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Working Paper 06/47
September 2006

Economics Working Paper Series

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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

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September 2006

Abstract

The paper first develops a theoretical model with different sectors, each providing a mechanism for capital accumulation and a channel through which energy prices affect growth. The conditions for a crowding out of sectoral capital accumulation by intensive energy use are derived. In the empirical part, estimations using different channels for a sample of 44 developed countries with five-year average panel data over the period 1975-1999 are presented. It is shown that, for a large variety of specifications, rising energy prices are not a threat to aggregate economic development, they can even be positive for long-run growth.

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

JEL Classification: Q43, O47, Q56, O41

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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. 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 multi-sector economy accumulating different productive stocks. In each sector, the primary input labour can be used either to produce a specific capital good, like physical, knowledge, human, and financial capital, or intermediate inputs for consumer goods. Learning effects support accumulation. Energy is the second primary input in intermediate goods production. In this way, the different channels through which higher energy prices may hinder or foster accumulation can be analysed separately. A second 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 the reallocation of labour takes place. The focus of this study is on the modelling of the dynamic interactions between the inputs, not on institutional or governmental behaviour explaining energy supply. Therefore, the model takes energy prices as given. The disaggregation of the economy is introduced to best capture the different crowding-out mechanisms. 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 the long-run growth process.

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 cross-country samples. The selected countries are quite similar 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. Following the 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 on energy demand, the effect of energy use on capital accumulation, and, finally, the effect of capital accumulation on growth.

Different types of capital are considered in the estimations. After performing the single-equation estimations we test a simultaneous system of the whole causal chain from energy to growth, using a special three-stage least squares procedure. This is done in order to capture the various interdependencies between the equations, especially between different types of capital investments. 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 will conclude from the regressions that, in the longer 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 many cases while energy is neutral with respect to growth in the remaining areas.

The present paper is related to 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), Norrbin and Bors (2004) and Mehlum, Moene and Torvik (2006). Empirical results on energy efficiency during growth are presented in Miketa and Mulder (2005) and Mulder and de Groot (2005). 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 empirical estimations are presented. Section 5 concludes.

2 The model

2.1 Aggregate economy

We present a stylised economy which includes the required elements of dynamic theory. The model economy consists of m different sectors producing consumer goods Y_i $(i = 1, ..., m)$ which are assembled from intermediate goods varieties x_{ij} $(j = 1, ..., k_i)$. In the equilibrium with symmetric intermediates, the output of sector i is determined by:

$$Y_i = \left[\int_0^{k_i} x_{ij}^{\beta} dj \right]^{\frac{1}{\beta}} = k_i^{\frac{1-\beta}{\beta}} X_i \tag{1}$$

with $0 < \beta < 1$ and $X_i = k_i \cdot x_i$. (1) postulates gains from diversification when assembling sectoral input. Aggregate consumption C is assumed to be given according to a Cobb-Douglas specification:

$$C = \prod_{i=1}^{m} Y_i^{\gamma_i} = \prod_{i=1}^{m} \left[k_i^{\frac{1-\beta}{\beta}} X_i \right]^{\gamma_i} \tag{2}$$

γ reflects the sectoral contribution to aggregate consumption. Intermediate input in sector i is manufactured with labour L and energy E, the primary inputs, under the assumption of a CES production technology; this yields for sector i:

$$X_i = \left[\lambda L_{X_i}^{(\sigma_i - 1)/\sigma_i} + (1 - \lambda) E_i^{(\sigma_i - 1)/\sigma_i} \right]^{\sigma_i/(\sigma_i - 1)} \tag{3}$$

with σ_i representing the sector-specific elasticity of input substitution. In a growing economy, new goods varieties are introduced in each sector. An additional intermediates variety needs an additional capital unit for production where sector i uses capital of type i; k_1, k_2,..., k_m represent the different types of capital in sectors $1, 2, ..., m$. In one of the sectors, capital is assumed to be knowledge capital and the capital unit needed to produce a new variety is a knowledge unity (usually called a "product design"), as in Romer (1990) and Grossman and Helpman (1991). Similarly, in another sector capital is assumed to represent physical capital; then by assumption each new variety needs one additional unit of (differentiated) physical capital for production. This applies for a new component manufactured with a new type of an industrial robot, for example. Similarly, there are sectors where additional units of other capital types like human and financial capital are needed to produce new intermediate inputs. In this way, each sector provides a channel through which energy has an impact on a type of capital accumulation. The possibility that labour can substitute for energy differs between sectors. As a consequence, a resource price increase has different effects on the various capital stocks which, in turn, have a capital specific effect on aggregate growth.

