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

Lucas Bretschger, ETH Zurich[1]

December 2007

Abstract

The paper first develops a theoretical model with different channels through which energy prices affect economic growth. The conditions for a crowding out of capital accumulation by intensive energy use are derived. In the empirical part, estimations using a system with five simultaneous equations for a sample of 37 developed countries with five-year average panel data over the period 1975-2004 are presented. It is shown that rising energy prices are not a general threat to long-term economic development. On the contrary, we find that decreasing energy input induces investments in physical, human, and knowledge capital, which fosters the growth rate.

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

JEL Classification: Q43, O47, Q56, O41

[1] CER-ETH Centre of Economic Research at ETH Zurich, ZUE F7, CH-8092 Zurich, Switzerland Tel. +41 44 632 21 92, Fax +41 44 632 13 62, email: lbretschger@ethz.ch. The author thanks two referees for helpful comments.

1 Introduction

The recent surge in fuel prices has given rise to concern 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 and 1989-90 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 debates that a 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 high energy prices, like Japan, perform quite well, while many low-energy price countries, especially less developed oil-producing economies, persistently show low growth rates. In the recent empirical literature, a negative effect of a high natural resource dependence on economic growth has been found, see Gylfason (2001, 2004) and Sachs and Warner (2001). It is argued that natural capital tends to crowd out different accumulation activities which ultimately drive the growth process. The causal chain from resource prices to an intermediate variable which is crucial for development is emphasised. How does this happen? Gylfason (2004, p. 1) writes: "An important challenge for economic growth theorists and empirical workers is to identify and map these intermediate variables and mechanisms." The present contribution takes this suggestion seriously and explores it for the case of energy resources in developed economies.

The paper at hand adds to the existing literature by consistently identifying and exploring the various energy-accumulation-growth channels, both theoretically and empirically. It considers a stylised economy accumulating a heterogenous capital stock with capital varieties consisting of different capital types. Growth is driven by an expansion in capital varieties. The primary inputs labour and energy can be used to produce specific capital goods, in particular physical, knowledge, or human capital, or intermediate inputs for consumer goods. Learning effects support accumulation and growth. The separation of the capital sector and the disaggregation of the capital stock are introduced to capture the different mechanisms governing the energy capital nexus in detail. In this way, the different channels through which higher energy prices may hinder or foster growth can be analysed separately. The decisive feature is the difference in the relative cost and demand conditions for the different capital types. An important feature of the model is that it emphasises structural change as an important means to increase accumulation. Accordingly, it becomes conceivable to argue that short-run effects of energy price changes can be very different from the long run, where inputs are reallocated between the sectors. Specifically, with poor input substitution an energy price increase might decrease labour demand in the intermediate sector and raise labour used to produce capital. It will turn out in the theoretical model that the elasticity of substitution between energy and labour in the intermediates production is a central variable governing the reallocation of labour and thus long-run growth.

The system of equations used in the empirical part follows the theoretical causal chain from energy to capital accumulation to growth. The approach presented here necessarily includes the formulation of several relationships: the impact of energy prices and income on energy use, the effect of energy use on the different capital types, and, finally, the effect of capital accumulation on growth. The empirical equations are derived from the theoretical model. As we deal with aggregates of different sectors, i.e. one intermediate goods and three capital goods sectors, the estimated coefficients do not directly reflect the parameters, but rather combinations of the parameters of the theoretical model.

The adopted empirical approach takes econometric problems of recent international panel studies into account. By concentrating on developed countries, the contribution reduces estimation problems of the large samples covering very different countries. The selected countries are not too different regarding factor endowments, market structures, and institutions. The time period under study covers a sufficiently long horizon and the use of five-year intervals helps to minimise business cycle effects. Energy is used in all the sectors. Accordingly, we test a simultaneous system of the whole causal chain from energy to growth, using a three-stage least squares procedure. In these estimations, consistency is achieved by instrumentation and efficiency is reached by appropriate weighting using the covariance matrix from the second of the three stages.

We conclude from the regressions that, in the long run, higher energy prices or lower energy input need not hamper economic development. On the contrary, we find that the crowding out of capital accumulation by abundant energy is confirmed for this set of countries. Put differently, a decrease of energy input raises the accumulation of physical, human, and knowledge capital significantly. The three channel effects turn out to be of similar size. 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. Provided that energy is less intensively used in the sectors which are important for growth, which is a relatively mild assumption, our results relate to the well-known Rybczynski theorem of trade theory. This points at the crucial importance of the sectoral structure of the economy, which in the present approach is different from most neo-classical type growth models.

The present paper is based on several strands of literature. Regarding theory, it is based on the seminal contributions of Solow (1974), Stiglitz (1974) and Dasgupta and Heal (1974, 1979). It incorporates new growth theory relying on Aghion and Howitt (1998), Romer (1990) and Grossman and Helpman (1991). Endogenous growth and resource economics are similarly combined in Bovenberg and Smulders (1995), Bretschger (1998), Scholz and Ziemes (1999), Groth and Schou (2002), Grimaud and Rougé (2003), Brock and Taylor (2004) and Xepapadeas (2006). Structural change in this context is treated by López, Anriquez and Gulati (2005). The "curse" of natural resources is the topic of Auty (1990), Gelb (1988), Gylfason, Herbertsson and Zoega (1999), Gylfason (2001), Sachs and Warner (2001), Papyrakis and Gerlagh (2003, 2006), Norrbin and Bors (2004) and Mehlum, Moene and Torvik (2006). Empirical results on energy efficiency and growth are presented in Miketa and Mulder (2005) and Mulder and de Groot (2005). A strand of empirical literature using VARs focuses on the causality question between energy and growth, see Glasure and Lee (1998), Soytas and Sari (2003), Stern (2000) and Stern and Cleveland (2004), where the productivity slowdown in the 1970s and 1980s is related to energy. Our model elaborates on these topics by developing a theoretical concept of causalities and predicting the impact of energy on productivities. Finally, for the simultaneous estimation of the channels between energy and growth, the paper applies the method of Tavares and Wacziarg (2001) and Wacziarg (2001).

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

2 Theoretical framework

2.1 The core model

The model introduces three basic elements which are highly useful for a simple yet general framework. First, it uses the growth mechanism of expansion-in-varieties which is well established in growth theory. Second, it includes different capital types, which are not only inputs but also outputs of specific production processes. Third, it considers energy as an input in all sectors of the economy.

Final output Y is assembled from intermediate goods varieties x_j where j is the index for the variety and the set of available varieties is given by the interval $[0, K]$. With symmetric intermediates $x_j = x$ it reads:

$$Y = A \left[\int_0^K x_j^\beta dj \right]^{\frac{1}{\beta}} = AK^{\frac{1-\beta}{\beta}} X \tag{1}$$

where A is a scaling factor and we have $0 < \beta < 1$ and $X = K \cdot x$ for the aggregate output of the x-firms. Time indices are omitted whenever there is no ambiguity. Intermediate input is manufactured with labour L and energy E, the primary inputs; prices of x-goods are given by a mark-up over marginal cost:

$$p_X = (a_{LX} \cdot w + a_{EX} \cdot p_E)/\beta \tag{2}$$

where the as denote Leontief input factors and w and p_E are the labour wage and the energy price, respectively. In a growing economy, new x-goods are introduced by investing in new capital varieties. Specifically, the production of each additional intermediate good requires one additional capital variant as an up-front investment. In the case of knowledge capital, a capital variety is normally labelled as "product design" or "patent", see Romer (1990) and Grossman and Helpman (1991). Baldwin et al. (2001) and related literature use the term "capital variety" in a broader sense, for a general capital input. We adopt this idea and hone their approach by introducing a composite capital good, which is built from different capital types. By doing so, we are able to capture the relative importance of the different types of capital for the growth process. Importantly, this also reveals the channels through which energy affects growth. We distinguish between physical capital k_P and non-physical capital k_N, which is divided in human capital k_H and private (embodied) knowledge capital k_B.

New capital goods are built in the capital sector, where K-producers use the different capital types k_P, k_H and k_B to introduce new K-varieties where the number of available varieties at each point in time is measured by K according to (1). The introduction of new capital goods, i.e. the increase of K, entails positive spillovers to public (disembodied) knowledge, which is a free input for the subsequent capital build-up. When public knowledge is proportional to the economy's cumulative investment experience it is equal to K. Assuming the elasticity of public knowledge in capital production to be η, the increase of capital in the time interval dt is $dK = f(k_P, k_N) \cdot K^\eta$ with $k_N = \tilde{f}(k_H, k_B)$. f and $\tilde{f}$ are linear homogeneous functions. As the model includes all major capital types, we have intensive learning effects and may thus assume $\eta = 1$. Thus for each new K-variety, a_{PK}/K units of k_P and a_{NK}/K units of k_N are needed; for the production of k_N, a_{HN} units of k_H and a_{BN} units of k_B are used, respectively.

