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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 develops a theoretical model with different channels through which energy affects 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 in the long run rising energy prices are not a threat to development. On the contrary, we find conditions under which decreasing energy input induces investments in physical and knowledge capital. A ten percent increase in energy prices is found to raise the growth rate by 0.4 percentage points.

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

The present paper considers the impact of energy on long-run economic development, both theoretically and empirically. Contrary to common thinking, we find that higher energy prices do not hamper the growth process. The regression results show that capital accumulation is crowded out by abundant energy use. Specifically, we find that a ten percent decrease in energy use raises growth by 0.14 percentage points through fostering investments in physical and knowledge capital. With an estimated price elasticity of energy use of -0.3 we conclude that an increase in energy prices by 10 percent increases the growth rate by 0.4 percentage points. 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. Comparing high-income countries, we see that in the USA and in Canada (end user) energy prices are moderate and the investment shares are comparatively low, while Japan has higher prices and higher shares. However, energy use has been increasing and the investment share decreasing in Japan over the last twenty years. Our model contributes to explain these facts by relating energy use and energy prices to investment and growth.

To derive the results we include two major effects which are often neglected in the energy-growth literature. First, we study a multi-sector economy and, specifically, the sectoral reallocation of inputs caused by changing energy use. Provided that energy is less intensively used in the sectors which are important for growth, a relatively mild assumption when thinking of knowledge and human capital, our results relate to the well-known Rybczynski theorem of trade theory. Second, we refer to endogenous growth theory so that level and growth effects of energy can be distinguished. Notably, we include the Hicksian mechanism of induced investment and innovation. This requires to introduce both physical and knowledge capital, which we complement by human capital, as endogenous variables. As a consequence, the theoretical model is able to identify and explore different channels through which energy use affects capital accumulation and growth.

To obtain a consistent production structure we distinguish between final output, intermediate input and primary input. Specifically, final output is produced by intermediate goods and capital, which are both manufactured by the (primary) inputs energy and labor. In this setting, capital is not only an input but also a sector-specific output, which is important to capture the various supply and demand effects governing capital accumulation. The model reflects the fact that energy intensities vary widely in the economy, which cannot be ignored in this context. Production of capital goods differs from that of consumer goods; it also varies between the different capital types. In addition, endogenous knowledge creation is a central part of the present approach, based on the seminal contributions of Romer (1990) and Grossman and Helpman (1991).[2]

The system of equations used in the empirical part follows the theoretical model, i.e. the causal chain from energy to capital accumulation to growth. In particular, the empirical part includes the formulation of the impact of energy prices and initial 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 results relate to the empirical literature on the "natural resource curse" where it is argued that natural capital tends to crowd out different accumulation activities, see Sachs and Warner (2001). Recent contributions have enlarged the set of considered relationships and variables, see Mehlum, Moene and Torvik (2006) and Brunnschweiler and Bulte (2008).[3] Building on the empirical results of the present paper, Peretto (2009) argues that (higher) energy taxes are predicted to increase welfare, which requires energy demand to be inelastic.

The estimation procedure sheds some new light on an earlier strand of lit-

[2] Theoretical models on natural resources and growth including endogenous knowledge are found in Bovenberg and Smulders (1995), Bretschger (1998), Barbier (1999), Scholz and Ziemes (1999), Grimaud and Rougé (2003), Brock and Taylor (2005), Xepapadeas (2006), Bretschger and Smulders (2006), and López, Anriquez and Gulati (2007).

[3] Empirical results on energy efficiency and growth are presented in Popp (2002), Miketa and Mulder (2005), Mulder and de Groot (2007), and Dalgaard and Strulik (2008). A strand of empirical literature using vector autoregressive regressions focuses on the causality between energy and growth, see Glasure and Lee (1998), Stern (2000), and Ugur and Sarib (2003).

erature focusing on empirical estimations of the substitution elasticity between capital and energy, see e.g. Berndt and Wood (1979). It is known that the empirical results on whether energy and capital are substitutes or complements are mixed. There are different attempts to explain the differences. Controversial issues are how to treat additional inputs like labor, how to include technology, which elasticity concept to choose and how to take into account adjustment costs and taxes. A serious critique is expressed in Solow (1987, p. 606) who states that direct estimates of factor substitutability based on aggregate data are "misleading" and the capital-energy complementarity debate "has been misfocused." He argues that elasticities are concepts of partial equilibrium models, which usually disregard general equilibrium responses and differences in energy intensities. These, however, are found to be important under realistic assumptions. The paper explains why the role of the elasticities is more complex than suggested in the capital-energy complementarity debate and how general equilibrium effects can be included in an energy-growth model.

We develop the theoretical approach in order to find appropriate estimation equations. Specifically, the theoretical model predicts which parameters determine the impact of energy on investment rates and growth. By using panel data and five-year averages we exploit cross-country and long-run information which is crucial as it is widely agreed that changes in energy conditions cause major adjustment costs in the economy. For the simultaneous estimation of the different impact channels we apply the method of Tavares and Wacziarg (2001), which takes econometric problems of recent international panel studies into account. We test a simultaneous system 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 find that energy prices have the (expected) negative effect on energy use, and that decreasing energy use has a positive impact on capital accumulation and growth. A decrease of energy input raises the accumulation of physical and knowledge capital significantly. These two channel effects turn out to be of similar size, while the effect through human capital is not significant. The results can be used for the evaluation of current energy tax and climate policies. The most obvious way to raise energy prices is indeed by increasing energy taxes, which curbs energy use and emissions while fostering investment.

