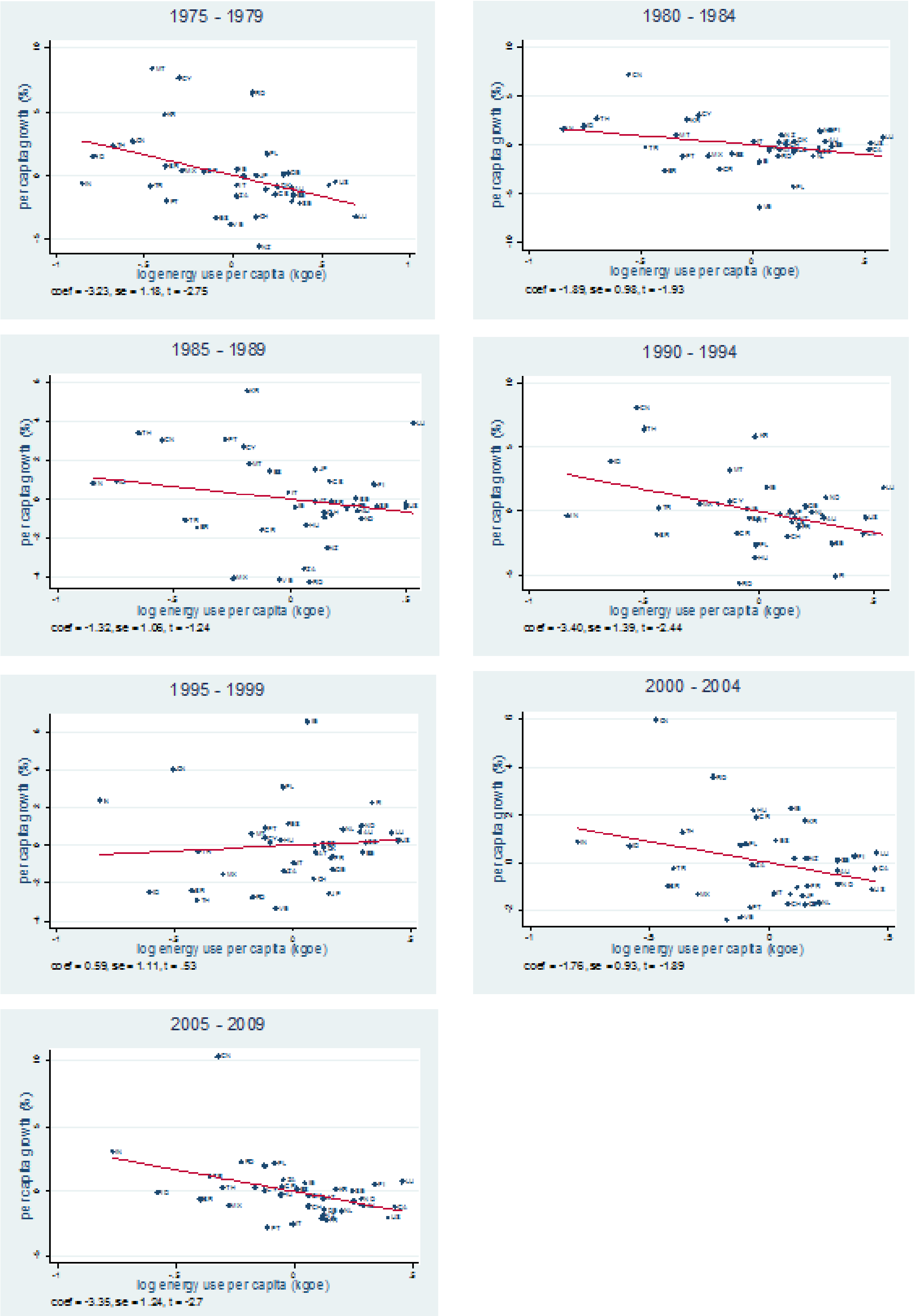
[7] Performing an additional panel regression with country-fixed effects and all period dummies shows that the impact of energy per capita on per capita growth is negative and significant; the same holds true for the impact of energy use per GDP.



Data source: WDI online (2012)

Figure 1: Log of energy per capita and per capita growth

Table 1: Investment and energy use in four selected countries 1975-2009

		investment rate	energy use per capita	energy use per GDP
USA	1975 - 1979	18.03	8,161.57	337.18
	1980 - 1984	18.19	7,498.28	287.87
	1985 - 1989	19.27	7,638.95	254.01
	1990 - 1994	18.31	7,689.49	238.33
	1995 - 1999	21.33	7,832.56	217.87
	2000 - 2004	22.13	7,876.77	195.67
	2005 - 2009	21.19	7,571.57	176.52
UK	1975 - 1979	15.24	3,678.52	218.50
	1980 - 1984	13.29	3,416.61	181.76
	1985 - 1989	16.13	3,607.41	163.97
	1990 - 1994	15.18	3,686.46	155.39
	1995 - 1999	16.16	3,787.17	141.04
	2000 - 2004	17.34	3,738.25	121.35
	2005 - 2009	17.24	3,468.40	104.39
Sweden	1975 - 1979	18.56	5,043.23	259.16
	1980 - 1984	16.87	5,000.68	241.26
	1985 - 1989	18.98	5,749.38	246.21
	1990 - 1994	17.33	5,505.82	230.78
	1995 - 1999	16.66	5,724.59	220.78
	2000 - 2004	17.47	5,669.23	187.58
	2005 - 2009	19.74	5,352.63	159.36
China	1975 - 1979	37.08	576.16	1,322.68
	1980 - 1984	34.34	617.81	1,034.04
	1985 - 1989	38.27	694.16	732.82
	1990 - 1994	37.34	776.58	580.54
	1995 - 1999	39.55	876.34	408.51
	2000 - 2004	40.50	978.60	310.22
	2005 - 2009	42.62	1,449.72	296.53

Data source: see table 2 in the Appendix

3 Theoretical framework

3.1 Energy and Growth

Standard model The standard production function with final output Y as a function of capital K, labor L, and energy E reads

$$Y\left(t\right)=F\left[K\left(t\right),L\left(t\right),E\left(t\right)\right], \tag{1}$$

where F is a linear homogeneous function and t the time index. Logarithmic differentiating of (1) yields

$$\hat{Y}\left(t\right)=\theta_{K}\hat{K}\left(t\right)+\theta_{L}\hat{L}\left(t\right)+\theta_{E}\hat{E}\left(t\right). \tag{2}$$

The hats denote growth rates, θs are the weighting factors, and the subscripts relate to the input.[8] Expression (2) is the well-known growth accounting relation, that is the relationship between the growth of inputs and the growth of output. It says that *ceteris paribus* energy growth effects output growth positively but is often interpreted as "determining" that "energy" is good for growth. This paper argues that there are several problems when drawing such conclusions or basing the empirical analysis on this framework. First, one has to carefully distinguish between the effects of energy *levels* and energy *growth*. Second, (2) is not based on a theory with optimizing behavior of the agents, it is rather a technical decomposition of a time series. Importantly, it ignores input supply conditions and causal relationships between the inputs. An especially important effect in this context is the impact of energy on capital goods production, which is generally different from the impact on final output. This suggests that $\hat{K}$ in (2) should be treated as an endogenous variable, both in terms of supply conditions and of demand derived from intertemporal household optimization, which is done in the following. Central requirements for a model to analyze the issues are (i) to derive conditions for endogenous capital accumulation when energy is an input, (ii) to analyze the impact of knowledge spillovers, according to endogenous growth theory, and (iii) to combine (i) and (ii) for long-term predictions in a framework with intertemporal optimization of the households.