The different capital types P, H, and B are produced under perfect competition with labour and energy as (primary) inputs, that is $k_i = \bar{f}_i(L_{ki}, E_{ki})$, $i = P, H, B$, with the linear homogeneous functions $\bar{f}_i$. As the capital types use the inputs with different intensities, we will obtain differentiated effects of energy prices on capital use below. The costs of investing in new K-varieties can be written directly in terms of w and p_E, see the appendix. With free market entry in the K-sector, the costs to build a new capital good c_K/K are equal to or larger than the market value of capital p_K:

$$(a_{LK} \cdot w + a_{EK} \cdot p_E)/K = c_K(w, p_E)/K \geq p_K \tag{3}$$

with equality if there is positive investment and economic growth, which is assumed in the following. The market value of a capital unit follows from the condition that investors earn the market interest rate r when investing in capital, thus earning profits π and capital gains $\dot{p}_K$:

$$\pi + \dot{p}_K = r \cdot p_K \tag{4}$$

Households maximise a lifetime utility function:

$$U(t) = \int_0^\infty e^{-\rho(\tau - t)} \log Y(\tau) d\tau \tag{5}$$

subject to the budget constraint:

$$\dot{V} \ = rN + wL - p_Y Y + \tau \tag{6}$$

where V is household wealth, r the interest rate, $N = K \cdot p_K$ are asset holdings, p_Y the consumer price index, and τ lump-sum transfers from the government. Households' optimisation excludes the energy sector, which for simplicity is assumed to belong to the government. Profits from energy production are transferred to households in a lump-sum fashion. Nothing pins down the price level of the considered economy, so that the price path of one nominal variable can be freely chosen while, at any point in time, all prices are measured against the chosen numeraire. The choice of the numeraire has no effect on real magnitudes. For convenience, prices are normalised such that aggregate consumer expenditures are constant and unity at every point in time:

$$p_Y Y \equiv 1 \tag{7}$$

The no-Ponzi-game condition requires that the value of household wealth approaches zero in the long run. Intertemporal optimisation yields that the growth rate of aggregate consumer expenditures equals the difference between the nominal interest rate r and the discount rate ρ (Keynes-Ramsey rule), which means with (7) that $r = \rho$, that is the nominal interest rate always corresponds to the subjective discount rate. The evolution of the real interest rate, which is crucial for the development of the economy, is not predetermined by (7). As aggregate consumer expenditures are normalised to unity, the present value of consumption from any point in time onward is equal to $1/\rho$, so that the intertemporal budget constraint is well-defined in this economy. Finally, it can be noted that no resources are used to assemble differentiated goods to final output; expenditures for Y thus equal those for X.

The market form in intermediates production is monopolistic competition. The mark-up over marginal costs for the optimal price of an intermediate good is $1/\beta$, so that, together with (1) and (7), we get the per-period profit flow to the holder of a capital unit π:

$$\pi = (1-\beta)/K \tag{8}$$

Using g to denote growth rates, i.e. $g_K \equiv \dot{K}/K$, we write the market equilibria for energy and labour as:

$$\begin{pmatrix} a_{EX}\left(p_E.w\right) \\ a_{LX}\left(p_E,w\right) \end{pmatrix} X + \begin{pmatrix} a_{EK}\left(p_E,w\right) \\ a_{LK}\left(p_E,w\right) \end{pmatrix} g_K = \begin{pmatrix} E \\ L \end{pmatrix} \tag{9}$$

On the lhs of (9), we have the demand for E and L by the intermediate goods and the capital sector, respectively, represented by the input factors and the levels of sectoral "output", where g_K appears as the output for capital because of the proportional positive spillovers.

We are now ready to analyse the growth rate of the model economy under different assumptions regarding energy. To derive a reference scenario, we first assume a constant energy supply. Subsequently, we will study the impact of variations in energy use and energy prices in the next subsection. With a constant supply of E and L, we get constant input prices and sector shares by (9). Using (3), (4), (7), and (8) equilibrium capital growth g_K becomes:

$$g_K = \frac{(1-\beta)}{c_K\left(p_E,w\right)} - \rho \tag{10}$$

Capital growth is high with large gains from specialisation (low β), a low discount rate ρ and low (marginal) cost in capital production c_K, which is in accordance with recent growth theory. To derive output growth we refer to (1) and further specify A which we do not take as a constant for two reasons. First, we aim at removing the link between the gains from diversification and the market power as suggested by Bénassy (1998). Second, we assume decreasing returns to diversification, which entails the convergence properties usually found in empirical growth estimations. Specifically, we define $A = K^{\alpha \cdot Y_0^{-\mu} - (1-\beta)/\beta} \cdot D^{-\nu}$ where $-(1-\beta)/\beta$ neutralises the mark-up factor from (1), α reflects the gains from diversification in the Bénassy fashion, and μ and ν ($\mu, \nu > 0$) are suited to reflect the retarding impact of an increasing diversification on productivity growth, related to output at the initial state Y_0 and independent from Y_0, respectively. We insert A into (1), write the equation in growth rates, use the normalisation $\nu \cdot g_D = 1$ and, finally, take logarithms to get:

$$g_Y = \ln \alpha + \ln g_K - \mu \ln Y_0 \tag{11}$$

where we have used $\ln(g_Y + 1) \cong g_Y$ and g_K is given by (10). In a market equilibrium with constant energy and labour input and positive capital investments we obtain a constant growth of K and a growth rate of Y which depends on Y_0 and thus decreases over time. This reflects the recent growth experience of developed countries. It is evident from (9) and (11) that faster capital accumulation and higher growth come at the expense of the quantity of manufactured output. Higher growth is thus not equal to higher welfare. However, we see from (3) and (10) that the production of new capital varieties benefits from positive spillovers, which are pure externalities. This means that free markets produce suboptimal capital accumulation and measures favouring investments increase welfare. They act as (incomplete) substitutes for political measures directly aiming at internalising externalities. We now turn to the comparative dynamics after changes in energy supply conditions.

2.2 Impact of energy use

In order to identify the relevant channels of transmission from energy prices to long-run growth, we now derive three implications of the theoretical model which can be tested empirically: (i) the impact of energy prices and output on energy use, (ii) the effect of energy use on the investment rates, and (iii) the impact of the investment rates on growth. As the modelling is focused on these transmission channels we adopt a simplified assumption regarding energy supply and assume it to be fully elastic. For most countries facing world energy supply this is realistic. Energy price changes are either due to changes in taxation or to supply effects like shocks, increasing extraction costs and/or resource rents. It can be noted that empirically taxes explain most of the variation in the end-user energy prices in the different countries, while the supply effects mainly affect the time path of prices. We use the factor market equilibria (9) and the capital market equilibrium (10), where c_K is given by wages and energy prices, see the appendix. In the following, σ_X and σ_K denote the elasticities of substitution between energy and labour in the intermediates and the capital goods sector, respectively, hats denote total differentials in logarithms, and $\tilde{\rho} = (\rho + g_K)/g_K > 1$. We are ready to derive:

Lemma 1 *In the dynamic model economy, the impact of the energy price p_E and output Y on energy use is given by the expression:*

$$\hat{E} = -\{\frac{b_1 b_3 \sigma_X^2 + \bar{b}\sigma_X(\sigma_K - \tilde{\rho}) + b_2 b_4 (\sigma_K - \tilde{\rho})^2}{b_5} + \tilde{b}\}\hat{p}_E + \Gamma \cdot (\hat{Y} - \gamma) \tag{12}$$

$$(b_1, b_2, b_3, b_4, b_5, \bar{b}, \tilde{b}, \Gamma, \gamma > 0)$$

Proof. see the appendix. ■

The parameters used in (12) are directly linked to the parameters of the theoretical model, see the appendix. According to (12), high input substitution in the intermediates sector (a high σ_X) leads *ceteris paribus* to a large negative impact of $\hat{p}_E$ on $\hat{E}$ and for $\sigma_K > \tilde{\rho}$ the effect of prices on energy use is unambiguously negative. The same holds true for $\sigma_X = \sigma_K = 0$. For the intermediate cases we normally get the same result. However, according to (12) an ambiguity may arise in theory with $\sigma_X > 0$ and $0 < \sigma_K < \tilde{\rho}$. Depending on the substitution elasticities in the two sectors, wages decrease or increase after changes of energy prices. In the mathematical supplement we show that, for a given Y, wages decrease with a rise of energy prices when $\lambda_{LX}\theta_{EX}\sigma_X + \lambda_{LK}\theta_{EK}(\sigma_K - \tilde{\rho}) < 0$ where we use θs and λs as cost shares and factor shares, respectively, e.g. $\theta_{EX} = a_{EX} \cdot p_E/p_X$ and $\lambda_{EX} = a_{EX} \cdot X/E$ etc. This wage drop causes a strong output effect which could eventually overcompensate the usual substitution effect. But we can show that this only happens when $\tilde{\rho}$ becomes high (which means a high discount rate) and the energy intensity in capital accumulation θ_{EK} is very large (which contradicts empirical observations). We thus conclude that the effect of $\hat{p}_E$ on $\hat{E}$ is expected to be negative as in the static one-sector economy but that, ultimately, empirical verification is needed to confirm the hypothesis, see the empirical estimations in the next section. The impact of output, i.e. the effect of $\hat{Y}$ on $\hat{E}$, is unambiguously positive. The result in *Lemma 1* is given for full wage flexibility, which applies for the longer run. When wages are not flexible we get an unambiguously negative impact of energy prices on energy use, given by $\hat{E} = -\tilde{b} \cdot \hat{p}_E$.

We next determine the impact of energy use on the different types of capital investments. We define the investment rate for capital type i, s_i, as the ratio of capital use k_i to aggregate output Y, i.e. $s_i = k_i/Y$, and denote $\sigma_{\tilde{K}}$ and σ_N as the elasticities of substitution between physical and non-physical capital and between human and knowledge capital, respectively. We are then able to show:

Lemma 2 *The effects of energy use on the investment rates depend on the substitution elasticities in capital goods production and on the input intensities; they are given by:*

$$\hat{s}_P = [\theta_{NK}(1-\sigma_{\tilde{K}})(\theta_{EN}-\theta_{EP}) + (\theta_{EP}-\theta_{EX})]\,\frac{\nu}{\Delta}\cdot\hat{E}-\gamma \tag{13}$$

$$\hat{s}_H = [\theta_{BN}(1-\sigma_N)(\theta_{EB}-\theta_{EH}) + (\theta_{EH}-\theta_{EX})]\,\frac{\nu}{\Delta}\cdot\hat{E}-\gamma \tag{14}$$

$$\hat{s}_B = [\theta_{HN}(1-\sigma_N)(\theta_{EH}-\theta_{EB}) + (\theta_{EB}-\theta_{EX})]\,\frac{\nu}{\Delta}\cdot\hat{E}-\gamma \tag{15}$$

$$(\nu = -\lambda_{LX}(\theta_{EX}+\theta_{LX}) - \lambda_{LK}\tilde{\rho}(\theta_{EK}+\theta_{LK}) < 0,\ \Delta < 0)$$

Proof. see the appendix. ■

The impact of energy on investment shares depends on changes in costs and returns in the different sectors which determine the reallocation of primary inputs. Technically, the elasticities of substitution between capital inputs $\sigma_{\tilde{K}}$ and σ_N and the cost shares θ expressing input intensities govern the result. When capital accumulation is less energy intensive than intermediate goods production we have $\theta_{Ei}-\theta_{EX} < 0$ $(i = P, H, B)$, otherwise $\theta_{Ei}-\theta_{EX} > 0$. This reflects the impact of energy on the cost of capital (cost effect). When the energy price/wage ratio increases, sectors with a low energy intensity have a cost advantage. Provided that $\sigma_{\tilde{K}} = \sigma_N = 1$, the return to the different capital types remains constant. Then, the impact of E on s_i is unambiguously negative, i.e. decreasing energy input raises investment for all capital types, provided that $\theta_{Ei}-\theta_{EX} < 0$. Note that by (1) the return for aggregate capital is constant, which is a common property of expansion-in-varieties models. When $\sigma_{\tilde{K}} \neq \sigma_N \neq 1$ we see for physical capital that a decreasing energy use raises the investment share provided that (i) $\theta_{EN} < \theta_{EP}$ and $\sigma_{\tilde{K}} < 1$ or (ii) $\theta_{EN} > \theta_{EP}$ and $\sigma_{\tilde{K}} > 1$. Given poor input substitution, physical capital investments increase with a decrease of energy supply, provided that the energy share for non-physical capital is smaller than for physical capital. In this case, a price rise of physical capital increases its share (θ_{PK}) and thus the return.

Regarding the reward for human capital, a decreasing energy use raises the investment share when $\theta_{EB} < \theta_{EH}$ and $\sigma_N < 1$ or $\theta_{EB} > \theta_{EH}$ and $\sigma_N > 1$. For knowledge capital, the opposite result applies, that is we have to reverse the inequality signs. Put differently, one of the two expressions is always positive. But note that the terms $\theta_{EH}-\theta_{EX}$ and $\theta_{EB}-\theta_{EX}$ are presumably much lower (i.e. more negative) than $\theta_{EP}-\theta_{EX}$ because human and knowledge capital are likely to be less intensive in energy use than physical capital. Thus with σ_N close to unity it is a likely outcome of the model that both of these capital types can profit from a drop in energy input.

We conclude that a shrinking energy input increases the investment rates, provided that capital accumulation is less energy-intensive than intermediate goods production, that differences in energy intensities between the capital and the intermediates sector are substantial, and that elasticities of substitution between capital types are close to unity. Physical capital is likely to obtain a higher reward, while non-physical capital is expected to gain from a comparative cost advantage. Of course, we need the empirical analysis to corroborate these predictions. Microeconomic foundation cannot predict the size of the elasticities. Note that poor input substitution is not automatically unfavourable as in the neoclassical growth model. The present framework with multiple sectors predicts a more differentiated impact of substitution elasticities in the economy. Poor input substitution fosters sectoral reallocation of inputs and thus sectoral change. In particular, poor input substitution leads to a sectoral reallocation of labour which is associated with a decrease in wages. The wage drop provides the incentives to increase capital accumulation.

Changes in the investment rates affect growth through the impact of each capital type on capital accumulation. Specifically, the investment rates s_i affect the use of the different capital types k_i in the accumulation of K. Any increase of k_i raises g_K, so that we predict a positive impact of all capital types on growth. We state:

Lemma 3 *The effects of the investment rates of the different capital types on growth g depend on the output elasticities in the capital sector; the growth equation reads:*

$$g_Y = \ln\alpha + \theta_{PK}\ln s_P + \theta_{NK}\theta_{HN}\ln s_H + \theta_{NK}\theta_{BN}\ln s_B + \ln Y - \mu\ln Y_0 \qquad (16)$$

Proof. *see the appendix.* ■

As can be seen from the above expression, the different investment rates have a positive impact on growth according to their relative share in capital accumulation. The positive effect of Y exhibits the scale effect of investments due to the positive spillovers, while the negative impact of Y_0 entails the convergence properties due to decreasing returns to specialisation.

2.3 The estimation equations

From *Lemmas* $1-3$ we directly derive the estimation equations for the empirical analysis. Due to the inherent multi-sector structure of the model economy, the estimated coefficients do not correspond directly to the parameters of the theoretical model but are closely linked to these parameters. Specifically, the impact of energy prices on energy use, the effect of energy use on investment rates and the growth impact of investment rates are estimated. All the specifications are in logarithms, which corresponds to the theoretical results. From *Lemma* 3 we take the growth equation as:

$$g = \epsilon_0 \cdot const + \epsilon_1 \ln s_P + \epsilon_2 \ln s_H + \epsilon_3 \ln s_B + \varepsilon_4 \ln Y_0 + \varepsilon_5 \cdot \ln \vec{Z}_g + \xi_g \qquad (17)$$