The remainder of the paper is organized 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 Basic structure

Final output Y is produced with capital K, which is a broad measure for accumulable inputs, and intermediate input flow X:

$$Y = F(K, X) \tag{1}$$

where F is a linear homogeneous function. Time indices are omitted. Capital accumulation and intermediates goods production depend on the inputs labor L and energy E according to:

$$\dot{K} = G_K(L_K, E_K) \cdot \kappa - \delta K \tag{2}$$

$$X = G_X(L_X, E_X) \tag{3}$$

where a dot denotes the time derivative and δ is a fixed parameter ($0 < \delta < 1$). In (2), $G_K(.)$ represents the increase in capital due to labor and energy input; κ reflects public knowledge and δ denotes the depreciation rate. Markets for (primary) inputs L and E are cleared when:

$$L_K + L_X = \bar{L} \tag{4}$$

$$E_K + E_X = E \tag{5}$$

where the lhs of (4) and (5) gives the demand from both sectors K and X; labor supply is assumed to be fixed.

2.2 Energy and capital

Combining $G_K(.)$ from (2) with (3)-(5) yields a 2x2 system according to:

$$\begin{pmatrix} a_{LK} \\ a_{EK} \end{pmatrix} G_K + \begin{pmatrix} a_{LX} \\ a_{EK} \end{pmatrix} X = \begin{pmatrix} \bar{L} \\ E \end{pmatrix} \tag{6}$$

where the as denote input factors with the subscripts denoting the respective input and output (e.g. $a_{LK} = L_K/G_K$). We are interested to find the effect of changing E on G_K. Because the as are not fixed but depend on input prices in a non linear way, we use differentials in logarithms, i.e. growth rates which we denote by hats. To show the impact of changes in energy use we set $\hat{E} \neq 0$ with energy prices being constant. Using λs for input shares (e.g. $\lambda_{LK} = L_K/L$) and θ_{XY} for the cost share of X in Y production ($X = \theta_{XY}/p_X$) we get:[4]

$$\lambda_{LK}(\hat{a}_{LK} + \hat{G}_K) + \lambda_{LX}(\hat{a}_{LX} - \hat{p}_X + \hat{\theta}_{XY}) = 0 \tag{7}$$

$$\lambda_{EK}(\hat{a}_{EK} + \hat{G}_K) + \lambda_{EX}(\hat{a}_{EX} - \hat{p}_X + \hat{\theta}_{XY}) = \hat{E} \tag{8}$$

[4] For the derivation of (7) - (9) see the appendix and Jones (1965).

where the appendix explains that $\hat{a}_{LK} = -\theta_{EK}\sigma_K\hat{w}$ and likewise for the other $\hat{a}$s; $\hat{w}$ is the growth rate of wages w and σ_j denotes the elasticity of input substitution in sector j. Solving (7) and (8) for $\hat{G}_K$ we obtain:

$$\hat{G}_K = \left(\lambda_{EK} + \lambda_{LK}\frac{S_E + D}{S_L - D}\right)^{-1}\hat{E} \tag{9}$$

with

$$S_L = \lambda_{LK}\theta_{EK}\sigma_K + \lambda_{LX}(\theta_{EX}\sigma_X + \theta_{LX}) > 0$$

"supply effect labor market"

$$S_E = \lambda_{EK}\theta_{LK}\sigma_K + \lambda_{EX}\theta_{LX}(\sigma_X - 1)$$

"supply effect energy market"

$$D = \theta_{KY}(1 - \sigma_Y)(\theta_{LX} - \theta_{LK})$$

"demand effect"

The terms S_L and S_E labelled "supply effect" give the impact of energy supply on capital growth through the change in relative production cost of capital goods on both input markets. Considering the supply effect alone, i.e. assuming $D = 0$ for a moment (which happens e.g. for $\sigma_Y = 1$), one can see from (9) that the relationship between energy and capital growth is positive when the elasticity of substitution in X-production is good, i.e. we have $\sigma_X > 1$ (for which the supply effect of energy is positive, i.e. $S_E > 0$). In this case, less energy input means lower capital growth because $S_E/S_L > 0$. Only in the opposite case, i.e. with $\sigma_X < 1$, less energy use can lead to higher capital growth. Thus with regard to the supply effect, we need *poor* input substitution to get higher growth with $\hat{E} < 0$.[5] The reason is that only with poor input substitution wages decrease enough to promote labor reallocation toward capital goods production in order to compensate for fading energy input.