The accumulation of the different capital types is associated with sector-specific learning-by-doing which means that capital investment raises the amount of sectoral public knowledge. With the assumption of proportional knowledge spillovers, k_i not only denotes the number of capital goods and the number of intermediate goods (and intermediate firms), but also the size of the knowledge stock in sector i. Sectoral knowledge stocks are a free input for the build-up of new capital goods in the same sector, according to:

$$\dot{k}_i = \frac{1}{a_i} L_{k_i} \cdot k_i^{\eta} \tag{4}$$

with a and η being the Leontief input factor for labour and the intensity of spillovers in capital accumulation, respectively, with $0 < \eta \leq 1$. In the theoretical part we assume for simplicity $\eta = 1$ so that the capital growth rate g_{ki} becomes:

$$g_{ki} \equiv \frac{\dot{k}_i}{k_i} = \frac{1}{a_i} L_{k_i} \tag{5}$$

Labour is free to move within each sector but not between sectors, which reflects that specific skills are needed in sectors which are characterised by a specific capital type. Population is constant. Energy, which is the more homogeneous input, is mobile between the sectors. The energy price p_E is exogenous, as explained above.

The equilibria on input markets are ($\forall i$):

$$L_i = L_{Xi} + L_{ki} = L_{Xi} + a_i \cdot g_{ki} \tag{6}$$

and

$$E = \sum_{i=1}^{m} E_i \tag{7}$$

With perfect competition in capital accumulation, the market value of a capital good p_{ki} equals the per-unit costs of capital production, which depend on the labour wage w_i and public knowledge k_i:

$$p_{ki} = (a_i w_i / k_i) \tag{8}$$

As no resources are used to assemble differentiated goods to final output, expenditures can be expressed in terms of C, Y_i or X_i. 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:

$$p_C C \equiv 1 \tag{9}$$

with p_C standing for the consumer price index. Households maximise a lifetime utility function:

$$U(t) = \int_0^\infty e^{-\rho(\tau - t)} \log C(\tau) d\tau \tag{10}$$

subject to the budget constraint:

$$\dot{V} = rN + wL - p_C C + \tau \tag{11}$$

where V is household wealth, r the interest rate, $N = \sum N_i = \sum k_i p_{ki}$ are asset holdings, and τ lump-sum transfers from the govenrment. Households' optimisation excludes energy stocks, which are assumed to belong to the government, for simplicity. Profits from energy production are transferred to households in a lump-sum fashion.

The transversality conditions 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 (9) 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 (9). 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.

The market form in intermediates production is monopolistic competition. The mark-up over marginal costs for the optimal price of an intermediate good is $1/\beta$ ($\forall i$), so that, together with (2) and (9), we get the per-period profit flow to the holder of a capital unit π in sector i:

$$\pi_i = \gamma_i (1 - \beta)/k_i \tag{12}$$

On capital markets, the return on capital investments (consisting of the direct profit flow and the change in value of the capital unit) is equal to the return on a riskless bond investment of the same size p_{ki} (with interest rate $r = \rho$):

$$\pi_i + \dot{p}_{ki} = \rho \cdot p_{ki} \tag{13}$$

2.2 Balanced growth

On a balanced growth path, all variables are assumed to grow at a constant (possibly zero) rate; wages and energy prices are constant. Totally differentiating (2) yields for consumption growth:

$$g_C = \sum_{i=1}^{m} \gamma_i \cdot g_{Yi} = \sum_{i=1}^{m} \gamma_i \cdot \left[(\frac{1-\beta}{\beta}) \cdot g_{ki} + g_{Xi} \right] \tag{14}$$

where in general we use the notation that g_h is the growth rate of variable h. The labour input in the various accumulation activities remains constant. Observing (3) we then get for balanced growth:

$$g_{Xi} = 0 \tag{15}$$

so that consumption growth is a weighted average of sectoral capital accumulation rates, according to:

$$g_C = (\frac{1-\beta}{\beta}) \sum_{i=1}^{m} \gamma_i \cdot g_{ki} \tag{16}$$

The capital growth rate for sector i, g_{ki}, is given by (5) which means that it increases with labour productivity $1/a_i$ and the labour input in the accumulation process L_{ki}. To determine L_{ki} we define the labour share in intermediates production as $\theta_i = w_i \cdot L_{Xi} / (p_{Xi} \cdot X_i) = w_i \cdot L_{Xi}/\gamma_i$ and write (6) as:

$$g_{ki} = \frac{1}{a_i} \left(L_i - \frac{\gamma_i \theta_i}{w_i} \right) \tag{17}$$

Using (8), (12) and (13) we can insert for the labour wage and obtain, $\forall i$:

$$g_{ki} = \frac{1}{1 + \frac{\theta_i}{1-\beta}} \left(\frac{L_i}{a_i} - \frac{\theta_i}{1-\beta} \rho \right) \tag{18}$$

Capital accumulation in sector i is the higher, the larger is the sectoral labour supply, the higher the productivity of labour in capital production, the larger the gains from diversification and the lower the discount rate. Moreover, the growth rate increases with a decreasing labour share θ_i in intermediates production, which is equivalent to a rising energy share $1 - \theta_i$. Inserting (18) into (14) yields for the overall economy:

$$g_C = \sum_{i=1}^{m} \gamma_i \cdot \left[\frac{(1-\beta)/\beta}{1 + (\theta_i/(1-\beta))} \left(\frac{L_i}{a_i} - \frac{\theta_i}{1-\beta} \rho \right) \right] \tag{19}$$

which says that consumption growth depends on the weights γ, the sectoral labour supplies L_i and productivities a_i as well as on the labour shares θ_i (the energy shares $1 - \theta_i$). Energy prices have an impact on the consumption growth rate via θ_i (or $1 - \theta_i$), to which we turn next. We will also show that θ_i is closely linked to the (sectoral) investment share which will be used for empirical estimations.