Multisector model In order to show the basic mechanisms at work I specify F in (1) as

$$Y\left(t\right)=F(\cdot)=K\left(t\right)^{\alpha}\left[\phi L_{Y}\left(t\right)^{\frac{\sigma-1}{\sigma}}+(1-\phi)E_{Y}\left(t\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{(1-\alpha)\sigma}{\sigma-1}}, \tag{3}$$

where $0<\alpha<1$ is the output elasticity of capital, $0<\phi<1$ is a share parameter, $\sigma\geq 0$ denotes the elasticity of substitution between labor and energy in Y-production, and the subscripts label the sector in which the input is used. Expression (3) is the simplest specific production function of the class given in (1) allowing to show the different effects of energy use on growth.[9] New capital goods are produced with the technology

$$\dot{K}(t)=AB(t)G(t)=AB(t)L_{K}\left(t\right)^{\beta}E_{K}\left(t\right)^{1-\beta}, \tag{4}$$

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[8] Given the linear homogeneity of F in (1), the factors equal the output elasticities and the cost shares of the respective inputs.

[9] The effect is present even with keeping a substitution elasticity between capital and the combined energy/labor input of unity, which plays an important role in Dasgupta and Heal (1974).

where a dot over a variable denotes the time derivative; A is a constant and B the stock of public knowledge. G represents (rival) input use in capital accumulation, which we label "investment" below.[10] Following (4), capital goods production differs from consumer goods in two respects. First, energy and labor have a substitution elasticity which is different from Y-production ($\sigma = 1$ is only a special case). Second, according to Arrow (1962), positive learning spillovers from capital investments add to the stock of public knowledge B, which is a free input into subsequent capital goods production. B is assumed to be proportional to K, weighted by diffusion intensity D

$$B(t) = DK(t), \quad \forall t. \tag{5}$$

The framework is general in the sense that, given the knowledge spillover from capital formation, labor, energy, and capital are all used in both sectors of the economy.[11] Production is complemented by the equilibria in the labor and the energy market

$$L_Y(t) + L_K(t) = \bar{L} \tag{6}$$

$$E_Y(t) + E_K(t) = E. \tag{7}$$

The lhs of (6) and (7) gives the labor and energy demand from both sectors Y and K; labor supply is assumed to be fixed, while energy is provided by foreign countries with a fully elastic supply.[12]

Intertemporal optimum When $\rho > 0$ is the pure time-preference rate and C consumption, the (intertemporal) optimum is obtained by maximization of utility U

$$U(t) = \int_0^{+\infty} e^{-\rho t} \frac{C(t)^{1-\sigma_c}}{1-\sigma_c} dt \tag{8}$$

subject to the restrictions (3), (4), (6), (7), and

$$p_Y(t)C(t) = p_Y(t)Y(t) - p_E(t)E(t) \tag{9}$$

where p_E denotes the energy price. The current-value Hamiltonian with the state variable K and the control variables C, L_Y, L_K, E_Y, E_K, and E reads

$$\begin{aligned} H = {} & U(C) + \mu_Y \left[p_Y F(K, L_Y, E_Y) - p_Y C - p_E E \right] \\ & + \mu_K ADK \cdot G(L_K, E_K) + \mu_L (L - L_Y - L_K) + \mu_E (E - E_Y - E_K) \end{aligned} \tag{10}$$

where μ_Y, μ_K, μ_L, and μ_E are the (shadow) values of consumption, capital, labor, and energy. The associated first-order conditions (A.1)-(A.7) are given in the appendix. A steady state is characterized by a constant sectoral allocation of labor and energy, so that by (3), (4), and (5) we have $\hat{Y} = \alpha \hat{K} = \alpha ADG$, with constant wages w and energy price p_E,

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[10] To use a CES technology in (4) would work as well but not add to understanding the issue.

[11] The use of rival capital for capital investments would not change the conclusions; the current formulation of (4) is closer to the seminal endogenous growth models like Grossman and Helpman (1991) where only primary inputs are used in all the sectors.

[12] The assumption on supply is made with a view toward the empirical application; domestic energy production would generate the same theroretical results.

and price of G, p_G. Manufacturing new capital goods becomes less expensive with increasing capital stock due to (4) and (5). By virtue of (3), with given w, p_E, and using p_Y for the price of Y and p_K for the rental price of capital, K, I get $\hat{Y} = \alpha\hat{K} = -\alpha\hat{p}_K = -\hat{p}_Y$ in steady state. Accordingly, consumer expenditures remain constant but real wages (w/p_Y) increase over time due to $\hat{p}_Y < 0$.

Steady state growth For steady-state consumption growth I derive, see the Appendix

$$\hat{C} = \frac{ADG - \rho}{1 - \alpha(1 - \sigma_c)}. \tag{11}$$

Expression (11) is the Keynes-Ramsey rule for the social optimum, showing that consumption growth depends positively on the investment efficiency A, knowledge diffusion intensity D, investments G, capital share α, and the elasticity of intertemporal substitution $(1/\sigma_c)$ but negatively on the discount rate ρ. Rising diffusion intensity D accelerates growth, which is the expected effect for a "productivity" parameter in the growth engine of the economy. It is evident from (11) that the steady-state behavior of the model has a close similarity to the class of so-called "AK-growth models".[13] Hence, despite the degree of complexity needed in the present context, long-run growth turns out to be determined in a way which is in accordance with standard growth theory. In the simplest version of the AK-models it is assumed that $Y(t) = F(\cdot) = AK$ and there is only one sector, the real return to capital is simply A, and consumption growth becomes $\hat{C} = (A - \rho)/\sigma_c$. In the present approach we have the same growth determinants (σ_c, A, ρ) but get two useful extensions. The first is similar to the seminal and richer "AK paper" of Rebelo (1991), who also assumes two different sectors for consumption and capital. With consumption growing at a rate $\alpha\hat{K}$ and capital goods growing at a rate $\hat{K}$ in steady state the mechanism to establish equality of wages and energy prices between the sectors is the divergence of sectoral output prices, i.e. $\hat{p}_Y = \alpha\hat{p}_K$. With $\alpha = 1$ the term $1 - \alpha(1 - \sigma_c)$ in the denominator of (11) simplifies to σ_c which usually appears in the consumption growth equation.[14] Second, the model adds to the literature by the inclusion of energy in a dynamic multisector setup. With G having the positive growth effect given by (11) it is established that an increase of inputs in the capital sector, L_K and E_K, has a positive growth effect (it affects $\hat{Y}$), while an increase of L_Y and E_Y has a positive level effect (it affects the level i.e. Y).[15] At the same time, (6) and (7) together with (3) make clear that the higher is the (steady state) growth rate of the economy the lower becomes the initial level of consumption. Accordingly, only a permanent *growth* of labor and energy used in the consumption sector can have a growth effect like the *level* of labor and energy used in the capital sector. As we consider permanent growth

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[13] The solution is given for the social optimum in order to show that the derived effects of energy emerge even when all the externalities of knowledge accumulation are internalized.

[14] Put differently, the marginal physical product of capital decreases with increasing capital due to $\alpha < 1$, but the relative price of consumer goods in terms of capital goods rises simultaneously. Given the proportional (linear) spillovers in capital accumulation, the two effects have equal size but opposite sign. In the one-sector AK-models the relative price of consumer and capital goods is unity by assumption and the marginal physical product of capital is independent of K (it equals the constant A).

[15] In the basic version of the Rebelo (1991) model it is assumed that only capital procuces new capital goods, i.e. $G = 1$ in the present model.

of labor and energy to be infeasible in the long run we concentrate on the growth effects of equilibrium levels of energy and labor in the capital sector in the following.

Two further remarks are warranted at this point. First, the constant (linear) growth given in (11) arises due to the assumption of proportional spillovers in (5). If we imposed less than proportional spillovers by setting $B(t) = DK(t)^{\eta}$ (with $\eta < 1$), we would get by (4) that the marginal physical product of capital decreases with increasing capital, so that consumption would finally converge to a constant like in the neo-classical growth model. We will apply the assumption in the empirical part below. Second, the theoretical model assumes energy prices to rise relative to consumer prices ($p_E = \bar{p}_E$, $\hat{p}_Y = -\hat{C} < 0$). If I relax the assumption and posit a different development of energy prices, energy use depends on the level of consumption and of income; this will also be analysed in the empirical part.