To derive the demand effect we need to sign the term $(1 - \sigma_Y)(\theta_{LX} - \theta_{LK})$ in D. Provided that intermediate goods production is relatively more intensive in energy use than capital goods production we have $\theta_{LX} - \theta_{LK} < 0$. Then, a high elasticity of input substitution turns the demand effect positive, i.e. we have $D > 0$ when $\sigma_Y > 1$. According to (9), the relationship between energy input and capital growth becomes negative for $S_E + D > 0$ when $S_L - D$ is (sufficiently) negative. Here, good input substitution (a large σ_Y) increases D which helps to achieve $S_L - D < 0$; this then supports the growth process when energy becomes more scarce. This is the effect used in the energy-capital complementarity debate

[5] With $\sigma_X < 1$, the second term determining S_E becomes negative, while a low σ_K helps to keep the first term low so that $S_E < 0$ and $\lambda_{EK} + \lambda_{LK}(S_E/S_L) < 0$ with σ_X, σ_K being small enough.

which, however, is only a part of the whole substitution effect, once we assume capital production cost to differ from the rest of the economy. We conclude that the effect of energy on capital accumulation does not depend on the *absolute* values of the elasticities of substitution but on the *relative* values comparing the demand and the supply side of capital production.[6]

2.3 Growth

Following (1), output growth is determined by:

$$\hat{Y} = \theta_{KY}\hat{K} + \theta_{XY}\hat{X} \tag{10}$$

where the θs are production elasticities (given F, cost shares equal output elasticities). We look at growth periods and assume, for simplicity, that sectoral use of inputs L and E (as derived in the previous subsection) only changes *between* the different periods and not within, where input prices remain at a constant level.[7] This may be due to wage contracts, the assumption of an exogenous (world) energy price, and the absence of supply shocks within the growth period. *Within* such a growth period we then have $\hat{E} = 0$, constant input prices and cost shares θ, and $\hat{X} = 0$ so that $\hat{Y} = \theta_{KY}\hat{K}$. We define the investment share s_K as:

$$s_K \equiv \frac{G_K}{Y} \tag{11}$$

and public knowledge κ (see 2) by:

$$\kappa \equiv \mu\frac{K^\eta}{Y} \tag{12}$$

which says that κ depends on a constant $\mu > 0$ and cumulative investment experience K^η $(0 < \eta < 1)$, which is divided by output to eliminate the scale effect. Dividing (2) by K and inserting (11) and (12) we obtain:

$$\hat{K} = s_K\mu K^{\eta-1} - \delta \tag{13}$$

which exhibits convergence of the capital stock as $\eta < 1$. The steady state capital stock K^* reads:

$$K^* = \left(\frac{\mu s_K}{\delta}\right)^{\frac{1}{1-\eta}} \tag{14}$$

With this we can study growth $\hat{Y}$ and convergence of Y according to, see e.g. Mankiw, Romer and Weil (1992):

$$\frac{d\ln Y}{dt} = \xi(\ln Y^* - \ln Y) \tag{15}$$

[6] Assuming equal elasticities for primary inputs L and E in all the sectors, one finds as a rule of thumb that for $\sigma_X = \sigma_K$ (sufficiently) lower than σ_Y the effect of $\hat{E}$ on $\hat{G}_K$ is negative so that lower energy input fosters capital growth.

[7] This simplifying assumption is made for convenience and is not essential for the result.

with $\xi > 0$ and where by (1) and (14):

$$\ln Y^* = \frac{\theta_{KY}}{1-\eta} \ln s_K + \frac{\theta_{KY}}{1-\eta} \ln \mu - \frac{\theta_{KY}}{1-\eta} \ln \delta + \theta_{XY} \ln X^*. \tag{16}$$

From (15) and (16) we see that growth depends positively on the investment rate s_K and the productivity of public knowledge μ; the depreciation rate δ has a negative impact while the level of intermediate input X^* is positive for growth exhibiting a scale effect in final goods production. The level of current/initial output has a negative effect on growth.

2.4 Capital types

To identify the importance of the different kinds of capital, like physical, human, and (private) knowledge capital we need to disaggregate K. This seems rewarding as it allows to distinguish between the different "channels" through which energy affects the growth rate. The different capital types have different production conditions, in particular different energy intensities. Assume each capital type I is accumulated with labour and energy input according to:

$$\dot{I} = f_I(L_I, E_I) \cdot A_I \qquad (I = P, H, B) \tag{17}$$

where P, H, and B, denote physical, human, and (private) knowledge capital, the f_Is are linear homogeneous functions, and the A_Is represent (exogenous) capital type-specific productivity parameters. The non-physical capital types H and B produce non-physical capital N which is used, together with P, to manufacture aggregate capital, so that:

$$K = \tilde{G}_K \left[P, N(H, B)\right] \tag{18}$$

Capital types will be used in two ways. First, the supply and demand effects studied with the help of (9) now apply for $\hat{P}$, $\hat{H}$, and $\hat{B}$ in exact the same way as for $\hat{K}$. For example, decreasing energy input evokes higher use of physical capital P when the substitution elasticity between K and N is high (demand effect) and the substitution elasticity of L and E in P-production is low (supply effect). We do not repeat this exercise for all capital types here; all we have to do is to apply the three effects S_L, S_E, D from (9) to each capital type. Second, the investment share s_K in (11) will be replaced by the shares s_I $(I = P, H, B)$ to determine steady state capital as in Mankiw, Romer and Weil (1992); for simplicity, the depreciation rate δ_I is assumed to be the same for all I.