where we predict $\epsilon_1,\ \epsilon_2,\ \epsilon_3 > 0$ and $\varepsilon_4 < 0$ from the model and the interpretation of ϵ_1, ϵ_2 and ϵ_3 is given by (16). Specifically, with ϵ_1, ϵ_2 and ϵ_3 we can calculate $\theta_{PK}, \theta_{NK}, \theta_{HN}$ and θ_{BN}. $\vec{Z}_g$ is a set of control variables and ξ denotes the error term. This specification is in accordance with the cross-country growth literature and includes all the channel variables as regressors. As controls $\vec{Z}_g$ we consider population growth, because (17) is expressed in per capita terms, and the size of the economy, which reflects Y appearing in (17). This reflects the impact of the country specific spillovers from the theoretical model. To determine the three investment rates, i.e. the channel variables, we employ the results of *Lemma* 2 and express investment rates, energy inputs, and the other variables in logarithms, so that the estimated coefficients can be interpreted according to the theoretical equations, which are given by differentials in logarithms. This yields:

$$\ln s_P = \delta_{P0} \cdot const + \delta_{P1} \cdot \ln E + \delta_{P2} \cdot \ln \vec{Z}_P + \xi_P \qquad (18)$$

$$\ln s_H = \delta_{H0} \cdot const + \delta_{H1} \cdot \ln E + \delta_{H2} \cdot \ln \vec{Z}_H + \xi_H \qquad (19)$$

$$\ln s_B = \delta_{B0} \cdot const + \delta_{B1} \cdot \ln E + \delta_{B2} \cdot \ln \vec{Z}_B + \xi_B \qquad (20)$$

with

$$\delta_{P1} = [\theta_{NK}(1-\sigma_{\tilde{K}})(\theta_{EN}-\theta_{EP}) + (\theta_{EP}-\theta_{EX})]\,\frac{\nu}{\Delta}$$

$$\delta_{H1} = [\theta_{BN}(1-\sigma_N)(\theta_{EB}-\theta_{EH}) + (\theta_{EH}-\theta_{EX})]\,\frac{\nu}{\Delta}$$

$$\delta_{B2} = [\theta_{HN}(1-\sigma_N)(\theta_{EH}-\theta_{EB}) + (\theta_{EB}-\theta_{EX})]\,\frac{\nu}{\Delta}$$

The control variables $\vec{Z}_P$ include scale effects, openness, capital type-specific parameters, and population dynamics. Specifically, the literature suggests that the size of an economy and population growth may have an impact on s_P in (18). Again, country specific scale effects might have an impact here, especially in the case of knowledge capital. Moreover, trade openness was recently found to have a significant impact on physical investments, see Wacziarg (2001). Also, an ageing society might invest more to sustain old-age consumption, which is also tested for. As additional controls in (19), the productivity and income are important issues. Returns of educational investments appear to be especially favourable when human capital stock and life expectancy are high. Also, demand for education rises more than proportionally with income. As education is close to government activities, government spending as a share of GDP has to be considered. Openness and population growth are again included in (19) to check for the impact of globalisation and labour dynamics. To put (20) into the right perspective, the literature assumes strong scale and spillover effects in research, which might be accompanied by certain indivisibilities of research projects, so that size variables have the most prominent role of controls in (20).

The expected signs of δ_{P1}, δ_{H1}, and δ_{B1} depend on cost shares and substitution elasticities which determine a cost and a return effect for each capital type. In case that $\theta_{Ei} < \theta_{EX}$ $(i = K, H, B)$ capital accumulation benefits from higher energy prices through cost advantages compared to intermediates (and thus final goods) production. For physical capital, the change in returns depends on whether $(1-\sigma_{\tilde{K}})(\theta_{EN}-\theta_{EP})$ is positive or negative, which is not determined by theory. The finding $\delta_{P1} < 0$ would mean that either both the cost and the return effect have a negative sign in (18), or that the term with the positive sign is smaller than the other term. For $\sigma_{\tilde{K}}$ being close to unity the total effect would be dominated by the cost term. For human and knowledge capital the expression $(1-\sigma_N)(\theta_{EB}-\theta_{EH})$ determines the change in returns after energy price increases. Finding $\delta_{H1}, \delta_{B1} < 0$ in the empirical estimations would say that the cost effect dominates for non-physical capital, as we know by (19) and (20) that the return effect is unfavourable for either H or B. This would suggest that σ_N is close to unity and/or $(\theta_{EH}-\theta_{EX})$ and $(\theta_{EB}-\theta_{EX})$ reach large negative values. Finally, the energy equation comes in two variants. The first version reads :

$$\ln E = \gamma_0 \cdot const + \gamma_1 \cdot \ln p_E + \gamma_2 \ln Y + \gamma_3 \cdot \ln \vec{Z}_E + \xi_E \tag{21}$$

with $\gamma_1 = \left[b_1 b_3 \sigma_X^2 + \bar{b}\sigma_X(\sigma_K - \tilde{\rho}) + b_2 b_4(\sigma_K - \tilde{\rho})^2\right]/b_5 + \tilde{b}$ and $\gamma_2 = \lambda_{LX}/ [\lambda_{LX}\theta_{EX}\sigma_X + \lambda_{LK}(\theta_{EK}\sigma_K + \theta_{LK}\tilde{\rho})] + \lambda_{EX}$ as derived in Lemma 1. We expect $\gamma_1 < 0$ and $\gamma_2 > 0$. We will use this variant in a first estimation equation to determine the impact of energy prices on energy use. In the simultaneous estimation of the whole system, however, we have to consider that both p_E and Y are endogenous variables. In particular, energy prices play an important role in the transmission of the impact of energy use on investment share. Specifically, inputs are reallocated between sectors according to relative input price changes. We thus modify (21) for the system estimations and write the second variant as:

$$\ln E = \zeta_0 \cdot const + \zeta_1 \cdot \ln Y_o + \gamma_2 \cdot \ln \vec{Z}_E + \xi_E \tag{22}$$

which says that energy use depends on (predetermined) initial income and the same set of controls as above. Put differently, the system of the empirical equations assumes that initial income affects energy use, which has an impact on investment shares, which drive economic growth.

3 Estimation Method and Data

3.1 Econometric issues

In empirical cross-country studies with large samples, econometric problems such as simultaneity, parameter heterogeneity and missing variables have to be especially considered, see Temple (1999). Simultaneity arises because the macroeconomic variables involved are highly interdependent. Appropriate instruments are needed to correct for the corresponding bias, which will be done below. Parameter heterogeneity is another pervasive econometric problem, which stems from the use of large samples including very different countries. On the one hand, problems of data quality and outliers are well known and can be addressed with appropriate sensitivity tests. But there are good reasons to suggest that the quality of the channels vary substantially when we compare many different countries, notably low developed countries and leading economies. If theory is richer than is expressed in the empirical specifications, the problem of omitted variables is also a serious obstacle for good estimation results.

By restricting our analysis to a limited number of developed economies with similar factor endowments and institutional backgrounds, using appropriate instruments, and adopting a simultaneous estimation approach we aim to reduce these econometric problems as far as possible.

3.2 Estimation strategy

To obtain quantitative information about the impact of energy prices we first estimate energy use for all time periods jointly using three-stage least squares, according to (21). Then, as the main step, the system consisting of equations (17)-(20) and (22) is estimated jointly using three-stage least squares. The advantage of this estimation method (e.g. compared to a dynamic GMM) is its ability to take care of the various cross-equation correlations. These occur when we assume 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 like several cost shares appear in more than one estimation equation. Cross-equation correlations thus appear to be highly important in our context so that 3SLS is more efficient than 2SLS. Moreover, the theoretical part derives three consecutive stages of the energy growth system, which call for a system estimation. Specifically, the used empirical system postulates that initial income affects energy use, which has an effect on the various investment rates, which in turn affect growth. This can be jointly estimated with 3SLS.

The procedure follows Tavares and Wacziarg (2001) and Wacziarg (2001). 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 2 and the fitted values of the endogenous variables of step 1 are used for an IV-GLS estimation 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. Similar to Tavares and Wacziarg (2001) we restrict all non-contemporary coefficients to zero.

The full system jointly determines growth, energy use, and the relevant channels in between. We assess the sign and magnitude of a specific channel taking into account all the other channels. By using a sufficient number of exogenous variables and instruments we aim at reducing the scope for omitted variable bias. As separate instruments for the 3SLS procedure we use economic, geographic, and demographic variables. Specifically, we introduce the average distance to trade partners, the land area, the age dependency ratio, the share of arable land, and life expectancy in all the estimations as exogenous instruments.

The various control variables directly included in the regression equations have been motivated in section 2.3. To have a robust benchmark, they are used throughout the growth and the energy equation while in the more sensitive part of the channel equations, they are introduced sequentially to check their relative impact and the robustness of the specification. To obtain an adequate interpretation of the results we use per-capita measures for income and energy use and capture the size of the economy with special variables.