Energy and growth If G was itself a (sector specific) input it would be obvious from (11) that a larger input base (higher G) would foster economic growth, a well-known scale effect emerging with proportional spillovers like in (5). But the present model comprises two sectors (Y, $\dot{K}$) and two primary inputs (L, E). Now, if an increase in one of the inputs benefits both sectors, goods production and capital accumulation both increase as a consequence, similar to the simple scale effect. However, the Rybczynski theorem from trade theory suggests that with an increase in one of the inputs one sector may loose, even in absolute terms. If the loosing sector turns out to be the capital sector, economic growth is harmed (fostered) by higher (lower) energy input.

For optimum sectoral input use, it is found from (A.2)-(A.5) that in each sector inputs are used up to the point where value marginal products are equalized between the sectors, the usual optimum condition for multi-sector models. A shift in energy prices causes a change in energy use and a sectoral reallocation of labor and energy. The Appendix shows that the impact of (the percentage change of) energy prices $\hat{p}_E$ on (the percentage change of) capital investment $\hat{G}$ is given by

$$\hat{G} = \frac{1}{\lambda_{LK}} \left[(1 + \tilde{\theta}_E)(\lambda_{LY}\theta_{EY}(1-\sigma) - \tilde{\theta}_E \right] \hat{p}_E \tag{12}$$

where λ_{LY}, $\lambda_{LK} > 0$ are the sectoral labor shares, the θs denote the cost shares with subscripts for inputs and outputs, and $\tilde{\theta}_E = \theta_{EK}/\theta_{LK} > 0$. From (12) we see that higher energy prices decrease investments (are bad for growth), provided that the elasticity of substitution in consumer goods production is high, i.e. $\sigma > 1$. However, if the elasticity of substitution is low, i.e. $\sigma < 1$, the effect is reversed and the relationship between energy prices and growth becomes positive, provided that (the absolute value of) the first term in squared brackets exceeds relative energy intensity $\tilde{\theta}_E$.

Discussion The basic mechanism at work is the reallocation of labor between the consumer and the capital sector caused by changing energy prices, shifting the economy to a different growth path. Provided that (sufficient) labor is reallocated from the capital to the consumer goods sector, a decrease of the growth rate of capital and output may be the consequence. Specifically, (12) shows that when energy becomes more expensive and less energy is used, a low input substitution elasticity in the consumer sector means that labor is released to the capital sector, which benefits growth. Hence, with increasing energy prices, poor input substitution in the consumer sector turns out to be favorable for growth. If, on the other hand, the substitution effect is high (high σ), less energy in the consumer goods sector calls for more labor for consumption goods, which is recruited from the capital goods sector, harming capital accumulation and growth. The result that bad substitution in consumer goods production promotes growth with increasing energy scarcity is in line with previous literature on multisector models and endogenous growth.[16] With $\sigma = 1$ the output and the substitution effect exactly offset each other. The main conclusion from the theoretical model is that an increase in energy prices may but need not have a positive growth effect in a social optimum. Why can it be desirable for an economy to choose a lower growth rate with lower energy prices? The reason is that low energy prices may increase the attractiveness of present consumption relative to capital accumulation and future consumption, given the production functions in both sectors and the impatience of households. This equally says that the (usually stressed) negative *level* effect of increasing energy prices (decreasing energy use) on output remains valid. Indeed, with *constant* capital and in the absence of sectoral reallocation of labor, decreasing E_Y in (3) causes a decrease in Y. To have more or less growth is not good or bad *per se* but the outcome of welfare optimization given the relative price of current and future consumption. The derived effect of σ is robust in case of model extensions but additional effects result in more complex models.[17]

Lessons for empirical study Following the theoretical model, several conclusions for an appropriate empirical model testing the impact of energy prices on growth can be drawn. First, the theoretical model shows that it is the impact of energy use and/or energy prices on capital investments which is decisive for the growth impact of energy. Hence, an appropriate empirical research design is needed to (i) estimate this specific effect and (ii) to confirm it in an integrated system approach. Second, as the capital stock may be disaggregated into different separate stocks, several channels capturing the impact of energy prices might be analyzed. Regarding the macroeconomic context, appropriate instrumental and control variables have to be used. Third, it emerges that the empirical estimation of a single aggregate input substitution elasticity is likely to be misleading because (i) it is sectoral substitution elasticities which matter, (ii) the sectoral elasticities have opposing impacts on the energy-growth nexus, and (iii) we cannot disregard general equilibrium effects. This is the reason why the empirical part refers to a full-fledged macroeconometric model and not to single substitution elasticities.

3.2 Estimation equations

I now turn to the implications of the theoretical model for empirical research.

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[16] See Bretschger (1998), Peretto (2009), and Bretschger and Smulders (2012).

[17] Allowing for a substitution elasticity between capital and the other inputs in (3) of unequal unity allows to show that, for this substitution elasticity, a high value would be favorable for growth in the context of energy scarcity; by adding more consumer sectors with CES-production functions reveals that it is not the absolute value of the elasticities in these sectors but the relative size, which matters for growth, see Bretschger and Smulders (2012).

Energy and investment Following the theoretical result, a change in energy prices has a direct impact on investments, see (12), where $\hat{G} = -\delta_p \hat{p}_E$ with $\delta_p = (\lambda_{LK})^{-1} \Big[(1+\tilde{\theta}_E)(\lambda_{LY}\theta_{EY}(1-\sigma)+\tilde{\theta}_E\Big] \lesseqgtr 0$. For reasons of data availability, see section 4, I will focus on energy use instead of energy prices in the following. The two variables are related by a regular demand function, see (A.20) in the Appendix, where I get $\hat{p}_E = (1/\delta_E)\hat{E}$ with $\delta_E < 0$. Combining the two equations and using logarithms instead of percentage changes we write

$$\log G = \overset{+/-}{(\delta_p/\delta_E)} \cdot \log E \tag{13}$$

where the sign of the the parameter δ_p is not determined by theory but subject to empirical scrutiny in the following. Expression (13) includes a scale effect, which can be eliminated by dividing both sides by income. This brings the model closer to standard growth theory suggesting to capture investments by investment shares. Using I and p_I for total income and the corresponding price index, the logarithm of the (real) investment share s becomes

$$\log s = \log(\frac{G}{I}) = \log(\frac{(\delta_p/\delta_E)E}{I}). \tag{14}$$

Merging E and I to a single variable allows to use E/I, which is the well-known energy efficiency (for which standardized international data are available). I also include the relative price (p_G/p_I) because the s from the statistics does not take into account relative prices. Adding a constant term δ_0 and a vector of control variables X then yields

$$\log s = \delta_0 + \delta_I \log(E/I) + \delta_G \log{(p_G/p_I)} + \delta_x \log X. \tag{15}$$

Equation (15) calls for the inclusion of country specific effects, because energy efficiency is likely to depend on country-specific factors related to country-specific access to technology. The scale effect of the theoretical growth model can also be addressed by using population size L instead of income I when introducing energy per capita (E/L) as a right-hand variable

$$\log s = \tilde{\delta}_0 + \delta_L \log(E/L) - \tilde{\delta}_G \log{(p_G/p_I)} + \tilde{\delta}_x \log \tilde{X} \tag{16}$$

where income per capita (I/L) can be used as one of the control variables in the $\tilde{X}$-vector. Following the seminal contribution of Mankiw, Romer, and Weil (1992), I will in the second part of the empirical estimations distinguish between different kinds of capital, that is the estimations include different investment rates for physical, human, and (private) knowledge capital.[18] To disaggregate capital K seems especially rewarding in this context as it allows us to distinguish between the different "channels" through which energy affects the growth rate. The different capital types are assumed to have different production conditions, in particular different energy intensities and substitution elasticities.

Growth equation As the present model determines long-run growth in accordance with recent theory, see (11), standard growth empirics can be applied for the growth equation. Capital investments are a crucial variable to explain economic growth. By combining

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[18] Infrastructure and social capital investments are not included; they would be more important for a larger dataset including poorer countries.