2.3 Impact of energy

According to (19), a low labour share (a high energy share) in intermediates production is favourable for steady state consumption growth. In every sector, profit maximisation of intermediate goods producers yields, taking (3) and assuming $\lambda = 0.5$ for simplicity, $\forall i$:

$$\theta_i = (1 - \theta_i) \left(\frac{E_i}{L_{Xi}} \right)^{\frac{1-\sigma_i}{\sigma_i}} \tag{20}$$

so that we get for percentage changes:

$$\hat{\theta}_i = (1 - \theta_i) \left[(1 - \sigma_i) / \sigma_i \right] \left(\hat{E}_i - \hat{L}_{Xi} \right) \tag{21}$$

with hats denoting growth rates. In the same way, we obtain for the impact of relative input prices on quantities:

$$\frac{E_i}{L_{Xi}} = \left(\frac{p_E}{w_i} \right)^{-\sigma_i} \tag{22}$$

where p_E is the (predetermined) energy price. Totally differentiating (22) gives:

$$\hat{E}_i - \hat{L}_{Xi} = -\sigma_i \cdot (\hat{p}_E - \hat{w}_i) \tag{23}$$

Every change of energy prices relative to wages ($\hat{p}_E - \hat{w}_i \neq 0$) means that the economy shifts to a new (balanced) growth path. The effect on the growth rate of the economy hinges on the size of the sector-specific elasticity of substitution σ_i. According to (23), a high elasticity σ_i means a large reaction of input quantities; the direction of the effect is given. From (21) we see that the impact of $\hat{E}_i - \hat{L}_{Xi}$ on

θ_i (and by this on growth through (18) and (19)) can be either positive or negative, depending on σ_i. Provided that in sector i substitution is poor ($\sigma_i < 1$), a relative increase of the energy quantity ($\hat{E}_i > \hat{L}_{Xi}$) or a decrease of the energy price ($\hat{w}_i - \hat{p}_E > 0$) brings about an increase in θ_i and a decrease in the sectoral capital growth rate; the opposite happens when substitution possibilities are good ($\sigma_i > 1$). This important result is somewhat unfamiliar in a neo-classical framework, but fits with multi-sector models of new growth theory, see e.g. Bretschger (1998). A low elasticity of input substitution promotes the reallocation of labour towards capital accumulation after energy price increases, which is favourable for growth.

The analysis so far applies to the long run with clearing labour markets. For the short run it is conceivable to assume that labour does not move between intermediates and capital goods production in the different sectors. Then we obtain g_{ki} as in (18), but for consumption growth we have to add a term Δ on the rhs of (16) with:

$$\Delta = \sum_{i=1}^{m} \gamma_i \cdot (1 - \theta_i) g_{E_i} \tag{24}$$

It can be seen from (24) that (in the short run) consumption growth is reduced with $g_{E_i} < 0$ which is consistent with the experience of the 1970s and 1990s. The lack of sectoral adjustment is the reason why the short-run impact of decreasing energy input is unambiguously negative in this model.

2.4 Estimation equations

In the long run, the aggregate effect of energy price changes is given by the three relations (23), (21) and (19), which we use for empirical estimations in the following way. First, following (23) we look at the impact of energy prices on energy use. Second, from (21) we scrutinise the impact of energy input on the different kinds of capital accumulation, which will provide information about the different crowding-out effects. For this purpose, we note that in each sector the share of labour used in the consumption sector θ_i can with (6) be expressed as $\theta_i = w_i(L_i - L_{ki})/\gamma_i$, while by (5) the investment rate s_i (defined as sectoral investment divided by consumer goods output plus investment) is given by $s_i = [1 + \gamma_i/w_i \cdot L_{ki}]^{-1}$. As both θ_i and s_i unambiguously depend on the same two variables L_{ki} and w_i (note that L_i and γ_i are constant) we can use the statistically available s_i instead of θ_i in the estimations below, with a high s_i being favourable for growth (as expected). Third, according to (19) we estimate a growth equation including the different types of capital (or capital accumulation). Here we note from (4) that initial income y_0 is a determinant of growth as soon as we have $\eta < 1$, which we assume in the empirical part. In all equations, we add appropriate control variables (including the income level) and error terms, as usual. Note that the variables from the theoretical model not explicitly included are represented by control variables below. We then arrive at a set of three estimation equations which read:

$$E_i = \alpha_0 \cdot const + \alpha_1 \cdot p_E + \alpha_2 \cdot y_0 + \alpha_3 \cdot \vec{Z}_E + \xi_E \tag{25}$$

