Energy prices, growth, and the channels in between: theory and evidence

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

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Abstract

The paper first develops a theoretical model with different sectors, each providing a channel for an impact of energy prices on growth. In the short run, growth is hampered by increasing energy prices. In the long run, however, capital accumulation may be crowded out by energy use. This happens in the sectors with poor substitution possibilities between primary inputs where growth increases with rising energy prices. In the empirical part, estimations using different channels and energy sources with five-year average panel data for a sample of 44 developed countries in the period 1975-1999 are presented. It is shown that, for a large variety of constellations, rising energy prices are not a threat to economic development, they can even be positive for growth.

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

JEL Classification: Q43, Q56, O41, O47

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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. Development in the last decades seems 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, rather than a blessing. In the same way, it is argued in the public debate that a lower energy input harms both output and output growth.

When we regard cross sections of countries, however, a rather different picture emerges. Various countries with high energy prices, like Japan, perform well while many low energy price countries, especially lower developed oil-producing economies, persistently show low growth rates. In the recent empirical literature, a negative effect of a high natural resource dependence, which is associated with low resource prices, on economic growth has been found, see Gylfason (2001, 2004) and Sachs and Warner (2001). This contrary view explains that natural capital tends to crowd out different accumulation activities which ultimately drive the growth process. The causal chain from resource prices on 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 identifies and explores 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 input for consumer goods. Learning effects support accumulation. In intermediate goods production, energy is the second primary input. In this way, the different channels through which higher energy prices may hinder or foster accumulation can be separately analysed. The capital input and the resulting effects on energy efficiency appear to be crucial to explain the development of energy use. Most strikingly, developed countries use only half as much oil per real unit of GDP compared to the mid-1970s. 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 price changes, like the previously-mentioned oil price jumps, can be very different from long-run effects, where the reallocation of labour is effective. 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 (very) large cross-country samples. The selected countries are quite similar, e.g. regarding factor endowments, market structures, and institutions, so that the aim of identifying and separating the different energy price effects seems to be feasible. 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 two types of relationships: the first is the impact of energy prices on capital accumulation, the second the effect of capital inputs on growth. Different types of capital and energy are considered in the estimations. We estimate the various equations jointly using three-stage least squares, so that consistency is achieved by instrumentation and efficiency is reached by appropriate weighting using the covariance matrix from the second stage of the procedure. We will conclude from the regressions that, in the longer run, higher energy prices need not hamper economic development. To the contrary, we find either that the crowding out of capital accumulation by abundant energy is confirmed or that energy prices are neutral regarding growth.

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), Xepapadeas (2003) and Brock and Taylor (2004). 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), Mehlum, Moene and Torvik (2002), Papyrakis and Gerlagh (2003) and Norrbin and Bors (2004). Empirical results on energy efficiency during growth are presented in Miketa and Mulder (2005) and Mulder and de Groot (2005). Finally, for the empirical 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. Finally, 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:

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

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:

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

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 input. 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:

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

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

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

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 homogenous input, is mobile between the sectors. The energy price p_E is assumed to be fixed by the government, which captures the large impact of the political sector and public enterprises on energy prices and taxes. Energy supply is assumed to be fully elastic so that energy markets clear at every point in time.

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:

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

where V is household wealth, r the interest rate, and $N = \sum N_i = \sum k_i p_{ki}$ firm asset holdings. Households' optimisation excludes energy stock which are assumed to belong to the government, for simplicity. 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. 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. Energy prices are fixed by political authorities and (nominal) wages are constant so that 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_{gi}. To determine L_{gi} 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, meaning a rising energy share, in intermediates production. 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 and productivities a as well as on the labour shares θ, to which we turn now.

2.3 Growth impact of energy prices

Energy prices have an impact on the consumption growth rate via the share θ, as seen from (19). In every sector, profit maximisation of intermediate goods producers yields, regarding (3) and assuming $\lambda = 0.5$ for simplicity, $\forall i$:

$$\frac{\theta_i}{1-\theta_i} = \left(\frac{w_i}{p_E}\right)^{1-\sigma_i} \tag{20}$$

where p_E is the (predetermined) energy price. Totally differentiating (20) gives:

$$\hat{\theta}_i = (1-\theta_i)(1-\sigma_i)(\hat{w}_i - \hat{p}_E) \tag{21}$$

with hats denoting growth rates. $\hat{w}_i$ never overcompensates an (exogenous) energy price change $\hat{p}_E$ in the model so that the effect of $\hat{p}_E$ on θ_i in (21) and capital growth through (18) solely hinges on the size of the sector-specific σ: Provided that substitution is poor in a sector ($\sigma < 1$), an energy price increase brings about a decrease in θ and an increase in the sectoral capital growth rate; the opposite happens when substitution possibilities are good ($\sigma > 1$). This important result is somewhat unfamiliar in neo-classical growth theory, see e.g. Solow (1974), but perfectly in line with new growth theory, see Bretschger (1998). The aggregate effect of energy price changes is thus given by the two relations (19) and (21) which will be both used for empirical estimation below. We note that the share of labour used in the consumption sector θ is closely related to the share of income used for consumption goods. Accordingly, we will use the share of income used for capital accumulation to measure the share of labour used in capital accumulation in the empirical part below.

The analysis so far applies for 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, an increase in energy prices evokes a negative output and employment effect in intermediates production, with constant labour in capital accumulation. For consumption growth we have:

$$g_C = \sum_{i=1}^{m} \gamma_i \cdot \left[\left(\frac{1-\beta}{\beta}\right) \cdot g_{ki} + (1-\theta_i) g_{E_i} \right] \tag{22}$$

It is seen from (22) that consumption growth is diminished when $g_{E_i} < 0$ with $g_{E_i} = -\hat{p}_{E_i}$ as $p_{E_i} \cdot E_i = \gamma_i(1-\theta_i)$. The whole expression becomes negative when the second term in brackets on the rhs of (22) is larger than capital growth given in the first term. In the model, the lack of sectoral adjustment is the reason why the short run impact of rising energy prices and decreasing energy input is negative.

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 method

In the present paper, the system consisting of equations (19) and (21) is estimated jointly using three-stage least squares. The procedure follows Tavares and Wacziarg (2001) and Wacziarg (2001). In the 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 applying this estimation procedure, consistency is achieved by instrumentation while efficiency is reached by appropriate weighting when using the covariance matrix from the second stage. 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 additional instruments we use geographic variables as well as country dummies. Specifically, we introduce in all equations the average distance to trade partners, the land area, and dummies for all the countries with the exception of the US as the reference country to avoid perfect collinearity.

3.3 Estimation strategy

We first start with physical capital investments and aggregate energy use. In the growth equation we follow the literature and introduce (the logarithm of) initial income in the growth regression which means, in terms of the model, that we assume $\eta < 1$, see (4), in the empirical part. As there is no series for aggregate energy prices available we use the variable "energy use per capita" instead; these data are provided for many countries in a good quality and in a standardised way. Then, step by step, we introduce additional types of capital and energy prices of specific sources, in accordance with the theoretical model. In this way, additional channels for the transmission of energy price shocks can be analysed.

We use savings rates or capital stock indicators instead of labour shares as the channel variable. With labour being the only input in accumulation, every increase in the savings rate necessarily entails a rise in the share of labour used in capital accumulation and, at the same time, a decrease of the share of labour in the intermediates production θ.

For the impact of energy prices on sectoral capital accumulation we have derived two possible cases from theory: (i) $\sigma < 1$ which means that θ decreases and the savings rate and capital growth increase and (ii) $\sigma > 1$ which means that θ increases and capital growth decreases. For (ii) consumption and income growth becomes negative with rising energy prices; for (i) consumption and income growth may have either sign, the result depends on σ_i, γ_i and g_{Xi}. Provided that the crowding out effect is strong and the contribution of the capital type i to growth significant, $\sigma_i < 1$ leads to a positive impact of rising energy prices on the growth rate of the economy.

3.4 The data

We collected data for 44 countries, which are Australia, Austria, Belgium, Brazil, Canada, China, Cyprus, Czechoslovakia, 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, Slovakia, Slovenia, Estonia, South Africa, Sweden, Switzerland, Thailand, Turkey, USA, and Venezuela. This is the country sample for which the International Energy Agency provides energy price data. In most equations, however, the lower or recently developed economies (in particular China, Czechoslovakia, Hungary, India, Indonesia, Kazakhstan, Latvia, Lithuania, Malta, Poland, Romania, Russia, Slovakia, Slovenia, Estonia and South Africa) could not be included because data are not available for all used parameters in the estimated equations. 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 prices as derived in the main part of the theoretical model.