3.3 The data

We collected data for 37 countries, which are 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 the country sample for which the International Energy Agency (IEA) provides energy price data and the other data are completely available. In the first set of estimated equations we also include some recently developed economies, in particular Czech Republic, Kazakhstan, Latvia, Lithuania, Russia, Slovak Republic, Slovenia, and Estonia. Based on the prices of single energy sources and the expenditure shares for the different sources, we calculate an average energy price for each country. It has to be noted that price data from the IEA are available for a much smaller set of countries and time periods compared to energy quantities (71 vs. 222 observations). In the other equations representing the full system of the econometric model we have a balanced panel. The five-year periods are 1975-79, 1980-84, 1985-89, 1990-94, 1995-99 and 2000-04. By using five-year averages we focus on the long-run impact of energy as derived in the main part of the theoretical model.

Table 1: Data
Variables and data sources

Variable	Description	Source
growth	real per capita GDP growth, const. prices, chain series	PWT 6.2
ci	average investment share	PWT 6.2
ingdp	initial GDP per capita	PWT 6.2
popgro	population growth	PWT 6.2
enusecap	energy use per capita (in KGOE)	WDI (2007)
open	exports+imports/GDP	PWT 6.2
schooling	initial years of average schooling	Barro/Lee (2000)
eduexp	education expenditure as a share of GDP	WDI (2005)
govshare	government spending as a share of GDP	PWT 6.2
enprice	energy price (index)	IEA, own calculations
area	land area	WDI (2007)
dist	average distance to trading partners	Barro/Lee (1994)
rdshare	R&D expenditures as a share of GDP	WDI (2007)
agriland	share of land area that is arable	WDI (2007)
lifeexp	life expectancy	WDI (2007)
agedep	ratio of dependents; people <15 + >64/others	WDI (2007)
size	initial income · population	PWT 6.2
pop	population	PWT 6.2
prilifuel	price of light fuel oil	IEA (2005)
priprlead	price of premium leaded gasoline	IEA (2005)
prilifuelin	price of light fuel oil industry	IEA (2005)
prihisuin	price high sulfur fuel oil industry	IEA (2005)
prigasin	price of gas industry	IEA (2005)
prielin	price of electricity industry	IEA (2005)

The data sources are described in table 1. WDI refers to the World Development Indicators of the World Bank and PWT 6.2 to the Penn Word Table from

Heston, Summers and Aten (2006), see also the exact references at the end of the paper. Table 2 provides summary statistics for the variables.

Table 2: Description of Variables

Variable	Obs.	Mean	Std.dev.	Min	Max
growth	222	0.02	0.03	-0.13	0.21
logci	222	1.34	0.13	0.85	1.61
logingdp	222	4.06	0.35	2.77	4.68
popgro	222	0.85	0.76	-0.93	3.49
logenusecap	222	3.41	0.33	2.53	4.03
logopen	222	1.74	0.26	1.02	2.44
logschooling	222	0.85	0.17	0.35	1.09
logeduexp	222	0.62	0.22	-0.55	0.91
loggovshare	222	2.90	0.29	2.02	3.56
logenprice	71	2.05	0.20	1.64	2.60
logarea	222	5.45	0.97	2.51	6.97
logdist	222	0.58	0.26	0.10	1.06
logrdshare	222	-0.09	0.42	-1.49	0.60
logagriland	222	1.56	0.32	0.53	1.92
loglifeexp	222	1.69	0.25	1.02	1.90
logagedep	222	-0.26	0.07	-0.37	0.004
logsize	222	11.34	0.68	9.24	13.0
logpop	222	7.32	0.78	5.54	9.11
prilifuel	149	2934.88	13024.14	30.47	96178.9
priprlead	145	34.5	253.3	0.13	2910.4
prilifuel	149	2934.88	13024.1	30.47	96178.9
prilifuelin	151	5268	32532	24.90	369656
prihisuin	159	3998.7	21018.41	20.36	208283.9
prigasin	142	2758.2	16978.9	23.64	173443.7
prielin	183	2.9	20.1	0.007	240.8

In table 3, we 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. Moreover, it can be shown that (end user) energy prices are highly determined by taxes which shows the impact of the government on these prices.

Table 3: Correlation of energy prices

	enprice	priprlead	prilifuelin	prihisuin	prigasin	prielin
enprice	1					
priprlead	0.8326	1				
prilifuelin	0.9118	0.7928	1			
prihisuin	0.8819	0.7195	0.7529	1		
prigasin	0.8480	0.6678	0.5781	0.7007	1	
prielin	0.7684	0.7207	0.5942	0.8614	0.6960	1

4 Empirical Evidence

The main equations derived from theory are now used to empirically identify the different channels in the energy-capital-growth relationships. In the first step we estimate the impact of energy prices *logenprice* and economic activity level *logingdp* on energy use per capita *logenusecap* according to (21). The instruments *logarea*, *logdist*, *loglifeexp*, *logagedep*, *logagriland*, and *logpop* as well as all the country dummies (with the exception of the US as the reference country to avoid perfect collinearity) are used throughout but do not appear in the table. Only when these variables are directly included in one of the equations results are reported. According to theory the coefficients are estimated for the variables in logarithms. All the price observations are included but, unfortunately, only a moderate number of observations emerges.

The results for the energy equation (21) are presented in table 4. As can be seen from the table, the negative impact of energy prices on energy use is confirmed throughout. The estimated parameter value is remarkably stable in the different specifications although not high for this set of countries and the used 5-year-averages. As expected, the scale variable measured in terms of income has a positive and highly significant effect on energy use. Again, the estimated elasticity is relatively moderate. The size of the economy measured by population has a positive impact on energy use while population growth has a negative effect. Globalisation as measured by trade openness has no significant impact on energy use but the area of the country and the age dependency of the society show negative signs. Overall, the variation of the dependent variable is well explained as confirmed by the R^2s. It has to be noted that the country dummy variables add substantially to the high coefficient of determination.

Table 4: Estimations results for energy use
Endogenous variable: logenusecap, estimation method 3 SLS

Variable	(1)	(2)	(3)	(4)	(5)	(6)
logenprice	-0.0502*	-0.0521**	-0.0575**	-0.0573**	-0.0614**	-0.0584**
	(0.027)	(0.025)	(0.025)	(0.025)	(0.024)	(0.025)
logingdp	0.233***	0.303***	0.236***	0.235***	0.178**	0.188**
	(0.060)	(0.062)	(0.069)	(0.069)	(0.073)	(0.078)
logpop	1.928***	1.748***	1.723***	1.726***	1.661***	1.662***
	(0.29)	(0.28)	(0.27)	(0.27)	(0.26)	(0.26)
popgro		-0.0288***	-0.0296***	-0.0290***	-0.0251***	-0.0259***
		(0.0098)	(0.0096)	(0.0095)	(0.0095)	(0.0097)
logopen			0.149*	0.151**	0.115	0.110
			(0.076)	(0.076)	(0.076)	(0.077)
logarea				-1.900***	-1.767***	-1.774***
				(0.33)	(0.32)	(0.32)
logagedep					-0.233**	-0.244**
					(0.12)	(0.12)
loglifeexp						-0.00874
						(0.024)
constant	-12.13***	-11.05***	-10.81***	-10.51***	-10.31***	-10.11***
	(1.99)	(1.92)	(1.87)	(1.87)	(1.87)	(1.87)
observations	71	71	71	71	71	71
R^2	0.99	0.99	0.99	0.99	0.99	0.99

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

We now turn to the simultaneous estimation of our multi-equation system. The growth relation (17), the channel equations for physical, human, and knowledge capital (18 - 20), and the energy use relation (22) are jointly estimated using three-stage least squares. The results cover the full sample of 37 countries and 6 time periods that is they apply for a balanced panel. Again, the country dummies are used in all the equations (but are not reported in the table), while $logarea$, $logdist$, $loglifeexp$, $logagedep$, and $logagriland$ are the additional instruments as in table 4.

The results are presented in table 5, which includes six representative equations (7-12). The specifications follow the theoretical considerations in section 2.3. The channel equations are varied with regard to the control variables while the more standard equations for growth and energy remain unchanged. In the first part of the table we see the results for the growth regression. We observe that they closely follow recent empirical growth literature. Initial income and the investment shares have the expected effects on real per capita growth and are significant. In particular, all three investment shares turn out to perform very well, with the expected signs and highly significant coefficients. The elasticities with respect to growth are highest for physical capital and somewhat lower for knowledge and human capital. Population growth has a negative impact but is not significant, while the size of the economy appears to be rather negative for growth, although the significance is at the 10%-level only in (12).

