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

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Abstract

The paper presents cross-country evidence for a negative relationship between energy use and economic growth. It develops a multisector framework to derive the growth impact of energy through capital investments and the effects of energy on investment activities from first principles. The empirical estimations are based on a structural model and use separate equations and system estimations for a sample of 37 developed countries with five-year average data over the period 1975-2009. The estimation results show a negative impact of energy use on investments in physical capital and knowledge formation. System estimations support the finding that decreasing energy input and increasing energy prices induce additional investments, which entail a positive growth effect counteracting the negative static effects of lower energy use.

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 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 stresses that level and growth effects of energy have to be carefully distinguished. If the energy input shrinks but everything else remains unchanged it is obvious that an economy cannot avoid a negative level effect. The more demanding question to ask is whether and under what conditions the economy experiences a positive growth effect which is able to counteract the level effect. To provide valid answers on these questions one necessarily has to treat capital as an endogenous variable and to perform empirical regressions estimating structural models. The strategy of the paper is to start from stylised evidence on energy, investments, and growth to motivate the construction of a theoretical model. Then, based on the structural model, different empirical equations are derived and estimated in several steps. The main purpose of the empirical part is to assess whether the hypotheses obtained from simple correlations between the main variables are corroborated and better specified when using econometric methods that are appropriate for testing the structural model. The paper finds that energy does not affect growth directly but has a negative impact on physical and knowledge capital accumulation, which constitute separate channels through which lower energy use fosters long-run growth.

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

[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."

knowledge capital; the two channel effects turn out to be of similar size, while the effect via human capital is not significant. These results are useful 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. The present paper also suggests that the estimation of single substitution elasticities[4] 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.[5] 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 more homogenous than in a sample with less developed 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.

Results from recent contributions using time series analysis differ from our conclusions. Specifically, Yuan et al. (2008), Lee and Chang (2008), and Sari and Soytas (2007) find a positive impact of energy on growth.[6] Time series models are very detailed in estimation 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.

The remainder of the paper is organized as follows. In section 2, empirical observation motivate the main model hypotheses. 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.

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

[5]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).

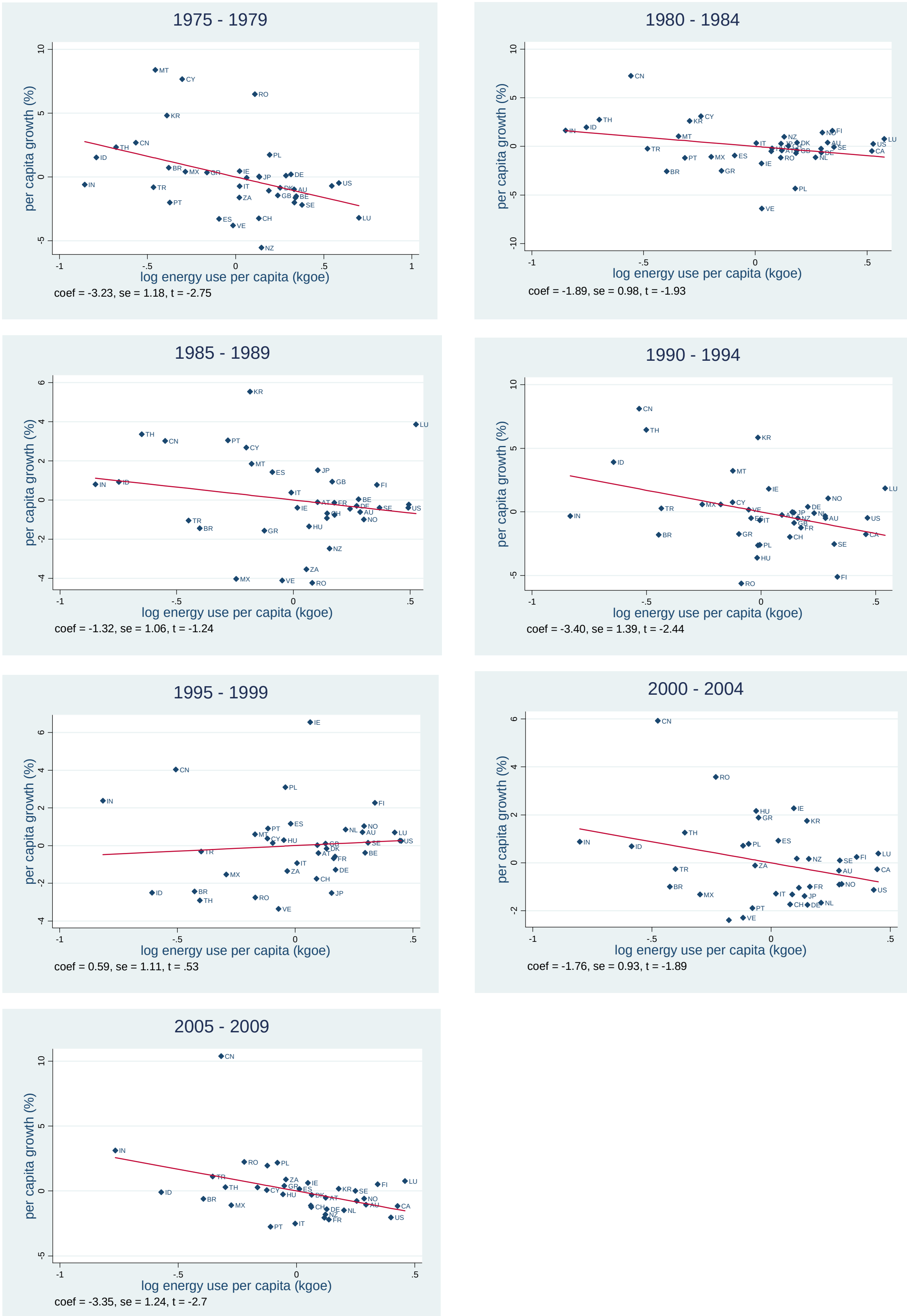
[6]Further literature with similar conclusions includes Stern (2000), Glasure and Lee (1997), Lee (2005) and Chontanawat et al. (2008), while Huang et al. (2008) find no evidence indicating that energy consumption leads economic growth and the seminal paper in this area, Kraft and Kraft (1978), finds evidence of unidirectional causality running from GDP to energy consumption.