The data sources are described in table 1. IEA refers to the International Energy Agency, WDI to the World Development Indicators of the World Bank, OECD to OECD Science and Technology Statistics 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 1: Data

Used variables and 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 og initial GDP per capita	PWT 6.1
popgro	population growth	PWT 6.1
enusecap	energy use per capita (in KGOE)	WDI (2005)
openc	exports+imports/GDP	PWT 6.1
schooling	initial years of average schooling	Barro/Lee (2000)
schoolend	end years of average schooling	Barro/Lee (2000)
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	Barro/Lee (1994)
dist	average distance to trading partners	Barro/Lee (1994)
liqliab	liquid liabilities (M3/GDP)	WDI (2005)
rdexptot	research expenditures total	OECD (2005)

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
openc	234	68.42	42.61	9.3	285.6
schooling	259	7.57	2.76	2.07	20.3
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	3.52e-14	190.5
rdexptot	95	21511	47125.9	220.2	266724.3

4 Empirical Evidence for Developed Countries

The two equations (19) and (21) derived from theory are now used to identify empirically the different channels in the energy-capital-growth relationships. The results are presented in several steps. In table 3, we use the investment share *ci* as channel variable and the energy use per capita *enusecap* as an indicator for the countries' aggregate energy prices (assuming the negative relationship between energy prices and *enusecap* given by the model). The first equation in the system is the growth equation, the second equation presents the determination of the channel variable. Several control variables are tested and added in both equations. The variables for (the logarithm of) initial income *logingdp*, population growth *popgro* and education *schooling* are standard in empirical growth literature. The time dummy variable for the period 1990-94 is included (but not separately reported) because it is always significant, the other period dummies have no impact on the result. The same variables *logingdp*, *popgro* and *schooling* are also introduced to explain the channel variable where, in addition, openness *openc* and financial capital *liqliab* are introduced.

Table 3: Estimation results for the investment channel
Endogenous variables: growth, ci; estimation method 3SLS (IV-GLS)

Variable	(1)	(2)	(3)	(4)	(5)
growth					
const	0.124***	0.083***	0.210***	0.210***	0.246**
	(0.03)	(0.03)	(0.05)	(0.05)	(0.06)
ci	0.001***	0.001***	0.001**	0.001**	0.001**
	(0.0004)	(0.0004)	(0.0005)	(0.0005)	(0.0006)
logingdp	-0.013***	-0.024***	-0.024***	-0.024***	-0.029***
	0.003	0.006	0.006	0.006	0.007
popgro	–0.005*	-0.002	-0.008***	-0.008***	-0.009***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.61)
schooling		0.003***	0.003**	0.003**	0.004***
		(0.001)	(0.001)	(0.001)	(0.001)
ci					
const	14.77	26.84*	3.34	17.29	18.33
	(13.65)	(14.32)	(15.07)	(17.87)	(16.79
enusecap	-0.004***	-0.003***	-0.002***	-0.002**	-0.003***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
logingdp	3.926**	1.553	5.301***	3.768	4.559*
	(1.80)	(1.90)	(2.08)	(2.32)	(2.41)
popgro	-0.168	0.460	0.060	0.108	-0.156
	(0.54)	(0.59)	(0.57)	(0.56)	(0.62)
schooling			-1.512***	-1.634***	-1.276***
			(0.43)	(0.43)	(0.48)
openc				0.051	
				(0.04)	
liqliab					0.020
					(0.03)
# of obs.	130	102	102	102	78
R^2 growth	0.23	0.22	0.22	0.22	0.30
R^2 ci	0.79	0.80	0.82	0.82	0.84
χ^2 growth	33.03	25.90	25.71	25.75	29.61
χ^2 ci	463.79	399.24	459.06	470.07	420.63

Standard errors in parentheses.

* Significant at the 10 % level

** Significant at the 5 % level

*** Significant at the 1 % level

We see from table 3 that the growth regression performs well in general, all the estimated coefficient have the expected signs. The investment share *ci*, our first channel variable, has a positive growth impact throughout the different specifications. Most importantly, we conclude from the lower part of table 3, presenting the channel equation, that the impact of energy use *enusecap* on the investment share *ci* is negative and highly significant in all the estimated equations. This is the first piece of evidence showing how energy use may crowd out capital accumulation and thus hamper the growth process. Regarding the other control variables, *logingdp* has a positive and *schooling* a negative impact on capital investments. Openness and financial capital have no explanatory power in this context.