The second part of table 5 concerns the physical capital channel. The effect of energy use on physical capital investments is negative and significant at the 1%- and 5%-level, respectively. The effect remains robust in the different specifications. The estimated elasticity varies between -0.18 and -0.27 so that, combined with the elasticity of 0.38 from the growth regression, we get a total elasticity of energy on growth through the physical investment channel of about 10 percent. According to the results, the size of the economy measured by *logpop* and openness are not significant; the effect of population growth is zero or weakly positive. The variable with a strong impact turns out to be *age dependency*, which has a positive and significant effect on physical capital accumulation.

The third part of the table (with *logeduexp* as endogenous variable) shows the results for the human capital channel. Energy use has a negative, significant, and robust impact on education expenditures, once the initial stock of human capital (*logschooling*) and initial income are controlled for. Including further control variables increases the estimated elasticity up to 0.9, in the simpler specifications it is similar to the elasticity of physical capital. Total elasticity of energy use on growth through the human capital channel thus varies between 4 and 11 percent. Initial years of average schooling and income have a positive and highly significant impact on education expenditures, which is conceivable. Somewhat surprisingly, the share of government expenditures of GDP has no effect on education expenditures in all the different specifications. Openness has a negative impact on education expenditures but it is only significant at the 5%-level in the last equation. Life expectancy and population growth have no effect on education according to the results.

Table 5: Estimation results for the system
Endogenous variables: growth, logci, logeduexp logrdshare, logenusecap

	(7)	(8)	(9)	(10)	(11)	(12)
growth						
logingdp	-0.133***	-0.122***	-0.125***	-0.128***	-0.126***	-0.127***
	(0.026)	(0.029)	(0.029)	(0.029)	(0.029)	(0.029)
logci	0.371***	0.367***	0.370***	0.366***	0.371***	0.394***
	(0.060)	(0.060)	(0.062)	(0.063)	(0.062)	(0.066)
logeduexp	0.123***	0.123***	0.115***	0.127***	0.118***	0.125***
	(0.027)	(0.027)	(0.028)	(0.028)	(0.029)	(0.030)
logrdshare	0.211***	0.205***	0.211***	0.213***	0.211***	0.222***
	(0.054)	(0.053)	(0.055)	(0.055)	(0.055)	(0.056)
popgro	-0.000672	-0.00322	-0.00310	-0.00260	-0.00241	-0.00186
	(0.0028)	(0.0031)	(0.0031)	(0.0031)	(0.0031)	(0.0032)
logsize	-0.0574	-0.0578	-0.0581	-0.0601	-0.0585	-0.0635*
	(0.035)	(0.035)	(0.037)	(0.037)	(0.037)	(0.037)
constant	0.679**	0.649**	0.662**	0.699**	0.669**	0.695**
	(0.33)	(0.32)	(0.33)	(0.34)	(0.33)	(0.34)
logci						
logenusecap	-0.284***	-0.281***	-0.298***	-0.208**	-0.180**	-0.181**
	(0.084)	(0.084)	(0.087)	(0.090)	(0.091)	(0.091)
logpop	0.0429	0.0171	0.0313	0.0540	0.0618	0.0552
	(0.076)	(0.077)	(0.079)	(0.077)	(0.077)	(0.077)
popgro		0.0151*	0.0162*	0.0128	0.0126	0.0137
		(0.0082)	(0.0084)	(0.0083)	(0.0083)	(0.0085)
logopen			0.0198	0.0705	0.0847	0.0762
			(0.049)	(0.052)	(0.052)	(0.053)
logagedep				0.336**	0.447***	0.428***
				(0.14)	(0.15)	(0.15)
constant	2.049***	2.224***	2.142***	1.638***	1.480***	1.541***
	(0.40)	(0.41)	(0.43)	(0.47)	(0.48)	(0.48)
logeduexp						
logenusecap	-0.280*	-0.287*	-0.822**	-0.908**	-0.916**	-0.933**
	(0.15)	(0.15)	(0.38)	(0.39)	(0.39)	(0.37)
logschooling	0.507***	0.523***	0.822***	0.860***	0.876***	0.886***
	(0.15)	(0.15)	(0.29)	(0.30)	(0.30)	(0.30)
logingdp	0.273***	0.266***	0.569***	0.596***	0.592***	0.611***
	(0.087)	(0.088)	(0.20)	(0.20)	(0.20)	(0.19)

Table 5 *contd.*

	(7)	(8)	(9)	(10)	(11)	(12)
loggovshare		-0.0206	-0.0638	-0.0682	-0.0672	-0.0698
		(0.054)	(0.055)	(0.056)	(0.056)	(0.055)
logopen			-0.260	-0.293*	-0.287*	-0.307**
			(0.16)	(0.16)	(0.17)	(0.16)
loglifeexp				0.0255	0.0262	0.0239
				(0.040)	(0.040)	(0.040)
popgro						-0.00350
						(0.012)
constant	0.103	0.198	1.062	1.238*	1.259*	1.275*
	(0.31)	(0.38)	(0.67)	(0.69)	(0.68)	(0.67)
logrdshare						
logenusecap	-0.701**	-0.715**	-0.702**	-0.691**	-0.595**	-0.666**
	(0.28)	(0.28)	(0.29)	(0.29)	(0.28)	(0.29)
logsize	0.930***	0.876***	0.872***	0.867***	0.736***	0.751***
	(0.14)	(0.15)	(0.15)	(0.15)	(0.16)	(0.16)
logpop		0.132	0.123	0.122	0.140	0.145
		(0.12)	(0.12)	(0.12)	(0.12)	(0.12)
logagedep					-0.468**	-0.302
					(0.21)	(0.22)
loglifeexp						0.0680
						(0.045)
constant	-8.764***	-9.109***	-9.038***	-9.010***	-7.996***	-8.029***
	(0.77)	(0.84)	(0.86)	(0.86)	(0.93)	(0.93)
logenusecap						
logingdp	0.562***	0.556***	0.557***	0.560***	0.555***	0.557***
	(0.037)	(0.039)	(0.039)	(0.039)	(0.039)	(0.039)
logpop	0.420***	0.429***	0.426***	0.423***	0.427***	0.426***
	(0.038)	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)
logopen	-0.185***	-0.194***	-0.191***	-0.193***	-0.184***	-0.186***
	(0.039)	(0.039)	(0.042)	(0.042)	(0.042)	(0.042)
constant	-1.866***	-1.902***	-1.884***	-1.876***	-1.897***	-1.889***
	(0.28)	(0.28)	(0.28)	(0.28)	(0.28)	(0.28)
observations	222	222	222	222	222	222
R^2 growth	0.36	0.33	0.35	0.37	0.36	0.48
R^2 logci	0.72	0.73	0.73	0.75	0.75	0.75
R^2 logeduexp	0.87	0.87	0.86	0.85	0.85	0.85
R^2 logrdshare	0.93	0.93	0.93	0.93	0.94	0.93
R^2 logenusecap	0.98	0.98	0.98	0.98	0.98	0.98

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

It is interesting to see the outcome with regard to knowledge capital, because this type of investment does not 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 specifications, that the estimated parameter values are reasonably stable and that significance is relatively high. Combining the estimated elasticity of around -0.7 with the result in the growth regression one obtains a channel effect for knowledge which is even higher than for physical and human capital. The second variable which is successful in the estimated equation is the size of the economy, which we interpret as strong indication of scale effects in this type of capital accumulation. Population size and life expectancy have no impact while age dependency seems to deter research efforts, but it is only significant in equation (11).

As the estimated coefficients for the effects of energy on investment rates are negative for all capital types, we conclude that either both the cost and the return effect as described in section 2.3 favour investments, or that the unfavourable effect (presumably the return effect) is comparatively small. This would suggest that the elasticities of substitution between the different capital types are close to unity and/or cost advantages of capital after energy price increases are large. In particular, by combining the estimation results from the growth equation and the channel equations, i.e. the estimated values of ϵ_1, ϵ_2 and ϵ_3 in (17) as well as δ_{H1} and δ_{B1} in (19) and (20) it turns out that capital production is more intensive in knowledge capital compared to human and physical capital and that the cost effects in the human and knowledge channels are highly important because both δ_{H1} and δ_{B1} turn out to be negative.

