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Energy Prices and Economic Growth: Theory and Evidence in the Long Run

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Abstract

In this paper, we attempt to derive and test the role of energy prices on economic growth. We first developed a two-sector endogenous growth model, based on Rebelo (1991). We modified the model such that consumption goods sector uses energy as an input along with capital. The model allows us to show that the growth rate of energy price has a negative effect on the growth rates of energy use and real GDP, consistent with the finding of van Zon and Yetkiner (2003), who studied a similar model by placing energy as an input in the intermediate goods sector. Following this, derived theoretical relationships between energy prices and economic growth and energy consumption were tested empirically using error-correction based panel cointegration tests and panel Autoregressive Distributed Lag (ARDL) approach. We applied this methodology on annual data of composite energy prices, GDP per capita and energy consumption per capita for fifteen countries for the period between 1978 and 2011. We found significant cointegration between energy prices and real GDP per capita as well as between energy prices and energy consumption per capita. Moreover, long-run elasticity estimates reveal a negative and significant impact of composite energy prices on both GDP per capita and energy consumption per capita.

Keywords: Two-sector model, energy price, endogenous growth, panel cointegration, panel ARDL.

JEL classification: O4, Q3, C3

1. Introduction

The impact of (rising) energy prices has never received substantial attention from growth economists, possibly because this has been perceived as a short to medium run issue.¹ Moreover, a plethora of empirical studies on short- or medium-term interactions between energy (especially oil) prices and macroeconomic indicators, since the pioneering study of Hamilton (1983), has suggested that the impact would in fact be temporary.² For instance, although sharp rises in oil prices, such as in 1973-74, 1978-80 and 1989-90 caused wide-scale recession in the world economy, the effects were not permanent.³ Yet, the stylized facts on US data for the period 1951–2010 indicate that the growth rate of energy prices may have had a negative effect on the growth rates of both energy demand and GDP (Figures 1.a–1.b).⁴ The effect, however, does not seem to be particularly strong, possibly due to the positive counter effects of other GDP determinants, such as technological advancement, or to the lag relationship between energy prices and GDP growth.

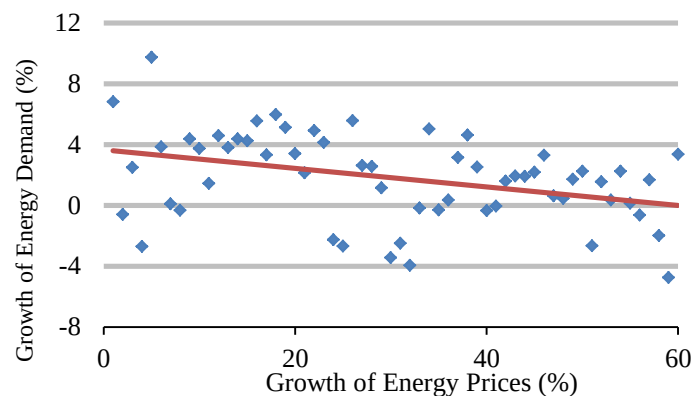


Figure 1a US Energy Demand Growth vs. Energy Price Growth
Source: Energy Information Administration (EIA)

¹ The attention of mainstream economic growth literature on the role of energy has been more on the optimal depletion problem and sustainability. Seminal works in this stream are as follows: Solow, 1974a, 1974b; Dasgupta and Heal, 1974; Stiglitz, 1974.

² See, for instance, Mork, 1989; Kahn and Hampton, 1990; Huntington, 1998; Brown and Yucel, 1999, 2002; Hamilton, 2003; Dickman and Holloway, 2004; Guo and Kliesen, 2005; Sill, 2007; Kilian, 2008; Oladosu, 2009.

³ We omit the 2007-2008 oil crisis, as its source and implications were different.

⁴ Energy data is downloaded from <http://www.eia.gov/totalenergy/data/monthly/#consumption> and the GDP per capita (PPP Converted, Chain Series, at 2005 constant prices) growth and relative price are downloaded from Penn World Table 7.1 (Heston et al., 2012).