The theoretical model explains that a shrinking energy input increases the investment rates, provided that elasticities of substitution are low on the supply side and high on the demand side.[8] One might assume that elasticities of substitution between capital types are close to unity or smaller and that non-physical capital has a high comparative advantage when energy becomes more scarce. But of course, we need the empirical analysis to corroborate these predictions. Microeconomic foundation cannot predict the (relative) size of the elasticities. At any rate, compared to the one-sector model, the present framework with multiple sectors (X, P, H, B) predicts a more complex role of substitution elasticities in the economy. It predicts that poor input substitution on the supply side fosters sectoral change. With a decrease in energy input we then have decreasing wages and a sectoral reallocation of labour, which increases capital accumulation and growth.

2.5 Energy

With a fixed labor supply, wages depend positively on K and Y. Given (fully) elastic energy supply in a single country, energy use is endogenous. Cost minimization leads high wage (high income) countries to use relatively more energy in all the activities. In addition, an important part of (end user) energy prices are (country-specific) taxes. So we write that, at the beginning of the growth period in time $t = 0$, energy use *ceteris paribus* depends on the output level Y_0 and energy prices p_{E0}:

$$E_0 = E_0(Y_0, p_{E0}) \tag{19}$$

where $\partial E_0/\partial Y_0 > 0, \partial E_0/\partial p_{E0} < 0$. (19) addresses the concern about possible reversed causality in the energy debate. In the present approach, the *level* of output affects the *level* of energy at the initial state which, in turn, affects capital and output *growth* as argued above.

2.6 Estimation equations

We now use the derived equations for the empirical analysis. Specifically, the growth impact of investment rates, the effect of energy use on investment rates, and the impact of (initial) output on energy use are estimated in a system approach. Following (15), (16), and (18) the growth equation reads:

$$\hat{Y} = \epsilon_0 c_Y + \epsilon_1 \ln Y_0 + \epsilon_2 \ln s_P + \epsilon_3 \ln s_H + \epsilon_4 \ln s_B + \epsilon_5 \cdot \ln \vec{Z}_g + \xi_g \tag{20}$$

where c_Y is a constant, ϵ_1 is the convergence parameter, and we predict $\epsilon_1 < 0$ and ϵ_2, ϵ_3, $\epsilon_4 > 0$ from the theoretical model. $\vec{Z}_g$ is a set of control variables and ξ_g denotes the error term. δ and μ are assumed to be equal for all countries. The

[8] Specifically, for P, H, and B, high σ_K and σ_N (demand effect) and low substitution elasticities between L and E in production (supply effect) are favorable for growth.

specification in (20) is in accordance with the cross-country growth literature and includes all the channel variables as regressors. As controls in $\vec{Z}_g$ we consider the size of the economy (according to the scale effect of X^*) and population growth.

To estimate the impact of energy on capital investments, total investment is replaced by investment shares as in (11). Specifically, the disaggregated investment efforts f_I (see 17) are divided by Y to obtain investment shares s_I which depend on energy use (see 9) and several control variables. As the s_Is do not depend on the scale of the economy, we use energy per capita e instead of total energy as explanatory variable.[9] We write:

$$\ln s_P = \delta_{P0} \cdot c_P + \delta_{P1} \cdot \ln e + \delta_{P2} \cdot \ln A_P + \delta_{P3} \cdot \ln \vec{Z}_P + \xi_P \tag{21}$$

$$\ln s_H = \delta_{H0} \cdot c_H + \delta_{H1} \cdot \ln e + \delta_{H2} \cdot \ln A_H + \delta_{H3} \cdot \ln \vec{Z}_H + \xi_H \tag{22}$$

$$\ln s_B = \delta_{B0} \cdot c_B + \delta_{B1} \cdot \ln e + \delta_{B2} \cdot \ln A_B + \delta_{B3} \cdot \ln \vec{Z}_B + \xi_B \tag{23}$$

where the signs of δ_{P1}, δ_{H1}, and δ_{B1} depend on the different substitution elasticities which determine the supply and the demand effect for each capital type, see (9) and (18). As regards the knowledge type-specific productivity parameters A_I there are different specifications. In the case of B, we employ the size of the economy (captured by population size and initial income) reflecting scale effects in research. These are suggested by the theory of spillovers as well as by empirical observations, e.g. the success of regional high-tech clusters. Moreover, certain indivisibilities of research projects favour larger scales. For H and education investment we include the existing education level of the population. Educational investments appear to generate positive spillovers so that returns are especially favorable when the human capital stock is high. In the case of P we think of the age structure of the population because an older population has higher needs for public and private infrastructure. An ageing society has to invest more to sustain old-age consumption.

Further control variables and the chosen estimation procedure take care of additional effects. Specifically, the literature suggests that government activities, the size of an economy, and population growth may have an impact on s_P in (21). As additional controls for s_H in (22), we consider that demand for education rises with income. Furthermore, as education is close to government activities and scale effects may arise, government spending as a share of GDP and the size of the economy have to be considered as well. Government share and population growth are included to determine s_B in (22). Finally, the energy equation reads:

$$\ln e = \zeta_0 \cdot c_E + \zeta_1 \cdot \ln Y_0 + \zeta_2 \cdot \ln \vec{Z}_E + \xi_E \tag{24}$$

[9] The difference between population size used to get e and output used for s, which is labor productivity, is then captured by the other right-hand variables.

which says that energy use depends on (predetermined) initial income and two additional controls, which are the size of the economy and openness. As the possible delinking of energy from income suggests a non-linear relationship we also include the square of initial income. Taken together, the system of the empirical equations assumes that initial income affects energy use, which has an impact on investment shares, which drive economic growth. The five equations (20), (21), (22), (23), and (24) form a system which is estimated simultaneously in section 4. Because of data issues the impact of energy prices on energy use is measured separately at the end.