$$s_i = \delta_0 \cdot const + \delta_1 \cdot E_i + \delta_2 \cdot y_0 + \delta_3 \cdot \vec{Z}_s + \delta_4 \cdot \xi_s. \tag{26}$$

$$g = \mu_0 \cdot const + \sum_i \mu_{1i} \cdot s_i + \mu_2 \cdot y_0 + \mu_3 \cdot \vec{Z}_g + \xi_g \tag{27}$$

where $\vec{Z}$ are vectors of control variables and ξ denote the error terms. For (25) and (26), non-linear relationships are also tested. The important parameters are α_1, δ_1, and μ_{1i}.We expect α_1 to be negative. The sign of δ_1 reveals the size of σ_i; provided that we have $\sigma_i < 1$, δ_1 becomes negative. Finally, the different μ_{1i} are predicted to be positive, exhibiting the growth effects of the different capital types.

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 especially to be 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 LDCs 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 rather similar factor endowments and institutional background, using appropriate instruments and adopting a simultaneous estimation approach we aim to reduce these econometric problems as far as possible.

3.2 Estimation strategy

In the following section, we first perform single-equation estimations with appropriate instruments. Each structural relationship is estimated for all time periods jointly using three-stage least squares. This applies for the energy price impact (25), the channel equations (26) and the growth equation (27). Then, the system consisting of equations (26) and (27) 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 restrictions which appear to be (potentially) important in this context. 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. The price equations (25) are not included in this system because price data are available for a much smaller set of countries compared to energy quantities (76 vs. 242 observations). As in Tavares and Wacziarg (2001) we restrict all non-contemporary coefficients to zero.

By using a sufficient number of exogenous variables and instruments we aim at reducing the scope for omitted variable bias. As separate instruments we use economic, geographic, and demographic variables. Specifically, we introduce the square of the log of initial income, the average distance to trade partners, the land area, the age dependency ratio, the share of arable land, the log of population, and life expectancy.

3.3 The data

We collected data for 44 countries, which are Australia, Austria, Belgium, Brazil, Canada, China, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Great Britain, Hungary, India, Indonesia, Ireland, Italy, Japan, Kazakhstan, Korea, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russia, Slovak Republic, Slovenia, Estonia, South Africa, Sweden, Switzerland, Thailand, Turkey, USA, and Venezuela. This is the country sample for which the International Energy Agency (IEA) provides energy price data. In several equations, however, the less or more recently developed economies (in particular China, Czech Republic, Hungary, India, Indonesia, Kazakhstan, Latvia, Lithuania, Malta, Poland, Romania, Russia, Slovak Republic, Slovenia, Estonia and South Africa) could not be fully included because data are not complete. Thus, automatically, more importance is attached to the high developed countries which is in line with the intended focus of this study. Based on the prices of single energy sources and the expenditure shares for the different sources, we calculate an average energy price. The five-year periods are 1975-79, 1980-84, 1985-89, 1990-94 and 1995-99. 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 6.1
ci	average investment share	PWT 6.1
logingdp	log of initial GDP per capita	PWT 6.1
popgro	population growth	PWT 6.1
enusecap	energy use per capita (in KGOE)	WDI (2005)
open	exports+imports/GDP	PWT 6.1
schooling	initial years of average schooling	Barro/Lee (2000)
schoolend	end years of average schooling	Barro/Lee (2000)
enprice	energy price (index)	own calculations
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)
area	land area	WDI (2005)
dist	average distance to trading partners	Barro/Lee (1994)
liqliab	financial capital (M3/GDP)	WDI (2005)
agriland	share of land area that is arable	WDI (2005)
lifeexp	life expectancy	WDI (2005)
agedep	ratio of dependents; people <15 + >64/others	WDI (2005)
sqlogingdp	square of log of initial GDP per capita	PWT 6.1
size	initial income · population	PWT 6.1
logpop	log of population	PWT 6.1
hitechex	high-tech exports (% of manuf. exports)	WDI (2005)

The data sources are described in table 1. WDI refers to the World Development Indicators of the World Bank and PWT 6.1 to the Penn Word Table from Heston, Summers and Aten (2002), 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	188	0.02	0.03	-0.13	0.21
ci	232	22.3	6.23	7.08	40.9
logingdp	227	9.21	1.41	-4.07	10.70
popgro	245	0.76	0.81	-1.27	3.49
enusecap	242	3301.49	2028.63	338.24	10802.58
open	234	68.42	42.61	9.3	285.6
schooling	259	7.57	2.76	2.07	20.3
enprice	76	130.4	66.7	44.1	399.4
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
area	198	1526.6	2840.7	0.5	9976
dist	166	4.3	2.7	1.27	11.5
liqliab	177	62.9	40.6	0.000	190.5
agriland	235	42.1	21.8	0	83.0
lifeexp	263	57.6	22.7	10.5	81.5
agedep	264	0.54	0.10	0.40	1.0
sqlogingdp	228	87.4	13.2	46.8	114.3
size	228	0.66	1.20	0.004	9.60
logpop	249	16.8	1.78	12.7	20.9
hitechex	154	13.0	15.0	0.23	139.1

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.