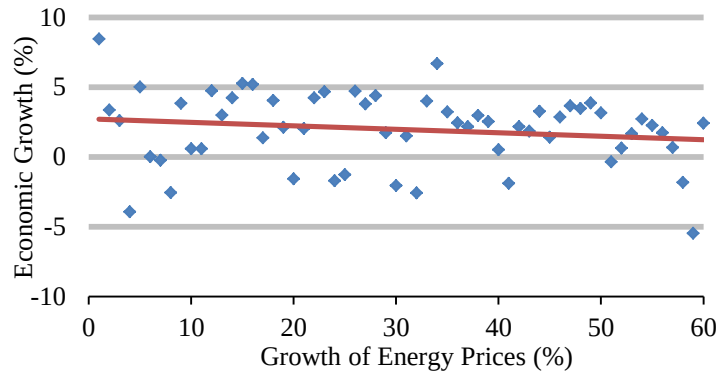


Figure 1b US GDP per capita Growth rate vs. Energy Price Growth
Sources: Energy Information Administration (EIA) and Penn World Table 7.1.

Although neither sufficiently scientific, nor strong, this result indicates that the issue is worthy for further analysis. For this purpose, we study a stylized model of an economy, in which an energy price-economic growth nexus is developed and tested. In the theoretical part of the paper, we develop a two-sector market economy à la Rebelo (1991). In our setup, the investment goods sector, the source of endogenous growth in the economy, uses only physical capital while the consumption goods sector uses both energy and capital as inputs. The reasoning behind this is that consumption goods sector has been responsible for the majority of energy consumption. For example, according to EIA's 2012 World Energy Outlook, the shares of transportation and residential sectors in total primary energy consumption slightly increased from 60.8% in 1990 to 60.9% in 2008 (Birol, 2012). The report also forecasts that those two sectors will remain to be dominant in energy demand with a total share changing between 59.4% and 59.8% until 2035.

Our model, further, presumes that the price of energy, whether renewable or non-renewable, is growing at a constant exogenous rate à la van Zon and Yetkiner (2003).⁵ In accordance with van Zon and Yetkiner (2003), we show that energy price growth has a negative effect on the growth rates of GDP per capita and energy demand. While van Zon and Yetkiner (2003), considering a three-sector model, have already shown the negative impact of rising energy price on economic growth, in their paper they have included energy as an input in the intermediate goods sector.⁶ Thus, our

⁵ In the Annex, we present the results of the model when energy price is a non-renewable and endogenous. From our research perspective, however, it is reasonable to keep energy price exogenous to the model.

⁶ Van Zon and Yetkiner (2003), which is in fact based on Romer (1990), uses energy in intermediate goods sector. Yet, as commonly known, intermediate goods are capital good varieties, thus intermediate goods sector can be considered as investment goods sector.

study complements van Zon and Yetkiner (2003), using energy in consumption goods sector.

The relationships derived in the theoretical part were tested empirically using an error-correction-based panel cointegration test and a panel Autoregressive Distributed Lag (ARDL hereafter) estimation for a group of countries, comprising Australia, Austria, Belgium, Canada, Denmark, France, Italy, Japan, the Netherlands, Norway, Portugal, Spain, Sweden, the United Kingdom and the United States. The data on real GDP per capita, energy consumption per capita and composite energy prices cover the period from 1978 to 2011. The test reveals that energy prices have a significant cointegration relationship with real GDP per capita as well as with energy consumption per capita. Moreover, we found that the energy prices have negative and significant long-run effect on both variables. The results support the derived theoretical relationships, not only of this article, but also of van Zon and Yetkiner (2003).