2 Cross-country Evidence

To further motivate the study and to get a first impression of the energy-growth nexus I present stylised 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 as right-hand variable. 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 only looking at time series and using annual data.

Of course, one also has to analyse the mechanism transmitting the effect of energy in detail, which will be done below. Following growth theory in the next section I will derive that capital 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 it 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, i.e. energy efficiency, have to be treated separately, which is done below.

[7] Performing a panel regression for the whole sample with country-fixed effects and period dummies also 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

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

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

$$\hat{Y}(t) = \theta_K \hat{K}(t) + \theta_L \hat{L}(t) + \theta_E \hat{E}(t). \tag{2}$$

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 between the growth of inputs and the growth of output. It says that *ceteris paribus* energy growth effects output growth positively. The paper argues that it is not appropriate to derive from (2) that "energy" is good for growth, mainly because of two reasons. First, one has to carefully distinguish between the effects of energy *levels* and energy *growth*; a permanent increase of energy input is not a likely option for the future. 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 consistent model 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 effect of energy on growth in detail I specify F in (1) as

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

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) demonstrating the different effects of energy use on growth. New capital goods are produced with the technology

$$\dot{K}(t) = AB(t)G(t) = AB(t)L_K(t)^{\beta} E_K(t)^{1-\beta}, \tag{4}$$

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

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.[9] Following (4), capital goods production differs from that of 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.[10] 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.[11]

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 ($w$), price of energy

[9] To use a CES technology in (4) would work as well but add unnecessary complexity.

[10] The use of rival capital for capital investments would not change the conclusions; the current formulation of (4) is close to the seminal endogenous growth models like Grossman and Helpman (1991).

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

(p_E), 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, 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.[12] 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", where $Y(t) = F(\cdot) = AK$. 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. The simplest version of the AK-models assumes only one sector so that the real return to capital is simply A and consumption growth becomes $\hat{C} = (A - \rho)/\sigma_c$. In the present approach I have the same growth determinants (σ_c, A, ρ) but get two useful extensions. The first is similar to 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.[13]

Second, the model adds to the literature by the inclusion of energy in a dynamic multi-sector 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).[14] 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 of labor and energy to be infeasible in the long run we

[12] 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.

[13] 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).

[14] 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.

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 from (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 will 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 section.

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 is in line with previous literature on multisector models and endogenous growth.[15] The main conclusion from the theoretical model is that an increase in energy prices has an ambiguous effect, i.e. it may but need not have a positive growth effect in a social optimum.[16] 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 the level of 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.

Lessons for empirical study Following the theoretical model, three conclusions for an appropriate empirical model can be drawn. First, the theoretical model shows that it is the impact of energy prices (and/or energy use) 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. Third, regarding the macroeconomic context, appropriate instrumental and control variables have to be used for a proper identification of the different model effects. Fourth, 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 and (ii) general equilibrium effects should not be disregarded. These are the reasons 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 formulation of appropriate estimation equations based on the theoretical model.