(3), (4), and (5) the theoretical model predicts that $\hat{Y} = \alpha\hat{K} = \alpha ADG$ i.e. increasing investment G raises economic growth. In growth empirics, it has become standard to use income growth instead of consumption growth as a right-hand variable (the two are identical in steady state) and to employ investment shares rather than total investments. Both specifications are consistent with the theoretical model of the paper. Moreover, empirical growth models do not rely on linear growth but include initial income I_0 as a right-hand variable in order to allow for convergence of income to a constant steady-state. In the present model, this is the consequence of assuming knowledge spillovers being given by $B(t) = DK(t)^{\eta}$ (with $\eta < 1$) entailing decreasing rather than constant returns to capital.[19] Measuring income in per capita terms, i.e. using $i = I/L$, I can express the growth equation in terms of $\hat{\imath}$ and i_0, and include a separate control variable to test for population growth. By adding a constant term and a vector of control variables M (including $\hat{L}$) I then arrive at the growth equation of the empirical model

$$\hat{\imath} = \gamma_0 + \gamma_S \log s(\cdot) + \gamma_i \log i_0 + \gamma_Z \log M, \tag{17}$$

which corresponds to previous growth empirics (e.g. Mankiw et al. 1992), with the important difference that s is now an endogenous variable, determined in a first stage by (15) or (16). According to (17) and the theoretical model, there is no additional, separate and direct impact of energy use on growth; this prediction will also be tested empirically.

Energy use The use of energy use per capita E/L or energy intensity E/I as a right-hand variable in (15) and (16) might call for an additional estimation equation because of possible endogeneity. First, cross-country evidence reveals that end-user energy prices are almost entirely explained by different country energy taxes, which we take as exogenous. Moreover, energy use is normally associated to the income level.[20] Including constant terms and control variables the third type of estimation equations of the system reads

$$\log(E/I) = \nu_0 + \nu_1 \log p_E + \nu_2 \log i_0 + \nu_T \log T. \tag{18}$$

$$\log(E/L) = \tilde{\nu}_0 + \tilde{\nu}_1 \log p_E + \tilde{\nu}_2 \log i_0 + \tilde{\nu}_T \log \tilde{T}. \tag{19}$$

It will be used in the system equations and as a first-stage estimation equation when testing (15) and (16).

Summary The system of empirical equations consists of the energy-investment equations for the different capital types (15), the growth equation (17) and the energy equation (18). Alternatively, when using energy per capita instead of energy per GDP, it consists of the equations (16), (17), and (19). The theoretical hypotheses and the expected signs can be visualized in the following relationship, showing the analyzed causal chain

$$\text{Initial conditions} \rightarrow \text{energy use} \overset{+/-}{\rightarrow} \text{investment rates} \overset{+}{\rightarrow} \text{growth}. \tag{20}$$

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[19] Any impact on growth, like the one from energy, is still present but only during transition towards the steady state.

[20] In the model, inspection of (9) and steady state conditions reveals that E remains constant when energy prices p_E grow relative to consumer prices p_Y; but if (end-user) energy prices grow less, the demand function (A.20) says that energy use depends both on the (end-user) energy price and initial income (p_E and i_0).

4 Estimation method and data

4.1 Estimation strategy

This section presents a strategy to identify the different effects in the causal chain given by (20) when using panel data as done below. Using subscripts t for the period and j for the countries I rewrite the estimation equation for the investment share (15) and energy efficiency as

$$\log s_{it} = \delta_0 + \delta_I \log \left(\frac{E}{I}\right)_{jt} \delta_G + \log \left(\frac{p_G}{p_I}\right)_{jt} + \delta_x \log X_{jt} + \nu_t + \varkappa_j + \epsilon_{jt}. \tag{21}$$

ν_t and $\varkappa_j$ are variables which are specific to periods and countries. In the same way, the growth equation is written as

$$\hat{\imath}_{jt} = \gamma_0 + \gamma_S \log s(\cdot)_{jt} + \gamma_i \log i_{0(jt)} + \gamma_Z \log M_{jt} + \tilde{\nu}_t + \tilde{\varkappa}_j + \tilde{\epsilon}_{jt}. \tag{22}$$

Country specific effects can be estimated by using panel estimation techniques (fixed effects or random effects estimations) or country dummies in the pooled data; period effects can be captured by using period dummies. The biggest challenge for an appropriate estimation of (21) and (22) is that I have to assume exogeneity of all the right-hand variables which are labeled Z and $\tilde{Z}$, i.e. the errors in the regression should have conditional mean zero so that $E(\epsilon_{jt} \mid Z_j) = 0$ and $E(\tilde{\epsilon}_{jt} \mid \tilde{Z}_j)$, $\forall t$.[21] But if an explanatory variable is endogenous in the theoretical model, a correlation with the disturbances in the empirical equation is very likely. Indeed, with the causal chain given in (20), investment rates and energy use are endogenous variables. The endogeneity of regressors can be addressed by the application of appropriate instrumental variable procedures. It is possible to identify causes of investment and growth if the instruments do not materially affect the endogenous variables through channels other than the variable of interest (the instruments are "valid") and if the instruments have a high correlation with the explaining variable of interest even after controlling for the exogenous regressors (the instruments are "strong"). It is now widely accepted that it is difficult to identify valid instrumental variables in the macroeconomic and especially the growth context, see Durlauf et al (2005).[22] The requirement of strong instruments can be empirically tested in a first stage regression with the help of the F-statistics. However, that instruments are uncorrelated with the error term has to rely on a good theoretical foundation and can in general not be tested. Hauk and Wacziarg (2009) show that no method can be applied to eliminate all possible sources of bias simultaneously.

To address both concerns of (possibly) invalid and weak instruments, I use two different procedures for the investment equation (21). In the main text, I report the results of the

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[21] For the problems applying macroeconomic cross-country regressions see Temple (1999) and Durlauf et al. (2005).

[22] Following Durlauf et al. (2005, p. 635), the validity of an instrument requires a positive argument that it cannot be a direct growth determinant or correlated with an omitted growth determinant. Even the widely used geographical and institutional may not be appropriate instruments in some contexts, they could be either direct growth determinants or correlated with omitted growth determinants, see Hauk and Wacziarg (2009).

system GMM estimator which augments the well-known Arellano-Bond difference equation with an equation in levels. The estimator exploits an additional set of moment conditions, instrumenting for the growth determinants in levels with their lagged differences. In general, the validity of these instruments is given by construction. In the appendix, I report the results of two-stage regressions using macroeconomic variables as instruments which are strong in terms of the F-test statistics. This procedures reveals whether the basic model mechanism of energy having an effect on investments is present when using both valid and strong instruments.

Because of lacking space I will not present similar GMM estimation results for the growth equation (17) and the energy equations (18)/(19) but I will check separately whether energy has an effect in the growth regression.[23] Then, I refer to the main conclusion of the previous section where the theory model has been summarized as a causal chain, see (20). For the empirical application, the possible correlation of cross-equation disturbances ϵ_{jt} and $\tilde{\epsilon}_{jt}$ then becomes a main focus. Assuming that indeed cross-equation disturbances are correlated, single equations estimations yield only consistent but not efficient estimates. In order to exploit efficiency gains from the correlation of error terms across time, one could use a variant of single-equation instrumental variables with each structural relationship being estimated for all time periods jointly. However, this method would still not exploit that error terms may not be independent across structural relationships. Dependence occurs when assuming that unobserved variables like institutional and macroeconomic conditions have an impact on all the system equations. This is very likely in our setting because we see from the theoretical model that crucial parameters appear in more than one estimation equation. Hence, cross-equation correlations seem indeed to be highly important. Moreover, the theoretical part derives three consecutive stages of the "energy-growth system", which call for a system estimation. The empirical estimation of the causal chain given in (20) suggests estimating such a system, i.e. a set of structural equations for various channels through which energy affects growth. This has some important advantages in both economic and statistical terms, it can be informative about underlying mechanisms in a way that other empirical growth research is not. From a statistical perspective, joint estimation of the structural equations is likely to bring efficiency gains, provided that all the equations are properly specified.