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, market structures, and institutional backgrounds, using appropriate instruments, and adopting a simultaneous estimation approach we aim to reduce these econometric problems as far as possible. We identify the relationships for developed countries, which are most important for world energy demand but often neglected in studies on the resource curse. The time period under study covers a sufficiently long horizon and the use of five-year intervals helps to minimize business cycle effects. This is advantageous because an economy needs sufficient time for adjustment which is difficult to grasp with annual data and/or pure time-series analysis.

3.2 Estimation strategy

For our system, equation-by-equation instrumental variables estimation on the structural form model could be applied. This would yield consistent but not efficient estimates, as cross-equation disturbance correlations are neglected. In order to exploit efficiency gains from the correlation of error terms across time, one could use a variant of single-equation instrumental variables with each structural relationship being estimated for all time periods jointly. However, this method would still not exploit that error terms may not be independent across structural relationships. Dependence occurs when assuming that unobserved variables like institutional and macroeconomic conditions have an impact on all the system equations. This is very likely in our setting because we see from the theoretical model that crucial parameters like several cost shares appear in more than one estimation equation. Cross-equation correlations thus seem to be highly important in our context. Moreover, the theoretical part derives three consecutive stages of the energy growth system, which call for a system estimation.

For these reasons we estimate the system consisting of equations (20), (21)-(23), and (24) jointly using three-stage least squares. The advantage of this estimation method (also compared to a dynamic GMM) is its ability to take care of all possible cross-equation correlations. 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. Finally, we additionally estimate energy use depending on energy prices for all time periods jointly using three-stage least squares.

The procedure of the system estimation 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 country dummy variables and additional exogenous variables and instruments the scope for omitted variable bias is largely reduced. As separate instruments for the 3SLS procedure we add two variables for the sectoral structure of the economy and the age structure of the population in all the estimations.

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.

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 (2005), own calculations
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)
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)

3.3 The data

We collected data for 37 higher-income 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 a country sample for which the relevant data are completely available. In the final equations using energy prices we also include some other economies, in particular the 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 equations representing the full system of the econometric model we have a balanced panel.

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
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
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
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

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. 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.

In the appendix 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 largely determined by taxes which shows the impact of the government on these prices.

4 Empirical evidence

We now turn to the simultaneous estimation of our multi-equation system. Specifically, the equations derived from theory are used to empirically identify the different channels in the energy-capital-growth relationships. The growth relation (20), the channel equations for physical, human, and knowledge capital (21) - (23), and the energy use relation (24) 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. The country dummies with the exception of the US as the reference country (to avoid perfect collinearity) are used in all the equations as right-hand variables but do not appear in table 3 because of lacking space. In addition, we use two instruments assumed to affect investment and energy use in all the estimated relationships. Specifically, we introduce life expectancy $loglifeexp$ for the expected payback period of investments and the share of arable land $logagriland$ to reflect the sectoral structure of the economy. According to theory the coefficients for the right-hand variables are estimated in logarithms.

The results are presented in table 3, which includes six representative equations (1)-(6). The specifications follow the theoretical considerations in section 2. 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 investments in physical capital, followed by human capital and, finally, knowledge capital. Population size, i.e. the scale, has no significant effect in any specification and population growth has a negative sign but is not significant either.