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 three equations derived from theory are now used to identify empirically the different channels in the energy-capital-growth relationships. The results are presented in the three steps as explained in the previous section. In the first step we aim at confirming the negative impact of energy prices *enprice* on energy use per capita *enusecap* according to (25). The results are presented in table 4. To take care of the income effect we include the (logarithm of) initial income *logingdp* in all specifications and add the control variables $area, agriland$, and *open* subsequently. The last specification includes all the remaining instruments $(sqlogingdp, dist, agedep, lifeexp)$. As can be seen from the table, the negative impact of energy prices on energy use is confirmed throughout. Based on column (4) of the table, the implied elasticity at the mean is -0.21. Land area and openness are found to have a positive impact on energy use. A non-linear specification of the equation does not alter the result.

Tables 5-8 present the single-equation results of our channel equations, giving the effects of energy use on the capital build-up. Table 5 refers to the important variable for the investment share *ci* and *enusecap* as in table 4. To check the robustness of the energy impact, we adopt different specifications. In the last column (5), we use the additional instruments $(sqlogingdp, area, agedep, agriland, logpop)$ and all country dummy variables (with the exception of the US as the reference country to avoid perfect collinearity), which are not reported in the table. Again, *logingdp* controls for the initial income; several other control variables are added in the equations (2) to (5). As a general result it turns out that the effect of energy use on investment is negative and significant under all specifications. The size of the impact depends on the specification of the equation, but we observe a crowding out of physical capital accumulation by increasing energy use in all equations.

In table 6, the effects of energy use on human capital formation are shown. As country dummies prove to be important in this case, they are included in all specifications; the same holds true for the instruments $sqlogingdp, area, agedep$, *agriland*, and *logpop*. Similar to physical capital, we find a negative impact of energy use on human capital (at the end of the period) throughout. While the first two specifications (1) and (2) show a relatively small estimated coefficient, the richer specifications (3) - (5) exhibit higher values with similar standard errors so that the coefficient becomes significant, in the last column (5) even highly significant. The income effect is significant and positive; note that the negative impact of the direct estimate in (4) and (5) is due to the inclusion of the squared variable, which is positive. According to the result, life expectancy turns out to be an important determinant for schooling decisions.

Table 4: Estimation results for energy use
Endogenous variable: enusecap; estimation method 3 SLS

Variable	(1)	(2)	(3)	(4)	(5)
enusecap					
const	-8957.87***	-9442.61***	-8021.01***	-8390.89***	-9958.37***
	(3662.50)	(3705.86)	(2676.44)	(2502.26)	(3825.70)
enprice	-5.23**	-5.10**	-5.05***	-5.40***	-9.07***
	(2.26)	(2.26)	(1.64)	(1.53)	(1.97)
logingdp	1373.25***	1418.32***	1311.53***	1266.40***	1419.71***
	(361.03)	(364.68)	(262.03)	(245.13)	(366.73)
area $^{\perp}$		0.07	0.12*	0.17***	0.94**
		(0.090)	(0.07)	(0.06)	(0.43)
agriland			-11.35***	-6.87*	-4.28
			(3.76)	(3.80)	(3.99)
open				8.33***	10.30***
				(2.68)	(3.13)
# of obs.	70	70	66	66	59
R^2	0.42	0.42	0.60	0.66	0.69
χ^2	50.42	51.37	100.96	125.44	132.18

Standard errors in parentheses.
* Significant at the 10 % level
** Significant at the 5 % level
*** Significant at the 1 % level

$^{\perp}$ measured in 1000 units

Table 7 treats the effects of energy on financial capital in a similar way. (6) uses the (remaining) instruments $area, lifeexp, agriland$,and $logpop$. The sign of the estimated parameter for energy is negative and highly significant; the crowding out seems to be pervasive. The income effect is positive or positive after a certain threshold is reached (observing the positive coefficient for the squared variable). Regarding knowledge capital, data are difficult to obtain for this set of countries. Popp (2002) uses U.S. patent data to estimate the effect of energy prices on energy-efficient innovations; he finds that both energy prices and the quality of existing knowledge have strongly significant positive effects on innovation. Thus crowding out seems also to be present for knowledge capital, at least in the world leading economy. The best measure we could find for a reasonable number of countries is high-technology exports (as a share of manufactured exports) *hitechex*. The corresponding results are presented in table 8. Instruments are included in all specifications. As seen from the table, energy use has a negative impact on high-tech exports, but the effect is not always significant. The selection of estimation results is representative for all possible specifications. The inclusion of *schooling* increases the standard error of the energy coefficient significantly. The size of the economy is positive and significant, revealing scale effects for high-tech exports. We interpret these results as an indication that the findings of Popp (2002) are likely to be similar in an international comparison. However, as the results are not very robust and the endogenous variable does not directly measure knowledge capital we choose to disregard this channel in the simultaneous estimations below. In general, non-linear specifications of the equations proved not to affect the main results as presented here.