Thus in the second part the paper employs all the variables that are endogenously determined in theory to estimate the system consisting of equations (17), (15), and (18) for energy efficiency and (17), (16), and (19) for energy per capita jointly using three-stage least squares. The advantage of this estimation method is its ability to take care of all possible cross-equation correlations.[24] In a first step, for each of the equations, a reduced-form coefficient matrix is estimated using OLS. In the second step, 2SLS is adopted to estimate the structural model. Finally, in the third step, the estimated covariance matrix

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[23] With regard to cross-country growth regressions, Durlauf (2009) concludes that some recent studies were not done with the necessary care but that careful cross-country studies are still highly warranted.

[24] The procedure follows Tavares and Wacziarg (2001) and Wacziarg (2001) postulating that initial income affects energy use, which has an effect on the various investment rates, which in turn affect growth.

from step 2 and the fitted values of the endogenous variables of step 1 are used for an IV-GLS estimation (feasible generalized least squares) applied to the stacked structural model. By doing so, consistency is achieved through instrumentation while efficiency is reached by appropriate weighting when using the covariance matrix from the second stage. Using country dummy variables and additional exogenous variables and instruments, the scope for omitted variable bias is reduced.[25] I check the validity of the used instruments with the F-statistics in the first stage. Finally, I additionally estimate energy use depending on energy prices for all time periods jointly using three-stage least squares.

4.2 The data

The dataset includes the world's richest (OECD) countries, specifically Australia, Austria, Belgium, Brazil, Canada, China, Cyprus, Denmark, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, Luxembourg, Malta, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, UK, USA, and Venezuela. This is a country sample for which the relevant data are completely available. The used time period 1975-2009 covers a sufficiently long horizon and the use of five-year intervals helps to minimize business cycle effects. The five-year periods are 1975-79, 1980-84, 1985-89, 1990-94, 1995-99, 2000-04, and 2005-09. It has to be noted that energy price data from the IEA are not available for all these countries and time periods ant that no aggregate price index is available.[26] This is why the impact of energy prices is estimated separately at the end. All the other estimation results are derived from a balanced panel of 37 countries and 7 time periods.

The data sources are described in table 1. WDI refers to the World Development Indicators of the World Bank and PWT 7 to the Penn Word Table from Heston, Summers and Aten (2011), see also the exact references at the end of the paper. Table 6 in the appendix provides summary statistics for the variables. In the appendix we also report the correlation between the different energy prices. It can be seen that the aggregate energy price is highly correlated with all its components so that it is representative for energy price movements.

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[25] The additional instruments (used for all the systems equations) for the demography, the spatial structure, and the technology level are derived from a priori theoretical reasoning and submitted to sensitivity tests.

[26] Based on the prices of single energy sources and the expenditure shares for the different sources, an average energy price for each country had to be specifically calculated.

Table 2: Data

Variables and data sources

Variable	Description	Source
growth	real per capita GDP growth, const. prices, chain series	PWT 7.0
ci	average investment share	PWT 7.0
ingdp	initial GDP per capita (in each 5-year period)	PWT 7.0
popgro	population growth	PWT 7.0
enusecap	energy use per capita (in KGOE)	WDI (2010)
enusegdp	energy use per constant $1000 GDP	WDI (2010)
open	exports+imports/GDP	PWT 7.0
eduexp	education expenditure as a share of GDP	WDI (2005)
govshare	government spending as a share of GDP	PWT 7.0
enprice	energy price (index)	IEA (2005/12), own calc.
rdshare	R&D expenditures as a share of GDP	WDI (2007)
shurbpop	share of urban population	WDI (2010)
lifeexp	life expectancy at birth	WDI (2007)
agedep	ratio of dependents; people <15 + >64/others	WDI (2007)
pop	population	PWT 7.0
phonecap	mobile and fixed-line telephone subscribers/pop	WDI (2010)
prilifuel	price of light fuel oil	IEA (2005/12)
priprlead	price of premium leaded gasoline	IEA (2005/12)
prilifuelin	price of light fuel oil industry	IEA (2005/12)
prihisuin	price high sulfur fuel oil industry	IEA (2005/12)
prigasin	price of gas industry	IEA (2005/12)
prielin	price of electricity industry	IEA (2005/12)

5 Estimation results

I first present the results for the single equation estimates of the investment relations (15) and (16) using system GMM. Table 3 includes three representative equations for energy per capita and energy per GDP. According to the theoretical model, I include energy use (per capita: A-C and per GDP: D-F), income, population size and the price of investment goods are included as regressors. In addition, I consider a further control variable from demography, age dependency, which is interesting because the share of the inactive population has an impact on redustribution claims which may conflict with investments.

Table 3: Estimation results, investment equation, system GMM

Endogenous variable: investment share

	(A)	(B)	(C)	(D)	(E)	(F)
logci						
logenusecap	-0.166***	-0.166***	-0.148***			
	(0.0422)	(0.0425)	(0.0413)			
logenusegdp				-0.106***	-0.0909***	-0.0958***
				(0.0330)	(0.0339)	(0.0321)
logingdp	0.122***	0.122***	0.0136	-0.0315**	0.00830	-0.0863***
	(0.0383)	(0.0406)	(0.0434)	(0.0146)	(0.0250)	(0.0269)
logpop	0.00520	0.00521	-1.51e-05	0.0211***	0.0226***	0.0205***
	(0.00671)	(0.00672)	(0.00657)	(0.00738)	(0.00742)	(0.00703)
logpriceinv		0.00214	0.100*		-0.101*	-0.0365
		(0.0513)	(0.0525)		(0.0514)	(0.0495)
logagedep			-0.461***			-0.539***
			(0.0787)			(0.0726)
L.logci	0.615***	0.616***	0.602***	0.595***	0.555***	0.492***
	(0.0426)	(0.0444)	(0.0431)	(0.0405)	(0.0455)	(0.0439)
Constant	0.544***	0.542***	1.595***	0.765***	0.799***	2.112***
	(0.125)	(0.131)	(0.220)	(0.151)	(0.152)	(0.228)
Obs.	222	222	222	222	222	222
Nr. ctries	37	37	37	37	37	37

Standard errors in parentheses

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

As can be seen from table 3, the effect of energy use per capita and per GDP both have a negative and highly significant impact on the investment share across the different specifications. Initial income has a positive effect on the investment share when using energy use per capita and a negative effect for energy use per GDP. The model specification with energy use per GDP exhibits a scale effect measure by the impact of labor size L. The prices of the investment goods *logpriceinv* have no significant impact on the investment share, but age dependency affects investments negatively as suspected. The negative sign can be explained by noting that the higher is age dependence in a society the higher is the redistribution between generations, which harms investments. The appendix reports in table A.4 the results of the fixed effects model for the same endogenous variable, investment share. Like with GMM I obtain a negative and significant impact of energy use on investments, which confirms the results of table 3.

The next task is the estimation of the growth relationship (17). Results of single-equation growth regression excluding and including energy use per GDP and per capita are presented in table A.5 in the appendix. The results are close to recent empirical growth literature. Importantly, energy use per capita and energy use per GDP have no positive direct impact on growth; on the contrary, it is negative and in the case of energy use per GDP even significant.

The results for the estimations of the simultaneous system using three-stage least squares are presented in table 4, which includes six representative columns (G)-(M). The specifications follow the theoretical considerations in section 2. The equations for the investment shares, i.e. the "channel equations," are varied with regard to the used control variables, while the more standard equation for growth remains unchanged and energy depends on income and other controls in a separate system equation.[27] Country dummy variables are used for the estimations for energy efficiency but are not reported in the table for space reasons; the same applies to period dummies, which are used in all the equations to capture time specific effects. I include additional instruments which are used in growth empirics and have a significant impact on the endogenous variables. Specifically, I include the share of urban population to have a measure for the structure of the economy which is potentially important, especially for investments. Introducing the demographic variables life expectancy at birth and age dependency is done in order to reflect the close links between macroeconomic decisions and the characteristics of the population. The share of telephone subscribers shows important aspects of the communications systems, which are important for the level of used technologies. These four instruments are all available in sufficient quality and quantity. Note that time invariant variables are not compatible with country dummies and that cultural and ethnical variables are not very promising for the current sample. The first-stage estimation results are not reported separately due to space reasons but the F-statistics show that the used instruments are strong.