The last part of table 5 reflects energy use and its dependence on various factors. Notably, initial income has a positive impact on energy use with an elasticity which lies around 0.5. Compared to the previous exercise in table 4, the impact is somewhat higher here. Population size has a positive and significant impact, which is intuitive. On the other hand, openness affects energy use negatively according to the results.

The overall regression statistics in table 5 are highly satisfactory. A large part of the variation of the endogenous variables is explained by the estimations. We 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.

We conclude that lower energy input raises growth through induced capital accumulation, in particular with physical, human, and knowledge capital. The three channel effects are of similar size. It is interesting to note that the negative impact of energy use on growth also emerges in this sample when including energy use directly in the growth regression. This confirms our main finding but is of course less detailed than the system estimations with the channels, where we find that knowledge capital seems to be a very powerful channel, physical capital is a reliable channel, and human capital is potentially important but shows a higher variation.

5 Conclusions

The theoretical model derived in this paper shows how economic growth is affected by energy inputs, revealing different channels which are determined by different types of capital accumulation. Crowding out of capital accumulation by abundant and cheap energy supply is shown to be closely linked to differences in energy intensities between consumer and capital goods production on the one hand and elasticities of substitution within the capital sector on the other.

The empirical results for 37 developed economies over the period 1975-2004 show that higher energy prices and tighter energy supply are not likely to be a curse for growth in the long run. On the contrary, we find that lower energy use has a positive dynamic impact in the long run. The mildest interpretation of the results suggests that the often-cited negative impact of lower energy input on growth is not evident in the long run. This holds true for all the channels included, that is physical, human, and knowledge capital. All these channels seem to be effective according to the results. They are of comparable size, with human capital showing the highest degree of variance and knowledge capital the highest expected value. The overall impact of energy use on growth is found to be characterised by an elasticity of around -0.3, with each capital type being about equally important as a transmission channel. It has to be noted, however, that these results only apply for the aggregate economy and for five-year averages. During the transition following higher energy prices, several sectors in the economy are expected to shrink.

The empirical results are reasonably robust because they emerge from an appropriate system using different specifications. The findings are in line with earlier contributions on the dutch disease and the resource curse. But contrary to existing literature, they are derived in a new theoretical setting and empirically verified for higher-developed countries. The model results can also be used when estimating the dynamic costs of 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.

References

[1] Aghion, Ph. and P. Howitt (1998): Endogenous Growth Theory, MIT Press, Cambridge MA.

[2] Auty, R.M. (1990): Resource-Based Industrialization: Sowing the Oil in Eight Developing Countries, Oxford University Press, New York.

[3] Baldwin, R.E., Ph. Martin, and I. P. Ottaviano (2001): Global Income Divergence, Trade, and Industrialization: The Geography of Growth Take-Offs, Journal of Economic Growth, 6: 5–37.

[4] Barro, R.E. and J.-W.Lee (2000): International Data on Educational Attainment: Updates and Implications, April 2000, http://cid.harvard.edu/ciddata/ ciddata.html.

[5] Barro, R.E. and J.-W.Lee (1994): Data Set for a Panel of 138 Countries, http:// cid.harvard.edu/ciddata/ciddata.html.

[6] Bénassy, J.P. (1998): Is there always too little research in endogenous growth with expanding product variety?, European Economic Review, 42, 61-69.

[7] Bovenberg, A.L. and S. Smulders (1995): Environmental Quality and Pollution-augmenting Technological Change in a Two-sector Endogenous Growth Model, Journal of Public Economics, 57, 369-391.

[8] Bretschger, L. (1998): How to Substitute in order to Sustain: Knowledge Driven Growth under Environmental Restrictions, Environment and Development Economics, 3, 861-893.

[9] Brock, W.A. and M.S. Taylor (2004): Economic Growth and the Environment: A Review of Theory and Empirics, forthcoming in the Handbook of Economic Growth, S. Durlauf and P. Aghion eds., North Holland.

[10] Dasgupta, P.S. and G.M. Heal (1974): The Optimal Depletion of Exhaustible Resources, Review of Economic Studies, 41, 3-28.

[11] Dasgupta, P.S. and G.M. Heal (1979): Economic Theory and Exhaustible Resources, Cambridge University Press.

[12] Gelb, A.H. (1988): Windfall Gains: Blessing or Curse? Oxford University Press, New York.

[13] Glasure, Y.U. and A-R. Lee (1998): Cointegration, error-correction, and the relationship between GDP and energy: The case of South Korea and Singapore, Resources and Energy Economics, 20/1:17-25.

[14] Grimaud A. and L. Rougé (2003): Non-renewable Resources and Growth with Vertical Innovations: Optimum, Equilibrium and Economic Policies, Journal of Environmental Economics and Management, 45, 433-453.

[15] Grossman, G.M. and E. Helpman (1991): Innovation and Growth in the Global Economy, MIT Press, Cambridge MA.

[16] Groth, C. and P. Schou (2002): Can Non-renewable Resources Alleviate the Knife-edge Character of Endogenous Growth?, Oxford Economic Papers, 54/3, 386-411.

[17] Gylfason, T. (2004): Natural Resources and Economic Growth: From Dependence to Diversification, CEPR Discussion Papers 4804.

[18] Gylfason, T. (2001): Natural resources, education, and economic development, European Economic Review, 45/4-6, 847-859.

[19] Gylfason, T., T. Herbertsson and G. Zoega (1999): A Mixed Blessing: Natural Resources and Economic Growth, Macroeconomic Dynamics, 3/2, 204-25.

[20] Heston, A., R. Summers and B. Aten (2006): Penn World Table Version 6.2, Center for International Comparisons at the University of Pennsylvania (CICUP), September 2006.

[21] International Energy Agency (2005): http://data.iea.org/stats/eng/main.html.

[22] Levine, R. and D. Renelt (1992): A Sensitivity Analysis of Cross-Country Growth Regressions, American Economic Review, 82/4, 942-963.

[23] López, R.E., G. Anriquez, and S. Gulati (2005): Sustainability with Unbalanced Growth: The Role of Structural Change, Working Paper, University of Maryland.

[24] Mehlum, H., K. Moene and R. Torvik (2006): Institutions and the Resource Curse, Economic Journal, 116, 1-20.

[25] Miketa A. and P. Mulder (2005): Energy Productivity across Developed and Developing Countries in 10 Manufacturing Sectors: Patterns of Growth and Convergence, Energy Economics, 27, 429-453.

[26] Mulder, P. and H.L.F. de Groot (2005): Sectoral Energy- and Labour-Productivity Convergence, Environmental and Resource Economics, forthcoming.

[27] Norrbin, S.C. and L. Bors (2004): How Robust is the Natural Resource Curse? Working Paper, Florida State University.

[28] Papyrakis, E. and R. Gerlagh (2003): Natural Resources: A Blessing or a Curse? Nota di Lavoro 8.2003, Fondazione Eni Enrico Mattei.

[29] Papyrakis, E. and R. Gerlagh (2006): Resource-Abundance and Economic Growth in the U.S.", European Economic Review, forthcoming.

[30] Popp, D. (2002): Induced Innovation and Energy Prices, American Economic Review, 92/1,160-180.

[31] Romer, P.M. (1990): Endogenous Technical Change, Journal of Political Economy, 98, S71-S102.

[32] Sachs, J. and A. Warner (2001): The Curse of Natural Resources, European Economic Review, 45, 827-838.

[33] Scholz, C.M. and G. Ziemes (1999): Exhaustible Resources, Monopolistic Competition, and Endogenous Growth, Environmental and Resource Economics, 13, 169-185.

[34] Solow, R.M. (1974): Intergenerational Equity and Exhaustible Resources, Review of Economic Studies, 41, 29-45.

[35] Stern, D.I. (2000): A multivariate cointegration analysis of the role of energy in the US macroeconomy, Energy Economics, 22/2, 267-283.

[36] Stern,-D.I and C.J. Cleveland (2004): Energy and Economic Growth, Rensselaer Polytechnic Institute, Working Papers in Economics.

[37] Stiglitz, J.E. (1974): Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths, Review of Economic Studies, 41, 123-137.

[38] Tavares, J. and R. Wacziarg (2001): How democracy affects growth, European Economic Review, 45/8, 1341-1378.

[39] Temple, J. (1999): The New Growth Evidence, Journal of Economic Literature, XXXVII, 112-156.

[40] Ugur S. and R. Sarib (2003): Energy consumption and GDP: causality relationship in G-7 countries and emerging markets, Energy Economics, 25/1, 33-37.

[41] Wacziarg, R. (2001): Measuring the Dynamic Gains from Trade, World Bank Economic Review, 15/3, 393-429.