The contribution of this paper to the literature is two-fold. Firstly, it shows that there is an enduring relationship between energy prices and economic growth and between energy prices and energy consumption à la van Zon and Yetkiner (2003), and hence increases the robustness of their findings. Secondly, to the best of the authors' knowledge, few studies test the empirical regularity on the long-term relationship between energy price and economic growth, although a number of studies analyze the long-term relationship between energy consumption and economic growth.⁷ Existing studies mostly use error-correction based models (VECM or VAR) along with the cointegration tests to interpret the relationships for different countries (e.g. Stern, 1993; Gardner and Joutz, 1996; Asafu-Adjaye, 2000; Jimenez-Rodriguez and Sanchez, 2005). Thus, this study explores an untapped area of potential research by applying panel cointegration tests and panel ARDL methodologies to analyze the long-term effects of energy prices on economic growth and energy consumption.

The set-up of this paper is as follows. In section 2 we present the basic model showing that endogenous growth is inversely affected by energy price growth. Section 3

⁷ Ozturk (2010) provides an extensive survey of the literature on energy consumption-economic growth nexus since the seminal study of Kraft and Kraft (1978). Most recent studies mentioned in this survey either uses ARDL approach to individual countries (e.g. Odhiambo, 2009; Ozturk and Acaravci, 2010; Wang et al., 2011; Acaravci and Ozturk, 2012), or panel data error-correction models (e.g. Lee, 2005; Mahadevan and Asafu-Aladje, 2007; Lee and Chang, 2008; Belke et al., 2011; Eggoh et al., 2011).

presents the empirical analysis. A summary and some concluding remarks are provided in section 4.

2. A Two-Sector Endogenous Growth Model

The model developed in this article is based on a closed economy with no government. We define overall utility of the representative consumer in the economy as $U(C_t) = \int_0^\infty e^{-\rho \cdot t} u(C_t) dt$, where felicity function is $u(C) = \frac{C^{1-\theta}-1}{1-\theta}$, C is the consumption level, ρ is the subjective rate of discount and $1/\theta$ represents intertemporal elasticity of substitution. We presume that there are two types of factor of production in the model: broader interpretation of physical capital, K , and energy, E . We further presume that there are also two sectors in the economy, namely investment goods sector and consumption goods sector. Following Rebelo (1991), we define production technology of the investment goods sector as follows:

$$Y_I = A \cdot K_I \quad (1)$$

In (1), Y_I represents output in investment goods sector, A is overall factor productivity, and K_I , a flow variable, is a broader interpretation of physical capital used in investment good production.

Consumption good is produced via flow variables physical capital (K_C) and energy (E) under constant returns to scale production technology defined as:

$$Y_C(\equiv C) = K_C^\alpha \cdot E^{1-\alpha} \quad (2)$$

We assume that total physical capital stock $K (= K_I + K_C)$ is fully employed.

Equilibrium process in the investment goods sector from profit equation $\Pi_I = p_I \cdot A \cdot K_I - R_I \cdot K_I$ leads to

$$p_I \cdot A = R_I \quad (3)$$

In (3), R_I is nominal rental rate (user cost) of physical capital in investment good production and p_I is the price of investment goods. For any K_I , $p_I \cdot A = R_I$ condition must be satisfied. Profit maximization of the consumption goods sector yields inverse demand functions for physical capital (employed in the sector) and energy. In particular, the nominal profit equation $\Pi_C = p_C \cdot K_C^\alpha \cdot E^{1-\alpha} - R_C \cdot K_C - R_E \cdot E$ yields

$$p_C \cdot \alpha \cdot K_C^{\alpha-1} \cdot E^{1-\alpha} = R_C \quad (4a)$$

$$p_C \cdot (1 - \alpha) \cdot K_C^\alpha \cdot E^{-\alpha} = R_E \quad (4b)$$

In equations (4a) and (4b), R_C is the nominal rental rate (user cost) of physical capital in consumption good production, R_E is the nominal price of energy and p_C is the price of consumption goods. Real energy price is defined as $q = \frac{R_E}{p_C}$, and à la von Zon and Yetkiner (2003), it was considered as growing at a constant rate, $\hat{q} > 0$, and that energy supply is infinite at the given energy price.