In table 4, different energy prices are introduced in the channel equation. The label "energy price" in the first column stands for the different energy prices given on the top of the table, indicated by the °. As a benchmark, we use again (the negative value of) energy use -*enusecap* in the first column. For the growth regression, presented in the upper part of the table, we refer to a standard growth specification. The results can be seen as satisfactory. In particular, the investment rate *ci* has the positive and significant impact on growth in five of the seven equations. Interestingly, the impact of energy prices on the investment rate, given in the lower part of the table, is either zero or positive. This means that in no case we find a negative impact of rising energy prices on the accumulation of physical capital, which is indeed remarkable.

Table 5 presents simultaneous estimations of four equations, the growth relation and three channel regressions. The different energy prices are used as in table 4. As now many variables are involved the sample for estimations becomes smaller. The three channels included are physical, human, and financial capital. As can be seen from the first part of the table, the impact of energy prices on physical capital is either positive and significant or close to zero. This corresponds to the previous results. For the human capital channel, presented by the variable *schoolend*, we see a very similar result in the second part of table 5. The impact of energy prices on education is either positive and significant or zero; in no case we obtain a negative and significant coefficient. A corresponding outcome can be seen when looking at the financial capital channel. The effect of energy prices is positive or absent, but not found to be negative for any energy source.

In table 6 we present results for knowledge capital which is treated separately. In fact, a reliable (positive) impact of R&D expenditures *rdexptot* on growth could not be found in this sample, although theory thoroughly confirms that this should be the case, in principle. Hence we only show the results concerning the channel regression, using the two-stage least squares method. We get a high R^2 but not a very high explanatory power in terms of the theoretical model. It is seen clearly that there is no negative impact of energy prices on research effort, for aggregate energy use we even find that less energy is good for R&D, again in line with the other results.

Table 4: Estimation results for different energy prices
Endogenous variables: growth, ci; estimation method 3SLS (IV-GLS)

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
°	- enusecap	prilifuel	priprlead	prilifuelin	prihisuin	prigasin	prielin
growth							
const.	0.124***	0.213***	0.151***	0.021	0.081***	-0.030	0.082***
	(0.12)	(0.005)	(0.05)	(0.04)	(0.03)	(0.04)	(0.03)
ci	0.001***	0.001**	0.001***	0.0001	0.001**	-0.0004	0.001***
	(0.0004)	(0.0005)	(0.0005)	(0.0005)	(0.0004)	(0.0005)	(0.0004)
logingdp	-0.013***	-0.024***	-0.016***	-0.0002	-0.010***	0.007	-0.010***
	(0.003)	(0.006)	(0.005)	(0.004)	(0.003)	(0.004)	(0.003)
popgro	–0.005*	-0.008***	-0.009*	-0.003	0.001	-0.004*	-0.002**
	(0.003)	(0.003)	(0.005)	(-0.003)	(0.003)	(0.003)	(0.003)
ci							
const	23.84	68.14***	0.003	85.50***	43.19***	62.57***	46.86***
	(16.25)	(16.70)	0.005	(14.78)	(15.77)	(12.47)	(15.24)
energy price°	0.0042***	0.0001*	0.027	0.0002**	0.0001	0.00001	-0.0005
	(0.001)	(0.0001)	(0.02)	(0.00007)	(0.0002)	(0.0001)	(0.10)
logingdp	3.926**	-4.705***	-3.815**	-6.524***	-2.140	-4.071***	-2.51
	(1.80)	(1.70)	(1.93)	(1.50)	(1.61)	(1.27)	(1.55)
popgro	-0.253	-0.377	-0.792	0.498	-0.543	-0.259	-0.478
	(0.003)	(0.56)	(0.74)	(0.49)	(0.55)	(0.37)	(0.49)
openc		0.054	0.048	0.010	0.320	-0.005	0.025
		(0.03)	(0.04)	(0.03)	(0.03)	(0.02)	(0.03)
# of obs.	130	98	93	99	108	92	120
R^2 growth	0.23	0.21	0.23	0.09	0.22	0.11	0.21
R^2 ci	0.79	0.82	0.80	0.84	0.84	0.90	0.84
χ^2 growth	32.71	24.14	26.58	7.61	26.25	11.86	30.47
χ^2 ci	458.78	460.02	10756.29	540.14	549.16	806.51	618.44

Standard errors in parentheses.