The growth regressions linking the channel variables to per capita growth are shown in table 9. They closely follow the empirical growth literature. Initial income, the investment share and human capital have the expected effects on real per capita growth and are significant. Population growth is not significant in all estimations, but this does not contradict the model of this paper. Financial capital is found to have no significant effect on growth. This also holds true for the logarithm of this variable, which is often used for LDCs but seems to be less important for developed countries. Finally, openness has a positive effect on growth.

In the third step, we turn to the simultaneous estimation of a multi-equation system. This is the only way to consider the cross-equation restrictions in the energy-capital-growth relationship. We estimate a system containing the growth relation and the channel equations for physical, human, and financial capital, using three-stage least squares. The used specifications are very similar to the tables 5-9. The results are reported in table 10. The instruments *sqlogingdp*, *area*, *lifeexp*, *agedep*, *agriland*, and *logpop* are used throughout. (5) additionally includes time dummies in the growth equation which are not reported in the table. In general, we observe that the most important results from the single-equation regressions are confirmed. Specifically, the impact of energy use on capital accumulation remains negative and significant, so that we find broad evidence for the crowding out of investment by abundant energy use. For all three channel equations, the estimations for *enusecap* are thus according to expectations. Somewhat surprisingly, *ci* looses significance in the growth regression, whereas the effect of *liqliab* is neutral, as before. On the other hand, the human capital variable turns out to be very stable, positive and significant for growth. Thus we conclude that human capital is the channel between energy and growth which survives all the tests made in this paper. The channel working through physical capital is also shown to be important in single-equation estimations; however, the (otherwise well-established) investment-growth link lacks significance in the simultaneous-equation approach. Finally, financial capital is affected by energy use, but its impact on growth cannot be confirmed for this set of developed countries.

Table 5: Estimation results for investment share
Endogenous variable: ci; estimation method 3 SLS

Variable	(1)	(2)	(3)	(4)	(5)
ci					
const	-16.78***	-1.58	9.18	6.05	0.27
	(6.61)	(10.76)	(12.17)	(12.57)	(13.71)
enusecap $^{\perp}$	-0.58**	-1.06***	-0.83*	-0.80*	-1.36***
	(0.28)	(0.44)	(0.45)	(0.45)	(0.56)
logingdp	4.40***	2.73**	1.65	2.02	4.42***
	(0.78)	(1.27)	(1.39)	(1.46)	(1.61)
schooling		0.46*	0.42	0.37	-0.80***
		(0.26)	(0.26)	(0.26)	(0.22)
popgro			-1.22*	-1.25*	-0.24
			(0.67)	(0.67)	(0.51)
lifeexp				-0.004	-0.06***
				(0.224)	(0.02)
# of obs.	222	138	138	137	129
R^2	0.16	0.07	0.10	0.10	0.80
χ^2	42.4	10.92	14.51	15.78	525.29

Standard errors in parentheses.
* Significant at the 10 % level
** Significant at the 5 % level
*** Significant at the 1 % level

$^{\perp}$ measured in 1000 units

Table 6: Estimation results for human capital
Endogenous variable: schoolend; estimation method 3SLS

Variable	(1)	(2)	(3)	(4)	(5)
schoolend					
const	-21.66***	-17.84***	-17.06***	31.54	61.56**
	(4.12)	(4.22)	(4.24)	(20.85)	(27.46)
enusecap$^{\perp}$	-0.12	-0.29	-0.31*	-0.48***	-0.78***
	(0.18)	(0.18)	(0.18)	(0.19)	(0.25)
logingdp	3.39***	3.03***	3.06***	-7.65*	-14.23***
	(0.47)	(0.48)	(0.48)	(4.52)	(5.94)
lifeexp		0.02***	0.01***	0.02***	0.03***
		(0.01)	(0.01)	(0.01)	(0.01)
ci			-0.03	-0.03	-0.001
			(0.03)	(0.03)	(0.03)
liqliab					0.005
					(0.01)
sqlogingdp				0.59***	0.95***
				(0.25)	(0.33)
# of obs.	157	157	157	157	110
R^2	0.90	0.91	0.91	0.92	0.92
χ^2	1568.40	1661.23	1680.33	1746.55	1216.93

Standard errors in parentheses.

* Significant at the 10 % level

** Significant at the 5 % level

*** Significant at the 1 % level

$^{\perp}$ measured in 1000 units

Table 7: Estimation results for financial capital
Endogenous variable: liqliab; estimation method: 3 SLS

Variable	(1)	(2)	(3)	(4)	(5)	(6)
liqliab						
const	-244.64***	-201.66***	-391.69***	-339.13***	1638.61***	1655.81***
	(46.88)	(45.95)	(62.19)	(69.53)	(425.60)	(438.40)
enusecap $^{\perp}$	-7.20***	-5.80***	-7.50***	-7.39***	-10.82***	-10.52***
	(2.22)	(2.14)	(2.46)	(2.43)	(2.32)	(2.38)
logingdp	35.70***	26.55***	46.40***	43.94***	-405.24***	-412.22***
	(5.68)	(5.87)	(7.69)	(7.74)	(95.85)	(99.42)
ci		1.68***	1.97***	1.92***	1.91***	2.55***
		(0.41)	(0.47)	(0.46)	(0.42)	(0.46)
schooling			-0.42	-0.89	-2.04	-1.28
			(1.54)	(1.54)	(1.42)	(1.45)
agedep				-42.96	-42.73*	-29.29
				(26.62)	(24.16)	(25.01)
sqlogingdp					25.52***	25.72***
					(5.43)	(5.65)
# of obs.	164	164	103	103	103	94
R^2	0.23	0.30	0.47	0.49	0.58	0.61
χ^2	48.34	69.54	93.00	97.96	141.03	146.89