No arbitrage condition implies that rental rate of capital in both sectors must be equal. Hence,

$$R_I \equiv R_C \Rightarrow p_I \cdot A = p_C \cdot \alpha \cdot K_C^{\alpha-1} \cdot E^{1-\alpha} \Rightarrow p \cdot A = \alpha \cdot K_C^{\alpha-1} \cdot E^{1-\alpha} \quad (5)$$

In (5), $p = \frac{p_I}{p_C}$ is relative price of investment goods in terms of consumption goods. Then, real user cost of capital (i.e. rental rate) is $RR = p \cdot A = \alpha \cdot K_C^{\alpha-1} \cdot E^{1-\alpha}$. One clear implication of equation (5) is that $\hat{p} = (\alpha - 1)\hat{K}_C + (1 - \alpha)\hat{E}$, where $\hat{p}$, $\hat{K}_C$ and $\hat{E}$ represent the growth rates of relative price of investment goods (p) and capital (K_C) and energy (E) used by consumption goods sector, respectively. Recall that standard definition of user cost of capital is as follows:

$$RR \equiv (r + \delta - \hat{p}) \cdot p \quad (6)$$

In (6), r is real interest rate in terms of consumption good price, δ is capital depreciation rate and $\hat{p}$ is the capital loss due to changes in price.

For competitive equilibrium, we also need to examine the representative consumer's optimization problem. To this end, under the assumptions provided so far, the present value Hamiltonian would be as follows:

$$H = e^{-\rho \cdot t} \cdot \frac{C^{1-\theta} - 1}{1-\theta} + \lambda \{r \cdot Assets + q \cdot E - C\} \quad (7)$$

In (7), *Assets* represents financial stock of the consumer and r is the real interest rate. We hereby assumed that the consumers receive $q \cdot E$ since they are treated as the owner of the energy resource stocks. First order optimization conditions are as follows:

$$\frac{\partial H}{\partial C} = 0 \Rightarrow e^{-\rho \cdot t} \cdot C^{-\theta} = \lambda \quad (8a)$$

$$\dot{\lambda} = -\frac{\partial H}{\partial Assets} \Rightarrow \dot{\lambda} = -\lambda \cdot \{r\} \quad (8b)$$

$$\dot{Assets} = \frac{\partial H}{\partial \lambda} \Rightarrow \dot{Assets} = r \cdot Assets + q \cdot E - C \quad (8c)$$

In addition to these conditions, transversality condition, $\lim_{t \rightarrow \infty} \lambda(t) \cdot Assets = 0$, must be satisfied. Equations (8a) and (8b) yield:

$$\frac{\dot{C}}{C} = \frac{1}{\theta} \{r - \rho\} \quad (9)$$

At equilibrium, financial assets must be equal to physical capital under a closed economy with no government assumption; $Assets = p(t) \cdot K(t)$. Using this information, we may transform the representative consumer's budget constraint. Firstly, $\dot{Assets} = \dot{p} \cdot K + p \cdot \dot{K}$. From (4b), real energy price is $q = (1 - \alpha) \cdot K_C^\alpha \cdot E^{-\alpha}$, and from (5) and (6) $r = A - \delta + \hat{p}$. Hence,

$$\begin{aligned} \dot{p} \cdot K + p \cdot \dot{K} &= p \cdot K \cdot (A - \delta + \hat{p}) + (1 - \alpha) \cdot K_C^\alpha \cdot E^{1-\alpha} - K_C^\alpha \cdot E^{1-\alpha} \Rightarrow \\ p \cdot \dot{K} &= p \cdot K \cdot (A - \delta) - \alpha \cdot K_C^\alpha \cdot E^{1-\alpha} \end{aligned}$$

If one substitutes $A \cdot p$ for $\alpha \cdot K_C^{\alpha-1} \cdot E^{1-\alpha}$ due to (5) and divide both sides by p , we end up with:

$$\dot{K} = (A - \delta) \cdot K - A \cdot K_C \quad (10)$$

Hence, the optimization problem of representative consumer yields (9) and (10).