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 $\delta_p = (\lambda_{LK})^{-1}((1 + \tilde{\theta}_E)(\lambda_{LY}\theta_{EY}(1-\sigma) + \tilde{\theta}_E))$. 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

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

[16] Introducing non-unitary substitution elasticities thoughout the model and adding more sectors reveals that it is not the absolute value of the elasticities but the relative size which matters for growth, see Bretschger and Smulders (2012).

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 I 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 for total income 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 the variable 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) will be the first equation to be tested below. I will account for the fact that 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 distinguish between different kinds of capital, that is the estimations include different investment rates for physical, human, and (private) knowledge capital.[17] 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 (3), (4), and (5) the theoretical model predicts that $\hat{Y} = \hat{I} = \alpha\hat{K} = \alpha ADG$ i.e. increasing investment G raises economic growth, which is again introduced in the form of investment shares. Notably, empirical growth models do not rely on linear growth but include initial

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

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 materializes when assuming knowledge spillovers being given by $B(t) = DK(t)^\eta$ (with $\eta < 1$) entailing decreasing rather than constant returns to capital.[18] 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,[19] 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

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

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

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

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

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

[18] Any impact on growth, like the one from energy, is still present but applies to transitional dynamics, which are normally assumed to last for more than several decades.

[19] See Mankiw et al. 1992, Wacziarg (2001), Tavares and Wacziarg (2001), and Hauk and Wacziarg (2009).

[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).

the countries I rewrite the estimation equation for the investment share (15) and energy efficiency as

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

ν_t and $\varkappa_j$ are variables which are specific to periods and countries. In the same way, the growth equation (17) is written as

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

The biggest challenge for an appropriate estimation of (21) and (22) is that I have to assume exogeneity of all the right-hand variables.[21] Specifically, the errors in the regression should have conditional mean zero.[22] However, 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 become endogenous variables. A second econometric issue is that, given the causal chain in (20), cross-equation disturbances between (21) and (22) are likely to be correlated.

In the following, I will address the endogeneity of regressors by using (appropriate) instrumental variables. With this procedure, it becomes possible to consistently 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").[23] To address both concerns of (possibly) invalid and weak instruments, I first estimate separate equations for investment (21) using two different estimation methods. In the main text, I introduce instruments that are uncorrelated with the error term by applying the Arellano-Bond estimation method. I report the results of the 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, by instrumenting for the investment determinants in levels with their lagged differences. The validity of these instruments is given by construction. In the appendix, I additionally report the results of another estimation method, where instruments are based on a theoretical foundation. The appendix shows the reults of two-stage regressions using macroeconomic variables as instruments for energy use which are strong in terms of the F-test statistics in the first stage. The procedure is aimed at revealing whether the basic model mechanism of energy having an effect on investment is effective when using both valid and strong instruments. Again as a separate equation I estimate the growth relationship (17). In particular, I check whether energy has a direct

[21] 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.

[22] See Temple (1999) and Durlauf et al. (2005) for an excellent exposition of the related issues.

[23] However, Hauk and Wacziarg (2009) show that no method can be applied to eliminate all possible sources of bias simultaneously. Following Durlauf et al. (2005, p. 635), 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).

effect on growth when using a fixed effects estimation to properly include country specific characteristics.

Then, the possible correlation of cross-equation disturbances, i.e. $E(\epsilon_{jt} \mid \tilde{\epsilon}_{jt}) \neq 0$, becomes the main focus of the empirical study. Assuming that cross-equation disturbances are correlated, single equations estimations yield only consistent but not efficient estimates. Joint estimation of the structural equations is likely to bring efficiency gains, provided that all the equations are properly specified. The empirical estimation of the causal chain given in (20) builds such a system. 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 from step two and the fitted values of the endogenous variables of step one 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. 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.[25] 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

[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.

[25] 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.

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.

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, with instruments used for investment and energy. 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 activities.

Table 3: Estimation results, investment equation, system GMM

Dependent 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
Wald						
Sargan						

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 energy per GDP both have a negative and highly significant impact on the investment share across the different specifications. The main model mechanism for the energy-growth nexus is thus established and confirmed. 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 dependent variable, investment share, where several instruments are used for energy use as in the system equation, see the discussion of the instruments below. As with GMM I obtain a negative and significant impact of energy use on investments, which confirms the results of table 3. The F-values for the first stage regressions of the channel estimations are given in the table and indicate that instruments are not weak.[26]

[26] Used instruments are logingdp, logagedep, loglifeexp, and logopen; for a more detailed motivation of the instrument choice see below with the 3SLS estimations.