Table 3: Estimation results for the system; 3 SLS

Endogenous variables: growth, logci, logeduexp, logrdshare, logenusecap

	(1)	(2)	(3)	(4)	(5)	(6)
growth						
logingdp	-0.137***	-0.129***	-0.125***	-0.113***	-0.113***	-0.113***
	(0.0258)	(0.0244)	(0.0252)	(0.0258)	(0.0259)	(0.0259)
logci	0.386***	0.354***	0.342***	0.338***	0.332***	0.330***
	(0.0703)	(0.0635)	(0.0640)	(0.0640)	(0.0655)	(0.0654)
logeduexp	0.243***	0.237***	0.205***	0.208***	0.209***	0.205***
	(0.0865)	(0.0770)	(0.0789)	(0.0789)	(0.0796)	(0.0795)
logrdshare	0.116**	0.102**	0.105**	0.0993**	0.0970**	0.0972**
	(0.0461)	(0.0454)	(0.0459)	(0.0459)	(0.0475)	(0.0475)
logpop	-0.0436	-0.0410	-0.0393	-0.0473	-0.0462	-0.0461
	(0.0338)	(0.0310)	(0.0315)	(0.0319)	(0.0325)	(0.0324)
popgro	-0.000883	-0.00114	-0.00139	-0.00295	-0.00290	-0.00227
	(0.00274)	(0.00268)	(0.00269)	(0.00292)	(0.00294)	(0.00295)
Constant	0.269	0.263	0.269	0.284	0.286	0.289
	(0.300)	(0.287)	(0.288)	(0.289)	(0.292)	(0.292)
logci						
logenusecap	-0.212***	-0.210***	-0.261***	-0.264***	-0.260***	-0.262***
	(0.0596)	(0.0605)	(0.0895)	(0.0903)	(0.0907)	(0.0907)
logagedep	0.137	0.187	0.189	0.157	0.163	0.161
	(0.118)	(0.122)	(0.122)	(0.125)	(0.126)	(0.126)
loggovshare		-0.0765**	-0.0973**	-0.0953**	-0.0959**	-0.0932**
		(0.0375)	(0.0402)	(0.0403)	(0.0404)	(0.0404)
logpop			0.0530	0.0307	0.0297	0.0269
			(0.0740)	(0.0750)	(0.0751)	(0.0751)
popgro				0.0103	0.00994	0.0136
				(0.00830)	(0.00831)	(0.00846)
Constant	2.159***	2.364***	2.183***	2.346***	2.344***	2.364***
	(0.202)	(0.234)	(0.437)	(0.447)	(0.447)	(0.447)
logeduexp						
logenusecap	0.0489	0.0472	0.0658	-0.0274	-0.0127	-0.0201
	(0.0716)	(0.0726)	(0.0728)	(0.0876)	(0.173)	(0.173)
logschooling	0.506***	0.510***	0.503***	0.462***	0.516***	0.544***
	(0.0903)	(0.0913)	(0.0910)	(0.0913)	(0.0922)	(0.0931)
logpop				0.132**	0.102	0.0949
				(0.0631)	(0.0961)	(0.0962)
loggovshare			0.0667**	0.0744**	0.0779**	0.0761**
			(0.0335)	(0.0336)	(0.0348)	(0.0348)

Table 3 *contd.*

	(1)	(2)	(3)	(4)	(5)	(6)
logingdp					-0.0149	-0.0200
					(0.0886)	(0.0886)
Constant	-0.0112	-0.00894	-0.247	-0.946**	-0.752	-0.671
	(0.197)	(0.199)	(0.233)	(0.403)	(0.590)	(0.591)
logrdshare						
logenusecap	-0.862***	-0.835***	-0.891***	-0.913***	-0.950***	-0.992***
	(0.300)	(0.301)	(0.315)	(0.316)	(0.329)	(0.326)
logpop	1.034***	1.020***	1.052***	1.115***	1.131***	1.184***
	(0.162)	(0.163)	(0.173)	(0.177)	(0.182)	(0.182)
logingdp	0.983***	0.971***	1.005***	0.973***	0.994***	1.020***
	(0.153)	(0.153)	(0.161)	(0.160)	(0.169)	(0.168)
loggovshare			0.0675	0.0687	0.0710	0.0608
			(0.0644)	(0.0644)	(0.0645)	(0.0639)
popgro						-0.0278**
						(0.0119)
Constant	-9.242***	-9.176***	-9.551***	-9.841***	-9.938***	-10.25***
	(0.857)	(0.860)	(0.984)	(1.003)	(1.030)	(1.028)
logenusecap						
logingdp	0.946***	0.917***	0.952***	0.888***	0.947***	0.992***
	(0.255)	(0.254)	(0.250)	(0.248)	(0.249)	(0.249)
sqlogingdp	-0.0483	-0.0446	-0.0502	-0.0431	-0.0506	-0.0571*
	(0.0321)	(0.0319)	(0.0314)	(0.0312)	(0.0313)	(0.0314)
logpop	0.414***	0.415***	0.425***	0.435***	0.437***	0.442***
	(0.0382)	(0.0381)	(0.0397)	(0.0402)	(0.0402)	(0.0403)
logopen	-0.206***	-0.206***	-0.206***	-0.207***	-0.206***	-0.197***
	(0.0423)	(0.0422)	(0.0420)	(0.0417)	(0.0422)	(0.0424)
Constant	-2.549***	-2.499***	-2.629***	-2.566***	-2.690***	-2.817***
	(0.562)	(0.560)	(0.555)	(0.553)	(0.554)	(0.556)
Observations	222	222	222	222	222	222
χ^2 growth	161.9	182.61	169.8	159.0	158.5	157.2
χ^2 logci	706.5	718.21	717.6	716.6	716.5	717.8
χ^2 logeduexp	2489	2490	2593	2549	2734	2737
χ^2 logrdshare	3729	3730	3617	3618	3615	3686
χ^2 logenusecap	9240	9241	9241	9242	9242	9240

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

The second part of table 3 concerns the physical capital channel. The effect of energy use on physical capital investments is negative and significant at the 1%-

level. According to the theoretical model, for this type of capital the elasticity of substitution is sufficiently bigger on the demand side as compared to the supply side. The measured effect remains robust in the different specifications. The estimated elasticity varies relatively little and is around -0.2, so that, combined with the estimated coefficient of 0.3 for the investment share *logci* in the growth regression, we get an impact of energy on the percentage growth rate through the physical investment channel of -0.06. According to this result, a ten percent decrease of energy input increases the growth rate by roughly half a percentage point through induced physical capital formation. Age dependency *logagedep* appears with the expected positive sign but is not significant. Government spending as a share of GDP has a negative effect on investments at the 5%-level. According to the results, the size of the economy measured by *logpop* and population growth *popgro* are not significant in this channel equation.