In the first part of table 4, the results for the growth regression are presented. They confirm the findings of the single equation estimations in table A.5. Initial income and the two investment shares for physical and knowledge capital have the expected positive and significant effects on real per capita growth. The elasticities for *logci* and *logrdshare* are slightly higher than the coefficients in the single equation estimation (table A.5). Education expenditures *logeduexp* have not a significant effect on growth; the same applies to population size *logpop* while population growth *popgro* has a negative impact which is significant on the 10 percent level. Trade openness *logopen* has a positive significant effect on development throughout, reflecting the dynamic forces of international division of labor and tougher competition on globalized markets.

The second part of table 4 (with *logci* as endogenous variable) concerns the physical capital channel. Most importantly, the effect of energy use per GDP on physical capital investments is negative and significant at the 1%-level. This confirms the single equation estimations; the effect is robust in the different specifications. The estimated elasticity varies relatively little and is around -0.2, so that, combined with an averaged estimated coefficient of 0.17 for the investment share *logci* in the growth regression, we get an impact of energy on the growth rate of -0.035. This is slightly higher than the value from the single equation estimates. According to this result, a ten percent decrease of energy use per unit of output increases the growth rate by 0.35 percentage points through induced

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[27] Energy is not included in the growth regression because this is neither indicated from the theory or from the results in table A.5; investment prices are not included because they are not available for human and knowledge capital and were not significant in the case of physical capital, see table 3.

physical capital formation. The same effect is materialized when measuring energy use in terms of energy per capita. All the estimated coefficients for *logenusecap* are negative and significant on the 1%-level. Among the control variables, age dependency *logagedep* has a negative and significant impact on the investment share in columns (I)-(M). Government spending as a share of GDP has a negative impact in the model using energy per capita. The impact of populations size *logpop* is negative throughout and and population growth *popgro* has a positive impact in this channel equation.

The third part of table 4 (with *logeduexp* as endogenous variable) shows the results for human capital accumulation. According to the results, energy use per GDP has no impact on education investments but energy per capita has. Because education expenditures are not significant in the growth regression this results has no further consequences for the issue at hand. The impact of age dependency is mixed but we observe a positive impact of government expenditures and a negative effect of population size.

The fourth part of the table represents the channel working through research expenditure shares. It is interesting to see the outcome with regard to knowledge capital, because (i) of the induced-innovation hypothesis and (ii) this type of investment does not too often appear in growth regressions. It can be seen from the next part of the table (with *logrdshare* as endogenous variable) that the impact of energy use on research investments is negative in all four out of six specifications and that the estimated parameter values are comparatively high; the estimated parameter values vary between the different specifications. This result seems to be quite remarkable by itself. Combining the estimated elasticities with the result in the growth regression one obtains a channel effect for knowledge which is of similar size like for physical capital. Age dependency has a negative and significant effect while the impact of government share is positive and highly significant. Population size and growth have no impact on knowledge capital.

The last part of table 5 reflects the dependence of energy use per output and per capita on various macroeconomic variables. Income per capita has a different impact depending on whether I use energy use per GDP or per capita. The positive impact in the case if energy use per capita is highly plausible. Age dependency and openness have a highly significant negative effect on energy use while the government share has a highly significant positive effect. All these effects are plausible and meeting the expectations.

The overall regression statistics in table 4 are highly satisfactory. I carried out several robustness checks. The sample size was reduced in the time and cross-section dimensions, which did not alter the main results. Moreover, the main variation by the inclusion of different exogenous variables has been demonstrated in table 5. I conclude that lower energy input raises growth through induced capital accumulation, in particular with respect to physical and knowledge capital. The channel effects for both capital types are of similar size.

Table 4: Estimation results of the system; 3 SLS

Endogenous varibales: growth, logci, logeduexp, logrdshare, logenusegdp/cap

	(G)	(H)	(I)	(K)	(L)	(M)
growth						
logingdp	-8.640***	-8.580***	-8.646***	-8.600***	-8.425***	-8.371***
	(1.535)	(1.537)	(1.538)	(1.564)	(1.566)	(1.566)
logci	17.94***	17.24***	17.25***	13.55**	13.46**	13.42**
	(6.419)	(6.431)	(6.431)	(6.576)	(6.581)	(6.579)
logeduexp	2.812	2.154	2.029	1.315	0.801	0.504
	(3.123)	(3.132)	(3.132)	(3.203)	(3.209)	(3.210)
logrdshare	5.124**	4.964**	5.027**	5.796***	5.636**	5.668**
	(2.191)	(2.194)	(2.193)	(2.247)	(2.250)	(2.249)
logpop	3.458	3.639	3.585	0.427	0.593	0.411
	(4.257)	(4.260)	(4.260)	(4.440)	(4.443)	(4.443)
popgro	-0.487*	-0.498*	-0.527*	-0.429	-0.440	-0.499*
	(0.281)	(0.282)	(0.282)	(0.293)	(0.294)	(0.296)
logopen	4.833***	4.999***	5.050***	5.795***	5.804***	5.799***
	(1.861)	(1.864)	(1.865)	(1.893)	(1.895)	(1.894)
Constant	-19.04	-19.44	-18.74	8.135	6.688	8.106
	(35.19)	(35.22)	(35.23)	(36.50)	(36.52)	(36.52)
logci						
logenusegdp	-0.220***	-0.236***	-0.177**			
	(0.0736)	(0.0793)	(0.0816)			
logagedep	-0.150	-0.172	-0.248**	-0.529***	-0.539***	-0.713***
	(0.115)	(0.115)	(0.120)	(0.113)	(0.110)	(0.130)
loggovshare		0.0203	0.0110		-0.194***	-0.163***
		(0.0835)	(0.0828)		(0.0561)	(0.0569)
logpop	-0.231*	-0.235*	-0.249**	-0.0174**	-0.0171**	-0.0164**
	(0.127)	(0.126)	(0.126)	(0.00817)	(0.00799)	(0.00791)
popgro			0.0182**			0.0249**
			(0.00869)			(0.0101)
logenusecap				-0.161***	-0.111***	-0.111***
				(0.0223)	(0.0261)	(0.0258)
Constant	3.854***	3.933***	4.017***	2.996***	3.074***	3.318***
	(0.990)	(0.988)	(0.985)	(0.248)	(0.244)	(0.260)

Table 4: Estimation results of the system; 3 SLS contd.

	(G)	(H)	(I)	(K)	(L)	(M)
logeduexp						
logenusegdp	-0.00156	-0.0382	-0.0313			
	(0.0669)	(0.0534)	(0.0536)			
logagedep	-0.537***	-0.0113	0.105	0.335**	0.363**	0.489***
	(0.183)	(0.152)	(0.185)	(0.164)	(0.149)	(0.176)
loggovshare		0.845***	0.825***		0.555***	0.533***
		(0.0692)	(0.0717)		(0.0758)	(0.0774)
logpop	-0.0600***	-0.0354***	-0.0364***	-0.0193	-0.0203*	-0.0208*
	(0.0153)	(0.0123)	(0.0123)	(0.0119)	(0.0108)	(0.0108)
popgro			-0.0164			-0.0181
			(0.0150)			(0.0137)
logenusecap				0.387***	0.244***	0.244***
				(0.0323)	(0.0352)	(0.0351)
Constant	1.974***	-0.0601	-0.235	-1.173***	-1.395***	-1.574***
	(0.335)	(0.314)	(0.351)	(0.360)	(0.329)	(0.354)
logrdshare						
logenusegdp	-0.181	-0.349***	-0.278**			
	(0.122)	(0.131)	(0.134)			
logagedep	-0.409**	-0.375*	-0.457**	-0.369*	-0.492**	-0.593***
	(0.191)	(0.192)	(0.199)	(0.212)	(0.217)	(0.226)
loggovshare		0.382***	0.369***		0.375***	0.367***
		(0.139)	(0.138)		(0.138)	(0.137)
logpop	0.127	0.136	0.116	0.187	0.167	0.140
	(0.207)	(0.205)	(0.204)	(0.201)	(0.200)	(0.199)
popgro			0.0206			0.0232
			(0.0142)			(0.0146)
logenusecap				-0.141	-0.417**	-0.347**
				(0.154)	(0.168)	(0.169)
logingdp				0.168	0.329***	0.241*
				(0.117)	(0.124)	(0.132)
Constant	0.194	-0.00147	0.104	-0.934	-0.710	-0.247
	(1.624)	(1.608)	(1.599)	(1.740)	(1.735)	(1.747)

Table 4: Estimation results of the system; 3 SLS contd.