* Significant at the 10 % level

** Significant at the 5 % level

*** Significant at the 1 % level

Table 5: Estimation results for different channels and energy prices
Endogenous variables: growth, ci, schoolend, liqliab; estimation method 3SLS (IV-GLS)

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
°	- enusecap	prilifuel	priprlead	prilifuelin	prihisuin	prigasin	prielin
Growth							
const	0.256***	0.13*	0.24***	0.13**	0.15**	0.025	0.149**
	(0.06)	(0.07)	(0.08)	(0.06)	(0.07)	(0.08)	(0.07)
ci	0.002***	0.001	0.001*	-0.00002	0.001***	-0.0002	0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.0006)
logingdp	-0.031***	-0.014*	-0.027***	-0.014*	-0.02***	-0.001	-0.02***
	(0.007)	(0.008)	(0.01)	(0.008)	(0.007)	(0.01)	(0.008)
popgro	-0.007**	0.0004	-0.01*	-0.005	-0.002	-0.006*	-0.003
	(0.003)	(0.004)	(0.006)	(0.004)	(0.004)	(0.004)	(0.003)
schooling	0.005***	0.001	0.002	0.003*	0.002	0.002	0.003**
	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)	(0.001)
liqliab	-0.00002	-0.00001	0.0001	0.00004	-0.00005	-0.00002	-0.0001
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
ci							
const	24.08	40.28**	46.26**	72.60***	38.53**	65.01***	37.62**
	(17.94)	(18.67)	(22.02)	(14.90)	(18.4)	(15.14)	(17.84)
energy price°	0.003**	0.0001	0.023	0.0002***	0.0001	-0.00001	0.033
	(0.001)	(0.0001)	(0.02)	(0.0001)	(0.0002)	(0.0001)	(0.1)
logingdp	1.71	-1.84	-2.28	-5.15***	-1.66	-4.36***	-1.55
	(2.3)	(1.9)	(2.4)	(1.5)	(1.9)	(1.5)	(1.8)
popgro	-0.414	-0.74	-1.46*	-0.11	-0.99*	-0.44	-0.90*
	(0.52)	(0.54)	(0.77)	(0.41)	(0.55)	(0.37)	(0.48)
openc	0.063*	0.06*	0.07	0.05*	0.08**	0.05*	0.061*
	(0.04)	(0.03)	(0.05)	(0.03)	(0.04)	(0.03)	(0.04)

cont. next p.

Standard errors in parentheses.

* Significant at the 10 % level

** Significant at the 5 % level

*** Significant at the 1 % level

Table 5 (cont.): Estimation results prices
Endogenous variables: growth, ci, schooling, liqliab; estimation methods 3SLS (IV-GLS)