The third part of the table (with *logeduexp* as endogenous variable) shows the results for the human capital channel. Energy use has no clear impact on education expenditures as regards the sign and is statistically not significant. The estimated values are very small in this case. The initial stock of human capital (*logschooling*) is highly favorable for education expenditures, the same holds true for government spending, which is conceivable. The size *logpop* has a marginally positive effect on education expenditures while initial income has no significant impact here.

It is interesting to see the outcome with regard to knowledge capital, because (i) of the induced-innovation hypothesis and (ii) this type of investment does not too often appear in growth regressions. It can be seen from the next part of the table (with *logrdshare* as endogenous variable) that the impact of energy use on research investments is negative in all specifications, that the estimated parameter values are reasonably stable and that significance is very high. This seems to be an extraordinary result by itself. Combining the estimated elasticity of around -0.9 with the result in the growth regression, one obtains a channel effect for knowledge which is of similar size and even a bit higher than that for physical capital. The next variables which are successful in the estimated equation is the size of the economy measured by *logpop* and initial income *logingdp*, which we interpret as strong indication of scale effects in this type of capital accumulation. The government share has no impact while population growth seems to deter research efforts, see equation (6).

As the estimated coefficients for the effects of energy on investment rates are negative for two out of three capital types, we conclude that either both the supply and the demand effect as described in section 2.3 favor investments, or that the unfavorable effect (presumably the return effect) is comparatively small. This would suggest that the elasticities of substitution between the different capital types are close to or smaller than unity and/or cost advantages of capital after energy price increases are large.

The last part of table 3 reflects energy use and its dependence on various factors. Notably, initial income has a positive impact on energy use while the square of the same variable has a negative effect. Separate estimations show that omitting the squared variable *sqlogingdp* leads to an elasticity for *logingdp* of 0.5, including it - as done here - gives a higher value but exhibits (somewhat weak) reverse forces when income becomes higher. Population size has a positive and significant impact, which is intuitive. On the other hand, openness affects energy use negatively according to the results. This may be explained by higher efficiency of resource use in more open economies.

The overall regression statistics in table 3 are highly satisfactory. 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 3. We conclude that lower energy input raises growth through induced capital accumulation, in particular with respect to physical and knowledge capital. The channel effects for both capital types are of similar size. Note that to find these results we have abstracted from biased and embodied technical change. These aspects would require an even more elaborate theoretical foundation.

Finally, in order to confirm the above-assumed negative impact of energy prices on energy use, we show a representative estimation result for energy use per capita as endogenous variable:

logenusecap =	- 0.298***	+ 0.606***	- 0.0565**	+ 0.0951	+ 1.826***
	(0.0689)	(0.0710)	(0.0270)	(0.0778)	(0.502)
	logenprice	logingdp	logpop	logopen	const

Standard errors in parentheses	
observations	71
R^2	0.75

The estimation method is 3SLS; *loglifeexp* and *logagedep* are again used as instruments. *Enprice* is an index of the different energy prices, see the appendix. All the price observations are included but only a moderate number of observations emerges. As can be seen from the result, the negative impact of energy prices on energy use is confirmed. With a value of -0.3 the estimated elasticity is clearly below unity, which fits with our expectations; when including country dummies the elasticity is even somewhat smaller. As expected, the scale variable measured in terms of income has a positive and significant effect on energy use. Again, the estimated elasticity is relatively moderate. The size of the economy measured by population has a negative impact while globalization as measured by trade openness has no significant impact on energy use.

Combining this result for the impact of energy prices on energy use with the channel equations estimates, we obtain that a 10 percent increase in energy prices is expected to raise the growth rate per capita by about 0.4 percentage points, which is not negligible in size. As the sign is positive, it is good news for long-run growth in times of increasing energy prices.

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 economic growth. 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 especially holds true for the channels working through physical and knowledge capital accumulation, which are roughly equally important as a transmission channel; human capital formation is found to be unaffected by energy use. Together with the negative impact of energy prices on energy use, the impact of energy prices on long-run growth becomes positive - an effect which is moderate but not negligible in size. 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 can be expected to shrink.

The empirical results are robust to 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. Finally, a combination of the long-run with short-run effects, as e.g. in an error-correction model, could be evaluated. This is left for future research.

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6 Appendix

6.1 Energy and growth

To find (7) and (8) we differentiate (6) according to:

$$da_{LK}G_K + a_{LK}dG_K + da_{LX}X + a_{LX}dX = 0 \tag{25}$$

$$da_{EK}G_K + a_{EK}dG_K + da_{EX}X + a_{EX}dX = dE \tag{26}$$

and

$$\frac{da_{LK}}{a_{LK}}\frac{a_{LK}G_K}{L}+\frac{a_{LK}G_K}{L}\frac{dGg_K}{G_K}+\frac{da_{LX}}{a_{LX}}\frac{a_{LX}X}{L}+\frac{a_{LX}X}{L}\frac{dX}{X}=0 \tag{27}$$

$$\frac{da_{EK}}{a_{EK}}\frac{a_{EK}G_K}{E}+\frac{a_{EK}G_K}{E}\frac{dG_K}{G_K}+\frac{da_{EX}}{a_{EX}}\frac{a_{EX}X}{E}+\frac{a_{EX}X}{E}\frac{dX}{X}=\frac{dE}{E} \tag{28}$$

yielding

$$\lambda_{LK}(\hat{a}_{LK}+\hat{G}_K)+\lambda_{LX}(\hat{a}_{LX}+\hat{X})=0 \tag{29}$$

$$\lambda_{EK}(\hat{a}_{EK}+\hat{G}_K)+\lambda_{EX}(\hat{a}_{EX}+\hat{X})=\hat{E}. \tag{30}$$