Standard errors in parentheses.
* Significant at the 10 % level
** Significant at the 5 % level
*** Significant at the 1 % level

$^{\perp}$ measured in 1000 units

Table 8: Estimation results for knowledge capital
Endogenous variable: hitechex; estimation method 3SLS

Variable	(1)	(2)	(3)	(4)	(5)
hitechex					
const	-37.95	-51.72*	-69.70***	-60.73	-69.32***
	(27.27)	(29.02)	(28.39)	(55.59)	(28.55)
enusecap $^{\perp}$	-1.33	-1.62	-2.58**	-2.20	-2.53**
	(1.14)	(1.15)	(1.14)	(2.36)	(1.20)
logingdp	5.94*	8.32**	10.56***	9.20	10.55***
	(3.21)	(3.66)	(3.58)	(6.69)	(3.59)
ci		-0.37	-0.48*	-0.64	-0.48*
		(0.28)	(0.28)	(0.47)	(0.27)
size			3.21***	3.20*	3.14***
			(9.60)	(1.74)	(1.10)
schooling				0.76	
				(1.20)	
open					-0.004
					(0.037)
# of obs.	134	134	134	66	134
R^2	0.03	0.04	0.11	0.11	0.11
χ^2	3.65	5.46	8.81	3.99	8.82

Standard errors in parentheses.

* Significant at the 10 % level

** Significant at the 5 % level

*** Significant at the 1 % level

$^{\perp}$ measured in 1000 units

Table 9: Estimation results for growth
Endogenous variable: growth; estimation method 3 SLS

Variable	(1)	(2)	(3)	(4)	(5)
growth					
const	0.09***	0.18***	0.19***	0.19***	0.19***
	(0.02)	(0.04)	(0.05)	(0.06)	(0.05)
logingdp	-0.013***	-0.021***	-0.022***	-0.023***	-0.02***
	(0.003)	(0.004)	(0.006)	(0.007)	(0.006)
ci $^{\perp}$	2.20***	1.40***	1.23***	1.14**	1.25***
	(0.37)	(0.33)	(0.50)	(0.51)	(0.45)
popgro $^{\perp}$	0.70	-5.11**	-6.10*	-5.05	-6.10*
	(2.61)	(2.45)	(3.17)	(3.43)	(3.17)
schooling $^{\perp}$		2.00***	2.24**	2.44*	2.22**
		(0.84)	(1.12)	(1.43)	(1.13)
liqliab $^{\perp}$			0.01	0.07	0.31 $^{\intercal}$
			(0.08)	(0.08)	(0.60)
open $^{\perp}$				0.15*	
				(0.09)	
# of obs.	181	141	93	87	92
R^2	0.20	0.24	0.21	0.26	0.22
χ^2	44.17	44.73	25.44	31.53	26.28

Standard errors in parentheses.
* Significant at the 10 % level
** Significant at the 5 % level
*** Significant at the 1 % level

$^{\perp}$ measured in 1000 units
$^{\intercal}$ log of liqliab

Table 10: Simultaneous estimation results for different channels and growth
Endogenous variables: growth, ci, schoolend, liqliab; estimation method 3SLS (IV-GLS)

Variable	(1)	(2)	(3)	(4)	(5)	(6)
growth						
const	0.19***	0.19***	0.20***	0.21***	0.22***	0.24***
	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)
logingdp ⊥	-20.59***	-20.88***	-21.86***	-22.50***	-23.36***	-26.32***
	(5.99)	(6.00)	(6.00)	(6.00)	(5.90)	(6.01)
popgro ⊥	-6.41**	-6.43**	-6.87**	-7.01**	-6.83**	-10.05***
	(3.19)	(3.18)	(3.18)	(3.19)	(3.13)	(3.37)
ci ⊥	0.68	0.69	0.64	0.40	0.31	0.56
	(0.59)	(0.59)	(0.59)	(0.59)	(0.59)	(0.58)
schooling ⊥	2.18**	2.27**	2.45**	2.45**	2.77***	2.50**
	(1.12)	(1.12)	(1.12)	(1.12)	(1.11)	(1.08)
liqliab ⊥	0.004	0.002	0.01	0.05	0.06	0.02
	(0.09)	(0.09)	(0.09)	(0.09)	(0.08)	(0.08)
size⊤						4.04***
						(1.69)
ci						
const	-17.00	-14.48	-1.32	1.87	1.85	2.56
	(11.47)	(12.09)	(13.20)	(13.50)	(13.50)	(13.50)
enusecap ⊥	-0.99***	-1.12***	-0.94**	-1.03**	-1.02**	-1.00**
	(0.42)	(0.47)	(0.47)	(0.47)	(0.47)	(0.47)
logingdp	4.74***	4.36***	3.00*	2.53	2.54	2.46
	(1.34)	(1.46)	(1.54)	(1.60)	(1.60)	(1.60)
schooling		0.19	0.26	0.23	0.21	0.23
		(0.30)	(0.29)	(0.29)	(0.29)	(0.29)
popgro			-1.45**	-1.31*	-1.34*	-1.31*
			(0.74)	(0.75)	(0.75)	(0.75)
lifeexp				0.03	0.03	0.03
				(0.03)	(0.03)	(0.03)