	(G)	(H)	(I)	(K)	(L)	(M)
logenusegdp/cap						
logingdp	-0.479*	-0.472*	-0.542*	0.702**	0.687**	0.638**
	(0.289)	(0.282)	(0.286)	(0.294)	(0.290)	(0.292)
sqlogingdp	0.0152	0.0157	0.0254	-0.0187	-0.0157	-0.00922
	(0.0375)	(0.0367)	(0.0372)	(0.0382)	(0.0376)	(0.0379)
logagedep	-0.701***	-0.664***	-0.674***	-0.703***	-0.682***	-0.698***
	(0.114)	(0.113)	(0.114)	(0.114)	(0.114)	(0.114)
loggovshare	0.199***	0.263***	0.264***	0.237***	0.262***	0.262***
	(0.0694)	(0.0711)	(0.0712)	(0.0707)	(0.0719)	(0.0719)
logopen	-0.290***	-0.283***	-0.282***	-0.159***	-0.152***	-0.152***
	(0.0521)	(0.0510)	(0.0514)	(0.0515)	(0.0507)	(0.0509)
Constant	5.548***	5.354***	5.490***	2.177***	2.113***	2.234***
	(0.652)	(0.641)	(0.648)	(0.666)	(0.658)	(0.662)
Observations	259	259	259	259	259	259

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

Finally, in order to confirm the above-assumed negative impact of energy prices on energy use, see equation (14), I show in table 5 two (representative) estimation result for energy use per capita and per GDP as endogenous variables for a (limited) sample of 194 observations:

Table 5: Estimation results; 3 SLS
Energy use and energy prices

	(N)	(O)
	logenusecap	logenusegdp
logenprice	-0.213***	-0.230***
	(0.0317)	(0.0330)
logingdp	0.800***	-0.110**
	(0.0452)	(0.0470)
logpop	0.00306	-0.00136
	(0.0199)	(0.0207)
logopen	0.0838	0.0600
	(0.0548)	(0.0569)
Constant	-0.217	2.423***
	(0.256)	(0.266)
Observations	194	194
R-squared	0.722	0.211

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

The number of observations is lower than for the system because international data sources do not report more datapoints for energy prices. The estimation method is 3SLS; $loglifeexp$ and $logagedep$ are used as additional instruments. $Enprice$ is an index of the different energy prices, see Table 7 in the appendix. As can be seen from the result, the negative impact of energy prices on energy use per capita and per GDP is confirmed. With a value of around -0.2 the estimated elasticity is clearly below unity, which fits with our expectations. Initial income has a positive and significant effect on energy use per capita while it is negative for energy use per GDP. The size of the economy measured by population and globalization measured by trade openness have no significant impact here.

6 Conclusions

The theoretical approach derives the mechanism through which energy affects the growth rate of an economy. The empirical results for 37 developed economies over the period 1975-2004 show that higher energy prices i.e. tighter energy supply do not affect economic growth negatively. On the contrary, I find for the developed economies that lower energy use has a positive growth impact in the long run. The most cautious interpretation of the results suggests that the often-cited negative impact of lower energy input on growth is not evident. This especially holds true for the channels working through physical and knowledge capital accumulation, which are roughly equally important as a transmission channel; human capital formation is found to be unaffected by energy use. Together with the negative impact of energy prices on energy use, the impact of energy prices on long-run growth becomes positive - an effect which is moderate but not negligible. Adopting the notion of the "scarcity paradox" means that dealing with energy scarcity is productive in the long run by inducing more capital accumulation. To conclude, in developed economies energy is not negligible or neutral with respect to growth but is found to have an effect which is quite different from general expectations. The empirical results are robust to using different specifications.

The usually stressed negative level effect of higher energy prices, when holding capital constant, is also present in the model used here. Assuming constantly increasing energy prices over time, e.g. as the result of active climate policies or increasing resource scarcity, one therefore has to compare a negative level effect and a positive growth effect. In dynamic integrated assessment models it has been found that in such a case the level effect is still higher than the growth effect; as a consequence, income development with active climate policies is somewhat lagging behind "business-as-usual." However, the gap between the two paths is narrowed substantially due to capital formation. Accordingly, costs of climate policies turn out to be moderate in a dynamic setting, see Bretschger et al (2011). The model results can be further used when estimating the dynamic costs of future energy and climate policies, which are associated with higher energy prices.

It would be interesting to apply the model including the channel mechanisms to a larger country sample. This would, of course, require a careful treatment of the different institutional and political conditions. Also, the model could be extended in order to capture the dynamic costs of climate change. This is left for future research.

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7 Appendix 1: Theory

The first order conditions of the problem in (10) are

$$H'(C) = 0 \Longleftrightarrow U'(C) = \mu_Y p_Y \tag{A.1}$$

$$H'(L_Y) = 0 \Longleftrightarrow \mu_Y p_Y F'(L_Y) = \mu_L \tag{A.2}$$

$$H'(L_K) = 0 \Longleftrightarrow \mu_K ADKG'(L_K) = \mu_L \tag{A.3}$$

$$H'(E_Y) = 0 \Longleftrightarrow \mu_Y p_Y F'(E_Y) = \mu_E \tag{A.4}$$

$$H'(E_K) = 0 \Longleftrightarrow \mu_K ADKG'(E_K) = \mu_E \tag{A.5}$$

$$H'(E) = 0 \Longleftrightarrow -\mu_Y p_E + \mu_E = 0 \tag{A.6}$$

$$H'(K) = \rho\mu_K - \dot{\mu}_K \Longleftrightarrow \mu_Y (p_Y F)'(K) + \mu_K ADG = \rho\mu_K - \dot{\mu}_K \tag{A.7}$$

Taking logarithmic differentials of (A.1) gives

$$-\sigma_c \hat{C} = \hat{\mu}_Y + \hat{p}_Y. \tag{A.8}$$

To calculate $F'(L_Y)$ I recast the F-function - without loss of generality - in the form of a power function (generalized Cobb-Douglas function) in which the exponents are the local elasticities of output with respect to the inputs, labelling the output elasticity for labor $(1-\alpha)\theta_{LY}$. Then, setting (A.2) and (A.3) equal I obtain

$$\mu_Y p_Y (1-\alpha)\theta_{LY} \frac{Y}{L_Y} = \mu_K \beta ADK \frac{G}{L_K}. \tag{A.9}$$

Because the F- and the G-function display constant returns to scale, the used output elasticities are equal to the (optimum) cost shares, i.e. $\alpha = p_K K/p_Y Y$, $\beta = wL_Y/p_G G$, and $\theta_{LY} = wL_Y/(1-\alpha)p_Y Y$.[28] θ_{LY} is constant in steady state because of constant wages and energy prices, see the main text and (A.16) below; I will also use $\theta_{EY} = 1 - \theta_{LY} = p_E E_Y/(1-\alpha)p_Y Y$.[29] Employing the cost shares in (A.9) I get for the steady state

$$\frac{\mu_Y}{\mu_K} = \frac{ADK}{p_G} = \frac{1}{p_K} \tag{A.10}$$

$$\hat{\mu}_K = \hat{\mu}_Y + \hat{p}_K \tag{A.11}$$

Dividing (A.7) by μ_K and using that $p_Y Y = const$ in steady state (see main text) so that $(p_Y F)'(K) = 0$ yields[30]

$$ADG - \rho = -\hat{\mu}_K \tag{A.12}$$

which is combined with (A.11) and (A.8) to have

$$\sigma_c \hat{C} + \hat{p}_Y - \hat{p}_K = ADG - \rho. \tag{A.13}$$

Observing that $-\hat{p}_Y = -\alpha\hat{p}_K = \hat{Y} = \hat{C}$ in steady state (see main text) finally gives (11). Using the cost shares I rewrite (6) as

$$\frac{\theta_{LY}(1-\alpha)p_Y Y}{w} + \frac{\beta p_G G}{w} = \bar{L} \tag{A.14}$$

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[28] Formally, these can be derived from profit maximization of firms.