Furthermore we have

$$\hat{X}=\hat{\theta}_{XY}-\hat{p}_X. \tag{31}$$

Inserting (31) into (29) and (30) yields (7) and (8). For $\hat{p}_X$ we use that the price p_X equals unit cost c_X and calculate:

$$\begin{aligned}
c_X &= a_{LX}w+a_{EX}p_E\\
\frac{dc_X}{c_X} &= \frac{da_{LX}}{a_{LX}}\frac{a_{LX}w}{c_X}+\frac{a_{LX}w}{c_X}\frac{dw}{w}+\frac{da_{EX}}{a_{EX}}\frac{a_{EX}p_E}{c_X}+\frac{a_{EX}p_E}{c_X}\frac{dp_E}{p_E}\\
\hat{c}_X &= \theta_{LX}\hat{a}_{LX}+\theta_{LX}\hat{w}+\theta_{EX}\hat{a}_{EX}+\theta_{EX}\hat{p}_E.
\end{aligned} \tag{32}$$

The cost minimization of a single firm producing X-goods, which takes w and p_E as given, yields:

$$\begin{aligned}
c_X &= a_{LX}w+a_{EX}p_E \quad \rightarrow \text{min!}\\
0 &= da_{LX}w+da_{EX}p_E\\
0 &= \frac{da_{LX}}{a_{LX}}\frac{a_{LX}w}{c_X}+\frac{da_{EX}}{a_{EX}}\frac{a_{EX}p_E}{c_X}\\
0 &= \theta_{LX}\hat{a}_{LX}+\theta_{EX}\hat{a}_{EX}
\end{aligned} \tag{33}$$

so that (32) can be rewritten as:

$$\hat{c}_X=\hat{p}_X=\theta_{LX}\hat{w}+\theta_{EX}\hat{p}_E. \tag{34}$$

To derive (9) we use (7) and (8) and introduce the elasticity of substitution, following Jones (1965), as:

$$\sigma_X=\frac{\hat{a}_{EX}-\hat{a}_{LX}}{\hat{w}-\hat{p}_E}$$

which yields in the optimum, i.e. with $\theta_{LX}\hat{a}_{LX}+\theta_{EX}\hat{a}_{EX}=0$, and with $\theta_{EX}+\theta_{LX}=1$:

$$\hat{a}_{LX}=-\theta_{EX}\sigma_X(\hat{w}-\hat{p}_E).$$

σ_K is introduced in exactly the same way. From the first order conditions for a profit maximum of Y-producers we know that $\theta_{XY}/\theta_{KY} = (w_K/p_X)^{1-\sigma_Y} \cdot const$ (where w_K is the unit cost of capital K) so that

$$\hat{\theta}_{XY} = \theta_{KY}(1-\sigma_Y)(\hat{w}_K - \hat{p}_X) \tag{35}$$

where $\theta_{XY} + \theta_{KY} = 1$. Now use $\hat{p}_E = 0$ and insert $\hat{p}_X = \theta_{LX}\hat{w}$ and $\hat{w}_K = \theta_{LK}\hat{w}$ into (35). Substituting the resulting expression as well as $\hat{a}_{LK} = -\theta_{EK}\sigma_K\hat{w}$, $\hat{a}_{LX} = -\theta_{EX}\sigma_X\hat{w}$, $\hat{a}_{EK} = \theta_{LK}\sigma_K\hat{w}$, $\hat{a}_{EX} = \theta_{LK}\sigma_X\hat{w}$, and $\hat{p}_X = \theta_{LX}\hat{w}$ into (7) and (8) we obtain:

$$\lambda_{LK}(-\theta_{EK}\sigma_K\hat{w} + \hat{G}_K) + \lambda_{LX}\left[-\theta_{EX}\sigma_X - \theta_{LX} + \theta_{KY}(1-\sigma_Y)(\theta_{LK} - \theta_{LX})\right]\hat{w} = 0 \tag{36}$$

$$\lambda_{EK}(\theta_{LK}\sigma_K\hat{w} + \hat{G}_K) + \lambda_{EX}\left[\theta_{LX}\sigma_X - \theta_{LX} + \theta_{KY}(1-\sigma_Y)(\theta_{LK} - \theta_{LX})\right]\hat{w} = \hat{E} \tag{37}$$

and

$$\lambda_{LK}\hat{G}_K + (-S_L + D)\hat{w} = 0 \tag{38}$$

$$\lambda_{EK}\hat{G}_K + (S_E + D)\hat{w} = \hat{E} \tag{39}$$

with S_L, S_E, D as defined in the main text, which by eliminating $\hat{w}$ yields (9).

6.2 Energy price data

In table 4, 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 4: 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