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
°	- enusecap	prilifuel	priprlead	prilifuelin	prihisuin	prigasin	prielin
schoolend							
const	22.28**	36.62***	18.48***	48.74***	114.03***	47.33***	33.66***
	(10.90)	(12.30)	(7.58)	(12.62)	(34.32)	(13.47)	(12.51)
ci	-1.16***	-1.06***	0.10***	-0.97***	-3.32***	-1.10***	-1.27***
	(0.11)	(0.19)	(0.09)	(0.14)	(0.41)	(0.16)	(0.14)
energy price°	0.003***	0.0001***	0.01*	0.0001***	0.0004	-0.0001	0.03
	(0.0008)	(0.94)	(0.005)	(0.00004)	(0.0003)	(0.00004)	(0.07)
logingdp	3.20***	-0.27	0.74	-1.76*	-3.04	-1.31	0.53
	(1.36)	(0.94)	(0.72)	(1.05)	(3.13)	(1.09)	(1.16)
popgro	-0.60**	-0.94***	-1.18***	-0.10	-3.32***	-0.46""	-1.21***
	(0.31)	(0.28)	(0.26)	(0.22)	(0.98)	(0.20)	(0.33)
openc	0.08***	0.08***	0.05***	0.05***	0.25***	0.06***	0.08***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.07)	(0.20)	(0.02)
liqliab							
const	22.28**	-154.90**	-141.52	-331.5***	-214.59***	-434.17***	-279.51***
	(10.90)	(77.89)	(56.62)	(114.66)	(70.05)	(91.53)	(69.85)
energy price*	0.003***	0.0001***	0.06	0.001	0.0004	0.001**	0.81
	(0.001)	(0.00002)	(0.07)	(0.0004)	(0.0003)	(0.001)	(0.54)
logingdp	3.20***	-0.27	19.44***	43.81***	31.66***	53.76***	37.41***
	(1.36)	(0.94)	(5.85)	(11.58)	(7.14)	(9.40)	(7.13)
popgro	-0.60**	-0.94***	1.32	-4.24	-11.59**	-3.82	-3.13
	(0.31)	(0.28)	(5.27)	(5.80)	(5.63)	(5.66)	(5.47)
openc	0.08***	0.08***	0.22**	-0.28*	-0.19	-0.10	-0.10
	(0.02)	(0.19)	(0.11)	(0.16)	(0.14)	(0.15)	(0.15)
# of obs.	84	63	54	63	67	61	76
R^2 growth	0.37	0.22	0.27	0.12	0.28	0.13	0.32
R^2 ci	0.86	0.88	0.87	0.91	0.9	0.9	0.9
R^2 schooling	0.34	0.47	0.85	0.73	-3.61	0.73	0.35
R^2 liqliab	0.40	0.25	0.36	0.28	0.34	0.38	0.30
χ^2 growth	46.82	16.48	20.46	8.40	22.44	8.47	32.76
χ^2 ci	519.80	491.13	375.91	684.59	577.53	769.22	641.63
χ^2 schooling	548.50	767.94	1316.33	836.60	122.0	952.57	514.53
χ^2 liqliab	56.30	20.91	30.42	24.16	34.04	36.99	33.12

Standard errors in parentheses. *, **, and *** significant at the 10, 5, 1 % level, respectively.

Table 6: Estimation results for knowledge capital
Endogenous variables: rdexptot; estimation method 2SLS (IV)

Variable	(1)	(2)	(3)	(4)	(5)	(6)
°	- enusecap	prilifuel	priprlead	prihisuin	prigasin	prielin
const (/1000)	-1340***	-860***	-170***	-1003***	-1116***	-1140***
	(512)	(222)	(48)	(287)	(332)	(301)
ci	1365.58	4523.7***	87.7	733.0	3617.5	2270.2
	(1616.2)	(1634.4)	(311.8)	(1791.8)	(2385.0)	(1633.3)
energy price°	29.88*	14.5	4438.2	70.5	71.9	355
	(16.63)	(21.7)	(3009.5)	(58.6)	(52.4)	(264)
logingdp(/1000)	166***	94***	20***	122***	123***	131***
	(60)	(27)	(5.80)	(37.16)	(43.24)	(35.05)
schooling (/1000)	7.46	3.61	1.41	-1.52	0.17	-1.26
	(6.50)	(4.61)	(1.09)	(7.21)	(7.75)	(6.05)
openc	-2037.0***	-1654.4***	-426.87***	-2058.8***	-1503.1***	-2332.1***
	(433.5)	(554.4)	(141.4)	(613.8)	(458.9)	(685.3)
# of obs.	65	59	53	56	47	63
R^2	0.95	0.96	0.95	0.96	0.97	0.94

Standard errors in parentheses.

* Significant at the 10 % level

** Significant at the 5 % level

*** Significant at the 1 % level

5 Conclusions

The theoretical model derived in this paper exhibits how economic growth is affected by energy prices, revealing the different channels which operate through sectoral capital accumulation. Crowding out of capital accumulation by abundant and cheap energy supply was shown to be closely linked to sectoral change between consumer and capital goods production.

The empirical results for developed economies in the period 1975-1999 show that there is no such thing as a curse of high energy prices for long-term growth. To the contrary, we find that high energy prices have either a positive dynamic impact or are neutral regarding development. This holds for all the channels included, that is physical, human, financial and knowledge capital. The results can be seen as robust because they emerge from many specifications and the appropriate estimation of different economic systems. They correspond to what has been found for larger samples when measuring energy and resource supplies in terms of quantities and not prices.

It would be interesting to see whether the outcome of this study can be confirmed using other variables, time periods, or country samples. Also, the inclusion of very recent data will be of large interest. This is left for future research.

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