cont. next p.

Standard errors in parentheses.

* Significant at the 10 % level

** Significant at the 5 % level

*** Significant at the 1 % level

⊥ measured in 1000 units

Table 10 (cont.): Simultaneous estimation results
Endogenous variables: growth, ci, schooling, liqliab; estimation methods 3SLS (IV-GLS)

	(1)	(2)	(3)	(4)	(5)	(6)
schoolend						
const	-21.85***	-17.40***	-15.78***	20.56	31.01	16.56
	(6.15)	(6.08)	(6.80)	(34.54)	(33.39)	(34.50)
enusecap $^{\perp}$	-0.36	-0.80***	-1.16***	-1.18***	-1.15***	-1.16***
	(0.22)	(0.25)	(0.31)	(0.29)	(0.28)	(0.29)
logingdp	3.59***	3.25***	4.08***	-4.44	-7.01	-3.47
	(0.68)	(0.67)	(0.77)	(7.96)	(7.68)	(7.94)
lifeexp		0.04***	0.03**	0.03***	0.03***	0.03***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
ci			-0.33***	-0.24***	-0.18*	0.25***
			(0.09)	(0.10)	(0.10)	(0.10)
sqlogingdp				0.47	0.60	0.41
				(0.44)	(0.43)	(0.44)
liqliab						
const	-415.56***	-343.26***	-344.98***	1571.16***	1576.29***	1569.99***
	(67.70)	(59.70)	(62.78)	(439.56)	(439.41)	(439.41)
enusecap $^{\perp}$	-9.70***	-5.51***	-5.74**	-9.06***	-9.08***	-9.15***
	(2.48)	(2.23)	(2.48)	(2.40)	(2.39)	(2.39)
logingdp	54.62***	34.36***	35.01***	-395.97***	-397.03***	-395.82***
	(7.90)	(7.40)	(7.93)	(99.62)	(99.59)	(99.59)
ci		4.28***	4.10***	3.90***	3.90***	3.87***
		(0.59)	(0.59)	(0.54)	(0.54)	(0.54)
schooling			0.09	-1.29	-1.24	-1.28
			(1.55)	(1.46)	(1.46)	(1.46)
agedep				-21.92	-22.02	-21.80
				(25.00)	(25.00)	(24.99)
sqlogingdp				24.49***	24.54***	24.50***
				(5.67)	(5.67)	(5.67)
# of obs.	93	93	93	93	93	93
R^2 growth	0.20	0.20	0.20	0.19	0.22	0.24
R^2 ci	0.12	0.12	0.17	0.18	0.18	0.18
R^2 schooling	0.90	0.91	0.85	0.89	0.90	0.88
R^2 liqliab	0.37	0.50	0.51	0.60	0.60	0.60
χ^2 growth	17.96	18.32	19.38	18.78	23.55	25.99
χ^2 ci	13.39	13.88	19.04	20.67	20.70	20.30
χ^2 schooling	879.45	961.90	748.80	902.65	956.67	880.05
χ^2 liqliab	56.31	127.03	122.61	169.60	169.95	169.20

Std errors in (). *, **, and *** sign. at the 10, 5, 1 % level. $^{\perp}$ in 1000 units

5 Conclusions

The theoretical model derived in this paper shows how economic growth is affected by energy inputs, revealing different channels of influence determined by sectoral capital accumulation. Crowding out of capital accumulation by abundant and cheap energy supply is shown to be closely linked to sectoral change between consumer and capital goods production.

The empirical results for developed economies over the period 1975-1999 show that tighter energy supply or higher energy prices are not likely to be a curse for growth in the long run. On the contrary, we find that lower energy use has either a positive dynamic impact or is neutral regarding development. Thus, 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 financial capital. While the channel operating through human capital is robust in all the estimations, physical capital is somewhat less successful in the final simultaneous-equation system. Financial capital turns out to be affected by energy use, but its impact on growth was not confirmed in this sample. It has to be noted, however, that aggregate results conceal sectoral change so that several sectors in the economy are expected to shrink with higher energy prices.

The empirical results are reasonably robust because they emerge from different specifications and the appropriate estimation of various systems of equations. 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.

It would be interesting to apply the model to a larger country sample. This would, of course, require a careful treatment of the different institutional and political conditions. This is left for future research.

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