[42] World Development Indicators (2005): http://publications.worldbank.org/WDI/.

[43] Xepapadeas, A. (2006): Economic Growth and the Environment, in: K.-G. Mäler and J. Vincent (Eds.), Handbook of Environmental Economics, Elsevier Science, Amsterdam.

6 Appendix

The appendix contains short proofs of the statements in the main text. Mathematical details are provided in a mathematical supplement to the paper.

6.1 Cost of K

θs denote cost shares, e.g. $\theta_{EX} = a_{EX} \cdot p_E/p_X$ etc. Then, $\hat{c}_K$ is calculated as:

$$\begin{aligned}\hat{c}_K &= \theta_{PK}(\theta_{LP}\hat{w} + \theta_{EP}\hat{p}_E) + \theta_{NK}(\theta_{HN} \cdot (\theta_{LH}\hat{w} + \theta_{EH}\hat{p}_E) + \theta_{BN}(\theta_{LB}\hat{w} + \theta_{EB}\hat{p}_E)) \\ &= \theta_{LK} \cdot \hat{w} + \theta_{EK} \cdot \hat{p}_E. \qquad (23)\end{aligned}$$

with $\theta_{LK} = \theta_{PK}\theta_{LP} + \theta_{NK}\theta_{HN}\theta_{LH} + \theta_{NK}\theta_{BN}\theta_{LB} > 0$ and $\theta_{EK} = \theta_{PK}\theta_{EP} + \theta_{NK}\theta_{HN}\theta_{EH} + \theta_{NK}\theta_{BN}\theta_{EB} > 0$.

6.2 Proof of lemma 1

Differentiate (9) and (10) to obtain:

$$\hat{E} = \lambda_{EX}(\hat{a}_{EX} + \hat{X}) + \lambda_{EK}(\hat{a}_{EK} + \hat{g}_K) \qquad (24)$$

$$0 = \lambda_{LX}(\hat{a}_{LX} + \hat{X}) + \lambda_{LK}(\hat{a}_{LK} + \hat{g}_K) \qquad (25)$$

$$0 = \hat{c}_K + (\frac{g_K}{g_K + \rho})\hat{g}_K \qquad (26)$$

We use $\tilde{\rho} = (\rho + g_K)/g_K > 1$ in (26) as well as $\hat{a}_{Eq} = \theta_{Lq}\sigma_q(\hat{w} - \hat{p}_E)$ and $\hat{a}_{Lq} = -\theta_{Eq}\sigma_q(\hat{w} - \hat{p}_E)$ for $q = X, K$ in (24) and (25). By solving (26) for $\hat{g}_K$ and (25) for $\hat{w}$ and inserting into (24) we obtain, see the mathematical supplement:

$$\hat{E} = -\{\frac{b_1 b_3 \sigma_X^2 + \bar{b}\sigma_X(\sigma_K - \tilde{\rho}) + b_2 b_4(\sigma_K - \tilde{\rho})^2}{b_5} + \tilde{b}\}\hat{p}_E + \Gamma \cdot (\hat{Y} - \gamma)$$

with:

$$\begin{aligned}
b_1 &= \lambda_{EX}\theta_{LX} > 0,\ b_2 = \lambda_{EK}\theta_{LK} > 0,\ b_3 = \lambda_{LX}\theta_{EX} > 0 \\
b_4 &= \lambda_{LK}\theta_{EK} > 0,\ b_5 = \lambda_{LX}\theta_{EX}\sigma_X + \lambda_{LK}(\theta_{EK}\sigma_K + \theta_{LK}\tilde{\rho}) > 0 \\
\tilde{b} &= \lambda_{EX}\theta_{LX}\sigma_X + \lambda_{EK}\theta_{LK}\sigma_K + \lambda_{EK}\theta_{EK}\tilde{\rho} > 0 \\
\bar{b} &= b_1 b_4 + b_2 b_3 > 0,\ \gamma = g_A + \frac{1-\beta}{\beta} g_K \geq 0 \\
\Gamma &= \frac{\lambda_{LX}}{\lambda_{LX}\theta_{EX}\sigma_X + \lambda_{LK}(\theta_{EK}\sigma_K + \theta_{LK}\tilde{\rho})} + \lambda_{EX} > 0
\end{aligned}$$

which reveals that $\hat{p}_E$ has an unambiguously negative impact on $\hat{E}$ when $\sigma_K > \tilde{\rho}$ and $\sigma_X = \sigma_K = 0$. In the short run, wages are not flexible; then, the impact of energy prices on energy use is unambiguous according to $\hat{E} = -\tilde{b} \cdot \hat{p}_E$.

6.3 Proof of lemma 2

To evaluate $\hat{s}_i$ we write:

$$\hat{s}_i = \hat{k}_i - \hat{Y} = \hat{\theta}_{ki} - \hat{p}_{ki} + \hat{p}_X - \gamma$$

We use the optimum conditions in the capital sector, i.e. $\theta_{PK}/\theta_{NK} = [p_P/p_N]^{1-\sigma_{\tilde{K}}}$ and $\theta_{HN}/\theta_{BN} = [p_H/p_B]^{1-\sigma_N}$ to derive the cost shares θ for the different capital types i where $\sigma_{\tilde{K}}$ and σ_N are the elasticities of substitution between physical and non-physical capital and between human and knowledge capital, respectively. Moreover, we express $\hat{\theta}_{ki}$ as well as $\hat{p}_X$ and $\hat{p}_{ki}$ in terms of input prices $\hat{w}$ and $\hat{p}_E$, which yields for capital type P, see the mathematical supplement:

$$\begin{aligned}
\hat{s}_P + \gamma &= \theta_{NK}(1 - \sigma_{\tilde{K}})(\hat{p}_P - \hat{p}_N) + (\theta_{LX} - \theta_{LP})\hat{w} + (\theta_{EX} - \theta_{EP})\,\hat{p}_E \\
&= [\theta_{NK}(1 - \sigma_{\tilde{K}})(\theta_{EN} - \theta_{EP}) + (\theta_{EP} - \theta_{EX})]\,(\hat{w} - \hat{p}_E)
\end{aligned}$$

where we have used $\theta_{LX} = 1 - \theta_{EX}$, $\theta_{LP} = 1 - \theta_{EP}$ etc. Similarly, we obtain for H and B:

$$\hat{s}_H + \gamma = \left[\theta_{BN}(1-\sigma_N)(\theta_{EB}-\theta_{EH}) + (\theta_{EH}-\theta_{EX})\right](\hat{w}-\hat{p}_E)$$
$$\hat{s}_B + \gamma = \left[\theta_{HN}(1-\sigma_N)(\theta_{EH}-\theta_{EB}) + (\theta_{EB}-\theta_{EX})\right](\hat{w}-\hat{p}_E)$$

To find $\hat{w}-\hat{p}_E$ we use (24), (25), (26), and $\hat{X} = -\theta_{LX}\hat{w} - \theta_{EX}\hat{p}_E$ to derive that $\hat{w}-\hat{p}_E = \frac{\nu}{\Delta}\hat{E}$, see the mathematical supplement. As we have $\Delta, \nu < 0$, it follows that a decrease in E causes an unambiguous decrease of the wage/energy price ratio. Inserting for the different capital types yields (13), (14), and (15) of the main text.

6.4 Proof of Lemma 3

Logarithmic differentiating $g_K = \dot{K}/K = f(k_P, k_N)$ with $k_N = \tilde{f}(k_H, k_B)$ yields:

$$\hat{g}_K = \theta_{PK}\hat{k}_P + \theta_{NK}\theta_{HN}\hat{k}_{HN} + \theta_{NK}\theta_{BN}\hat{k}_B$$

Inserting $\hat{k}_i = \hat{s}_i + g_Y$ gives

$$\hat{g}_K = \theta_{PK}\hat{s}_P + \theta_{NK}\theta_{HN}\hat{s}_H + \theta_{NK}\theta_{BN}\hat{s}_B + g_Y$$
$$\ln g_K = \theta_{PK}\ln s_P + \theta_{NK}\theta_{HN}\ln s_H + \theta_{NK}\theta_{BN}\ln s_B + \ln Y$$

Inserting into the growth equation (11) yields:

$$g_Y = \ln\alpha + \theta_{PK}\ln s_P + \theta_{NK}\theta_{HN}\ln s_H + \theta_{NK}\theta_{BN}\ln s_B + \ln Y - \mu\ln Y_0 \qquad (27)$$