Results of growth regressions with country fixed effects based on (17), excluding and including energy use per GDP and per capita, are presented in table A.5 in the appendix. The results show a positive and significant impact on investments in physical and knowledge capital which is also the case with trade openness. Initial income and and population growth affect income growth negatively, which is close to empirical growth literature.[27] Importantly, energy use per capita and energy use per GDP have no positive significant direct impact on growth.

The results for the estimations of the simultaneous system using three-stage least squares are presented in table 4, which includes six representative equations in the 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.[28] 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. The instrumentation strategy consists in finding determinants of the right-hand variables which are motivated by theoretical considerations.[29] Accordingly, I include such instruments which have a predictable and statistically significant impact on energy use and investment shares. One aspect which is important in reality but not covered in the theoretical model is the spatial organization of the economy. Accordingly, I include the share of urban population as an instrument in the system equations. It is conceivable that it affects investments and energy use; it is not evident that it should be a growth determinant. A first look at the data shows that e.g. smaller European countries like Denmark have larger urban population shares than big countries like the USA but similar growth rates. Of course, the validation of the instrument is only possible when looking at the first stage of the regression. To capture the impact of another parameter not captured in theory, demography, I use life expectancy at birth and age dependency as instruments in the system equation. Again, demography has an impact on investments and energy use but is not included in standard growth theory. As an example, Japan has a very specific demography which might (partly) explains its specific investment behavior. A final part is the technology level and the country infrastructure, which also determines the right-hand variables of the system. Here I use the share of telephone subscribers as an instrument to capture the impact of communications systems. These four instruments are all available in sufficient quality and quantity.

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

[27] See e.g. Mankiw et al. (1992) and Hauk and Wacziarg (2009).

[28] 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.

[29] The paper follows Tavares and Wacziarg (2001) but has to limit the number of instruments because it includes country specific effects and the sample excludes low developed countries.

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* do not have 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, I get an impact of energy on the growth rate of -0.035. This is slightly higher than the value obtained from the single equation estimates. The same effect materializes 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 next two parts of the table present two investment equations which are not reported as separate equation estimations due to lack of space. 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 result 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 of research investments. Technology development is generally considered as a main driver of growth. More specifically, it is interesting to estimate the result for knowledge capital because (i) of the induced-innovation hypothesis of Hicks (1932) 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. The F-statistics of the first-stage estimation results show that the used instruments are strong. I carried out several robustness checks. The sample size was reduced in the time and cross-section dimensions, which does not alter the main results. The same holds true for the estimations excluding the oil-exporting countries. Moreover, the main variation by the inclusion of different exogenous variables has been demonstrated in table 4.

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
χ growth						
χ logci						
χ logeduexp						
χ logrdshare						
χ energy						
F-test logci						
F-test logeduexp						
F-test logrdshare						

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. 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.

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

Standard errors in parentheses

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

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.[30] 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 $\theta_{LY} = wL_Y/(1-\alpha)p_Y Y$.[31] 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 $\theta_{EY} = 1 - \theta_{LY} = p_E E_Y/(1-\alpha)p_Y Y$.[32] 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[33]

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

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 cost shares I rewrite (6) as

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

[31] Formally, these can be derived from profit maximization of firms.
[32] Note that θ_{LY} and θ_{EY} will not be constant in comparative dynamics below.
[33] 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

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

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

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

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
F-values 1st stage						

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***	-4.409***
	(1.404)	(1.847)	(0.706)
logci	9.451***	9.784***	7.108***
	(2.231)	(2.241)	(1.330)
logeduexp	-3.135	-2.530	-1.651
	(1.904)	(1.955)	(1.020)
logrdshare	3.031**	3.372***	2.208***
	(1.221)	(1.246)	(0.510)
logpop	2.640	2.716	-0.307
	(3.714)	(3.708)	(0.235)
popgro	-0.489*	-0.563*	-0.321*
	(0.294)	(0.298)	(0.188)
logopen	6.799***	6.182***	2.287***
	(1.686)	(1.747)	(0.679)
logenusecap		-3.008	
		(2.273)	
logenusegdp			0.0905
			(0.904)
Constant	-10.43	-6.992	10.67*
	(26.19)	(26.28)	(5.474)
Observations	259	259	259
Number of countries	37	37	37

Standard errors in parentheses

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