[29] Note that θ_{LY} and θ_{EY} will not be constant in comparative dynamics below.

[30] It equally holds that $(p_Y C)'(K) = 0$.

From profit maximization in the Y-sector I get the relative input demand and the ratio of the cost shares for labor and energy according to

$$\frac{L_Y}{E_Y} = \left(\frac{\phi}{1-\phi}\right)^{\sigma} \left(\frac{w}{p_E}\right)^{-\sigma} \tag{A.15}$$

$$\frac{\theta_{LY}}{\theta_{EY}} = \left(\frac{\phi}{1-\phi}\right)^{\sigma} \left(\frac{w}{p_E}\right)^{1-\sigma} \tag{A.16}$$

To avoid a number of extra terms it is convenient to choose, following Grossman and Helpman (1991), consumer expenditures as numeraire so that $p_Y Y \equiv 1$. Then, I get $Y = 1/p_Y$ and $p_K ADK = p_G = \alpha p_Y Y = \alpha$ from which I obtain $\hat{p}_G = 0$. Using λs for input shares ($\lambda_{LY} = L_Y/L$, $\lambda_{LK} = L_K/L$) and differentiating (A.14) I get

$$\lambda_{LY}(\hat{\theta}_{LY} - \hat{w}) + \lambda_{LK}(\hat{G} - \hat{w}) = 0 \tag{A.17}$$

Taking logarithmic differentials of (A.16), observing that $\theta_{EY} = 1 - \theta_{LY}$ (so that $\widehat{\theta_{LY}/\theta_{EY}}$ $= \hat{\theta}_{LY}/\theta_{EY}$), and inserting into (A.17) yields

$$\lambda_{LY}\theta_{EY}\,(1-\sigma)\,(\hat{w} - \hat{p}_E) - \hat{w} = -\lambda_{LK}\hat{G} \tag{A.18}$$

which can be solved for $\hat{G}$ in terms of the (exogenous) $\hat{p}_E$ and the (endogenous) $\hat{w}$. To relate the two input prices, I use $\hat{p}_G = 0$ to obtain

$$\hat{w} = -\frac{\theta_{EK}}{\theta_{LK}}\hat{p}_E = -\tilde{\theta}_E\hat{p}_E \tag{A.19}$$

which is used in (A.18) yielding (12) in the main text. Expressing (7) in percentage changes and using cost shares yields the relationship between the (percentage change of) energy prices and the (percentage change of) energy use

$$\{\lambda_{EY}\left[\theta_{LK}\,(1-\sigma)\,(1+\tilde{\theta}_E) - 1\right] - 1\} \cdot \hat{p}_E = \delta_E\hat{p}_E = \hat{E} \tag{A.20}$$

where $\delta_E < 0$ with $\sigma > 1$ and with $\sigma < 1$ when $\tilde{\theta}_E < 1$ which is confirmed in table A.5.

8 Appendix 2: Empirics

8.1 Data

Table A.1: Summary statistics

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**	**Obs**
growth	2.62	2.44	-5.05	14.01	259
logci	1.37	0.1	1.09	1.66	259
logingdp	4.15	0.35	2.83	4.85	259
popgro	0.85	0.76	-1.14	4.23	259
logenusecap	3.41	0.33	2.47	4.02	259
logenusegdp	2.25	0.18	1.92	3.12	259
logopen	1.75	0.27	1.01	2.49	259
logeduexp	0.62	0.19	-0.23	0.91	259
loggovshare	1.21	0.13	0.84	1.46	259
logenprice	-0.72	0.3	-2.55	-0.02	194
logrdshare	-0.07	0.43	-1.49	0.59	259
logshurbpop	1.81	0.15	1.26	1.99	259
loglifeexp	1.86	0.04	1.71	1.92	259
logagedep	1.73	0.07	1.59	1.99	259
logpop	7.3	0.8	5.53	9.12	259
logphonecap	-0.53	0.64	-2.75	0.28	259
logpriceinv	1.89	0.16	1.39	2.19	259

Table A.2: Summary energy prices

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**	**Obs**
prilifuel	0.15	0.14	0	1	158
priprlead	0.25	0.15	0	1	132
prilifuelin	0.19	0.16	0	1	155
prihisuin	0.17	0.13	0	1	152
prigasin	0.29	0.19	0	1	152
prielin	0.29	0.19	0	1	188

Table A.3: Correlation of energy prices - Price Index

	enprice	prilifuel	priprlead	prilifuelin	prihisuin	prigasin	prielin
enprice	1						
prilifuel	0.8073	1					
priprlead	0.7951	0.8742	1				
prilifuelin	0.7899	0.9013	0.7797	1			
prihisuin	0.7576	0.8896	0.7923	0.7307	1		
prigasin	0.7909	0.6709	0.7035	0.5743	0.7304	1	
prielin	0.7554	0.7072	0.7758	0.6666	0.5854	0.6606	1

Fixed effects instrumental variable regression for the investment share: Table A.4 presents the results for single equation estimations of the investment share for physical capital; in the first-stage regression results (not reported in detail) the F-tests exceed the value of 10 (instruments are strong).

Table A.4: Estimation results, IV-FE estimation

Endogenous variable: logci, instruments: logingdp logagedep loglifeexp logopen

	(1)	(2)	(3)	(4)	(5)	(6)
logci						
logenusegdp	-0.467***	-0.472***	-0.410**			
	(0.149)	(0.150)	(0.162)			
logingdp	-0.164**	-0.166**	-0.112	0.309***	0.310***	0.305***
	(0.0663)	(0.0664)	(0.0877)	(0.101)	(0.101)	(0.107)
logpriceinv		0.0122	0.00496		0.000123	-0.00112
		(0.0595)	(0.0588)		(0.0616)	(0.0619)
logagedep			0.119			0.0225
			(0.131)			(0.163)
logenusecap				-0.524***	-0.526***	-0.507**
				(0.173)	(0.173)	(0.222)
Constant	3.098***	3.093***	2.540***	1.875***	1.877***	1.796***
	(0.592)	(0.591)	(0.839)	(0.236)	(0.262)	(0.645)
Observations	259	259	259	259	259	259
Number of countries	37	37	37	37	37	37

Standard errors in parentheses

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

Fixed effects single equation regression for growth: Table A.5 presents results testing the separate impact of energy.

Table A.5: Estimation results; FE estimations

Endogenous variable: growth

growth	(1)	(2)	(3)
logingdp	-6.863***	-5.271***	-11.15***
	(1.404)	(1.847)	(1.538)
logci	9.451***	9.784***	10.16***
	(2.231)	(2.241)	(2.101)
logeduexp	-3.135	-2.530	-0.335
	(1.904)	(1.955)	(1.862)
logrdshare	3.031**	3.372***	4.051***
	(1.221)	(1.246)	(1.163)
logpop	2.640	2.716	4.362
	(3.714)	(3.708)	(3.505)
popgro	-0.489*	-0.563*	-0.648**
	(0.294)	(0.298)	(0.277)
logopen	6.799***	6.182***	3.207*
	(1.686)	(1.747)	(1.718)
logenusecap		-3.008	
		(2.273)	
logenusegdp			-11.41***
			(2.106)
Constant	-10.43	-6.992	24.22
	(26.19)	(26.28)	(25.44)
Observations	259	259	259
R-squared	0.238	0.244	0.330
Number of countries	37	37	37

Standard errors in parentheses

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