The model can be solved via the first order conditions derived from the optimization problems of representative firms and consumer. Firstly, if we use $r = A - \delta + \hat{p}$ obtained from equation (6) in (9), we get $\frac{\dot{C}}{C} = \frac{1}{\theta} \{A - \delta + \hat{p} - \rho\}$. Substituting $\hat{p} = (\alpha - 1)\hat{K}_C + (1 - \alpha)\hat{E}$ from (5) instead of $\hat{p}$, we find $\frac{\dot{C}}{C} = \frac{1}{\theta} \{A - \delta + (\alpha - 1)\hat{K}_C + (1 - \alpha)\hat{E} - \rho\}$. As $\hat{C} = \hat{Y}_C = \alpha\hat{K}_C + (1 - \alpha)\hat{E}$ due to equation (2),

$$\begin{aligned} \alpha\hat{K}_C + (1 - \alpha)\hat{E} &= \frac{1}{\theta} \{A - \delta + (\alpha - 1)\hat{K}_C + (1 - \alpha)\hat{E} - \rho\} \Rightarrow \\ (1 - \alpha + \alpha\theta)\hat{K}_C + (1 - \alpha)(\theta - 1)\hat{E} &= A - \delta - \rho \end{aligned}$$

Finally, as $\alpha\hat{K}_C - \alpha\hat{E} = \hat{q}$ due to (4b), we obtain

$$\hat{E} = \frac{1}{\theta} \left(A - \delta - \rho - \frac{(1 - \alpha + \alpha\theta)}{\alpha} \hat{q} \right) \equiv g' \quad (11a)$$

$$\hat{K}_C = \frac{1}{\theta} \left(A - \delta - \rho - \frac{(1-\alpha)(1-\theta)}{\alpha} \hat{q} \right) \equiv g \quad (11b)$$

$$\hat{C} = \hat{Y}_C = \frac{1}{\theta} \left(A - \delta - \rho - \frac{(1-\alpha)}{\alpha} \hat{q} \right) \equiv \alpha g + (1-\alpha)g' \quad (11c)$$

where $\hat{q}$ is the growth rate of energy prices. Equations (11a-11c) imply that energy price growth has negative impact on the growth rate of energy use, as also shown by van Zon and Yetkiner (2003). Note that $\frac{1-\alpha+\alpha\theta}{\alpha} > \frac{(1-\alpha)(1-\theta)}{\alpha}$ and that $\frac{1-\alpha+\alpha\theta}{\alpha} > \frac{1-\alpha}{\alpha}$. We will assume that the condition; $A - \delta - \rho > \frac{(1-\alpha+\alpha\theta)}{\alpha}$ holds, hence all growth rates above are positive. We may now solve the rest of the model under this assumption. First of all, using $\hat{p} = (\alpha - 1)\hat{K}_C + (1 - \alpha)\hat{E}$ equality, one can easily show that

$$\hat{p} = - \left(\frac{1-\alpha}{\alpha} \right) \hat{q}$$

This result can also be expressed as $p(t) = p(0) \cdot e^{-\left(\frac{1-\alpha}{\alpha}\right)\hat{q} \cdot t}$.⁸ As long as growth rate of energy price is positive, relative price of investment goods in terms of consumption goods $p(t)$ approaches zero. From the equality of $r = A - \delta + \hat{p}$, we may show that

$$r = A - \delta - \left(\frac{1-\alpha}{\alpha} \right) \hat{q}$$

Obviously, real interest rate and hence growth rate of consumption level, $\hat{C}$, are positive if and only if $A - \delta > \left(\frac{1-\alpha}{\alpha} \right) \hat{q}$. Moreover, from equation (8b) we get,

$$\hat{\lambda} = - \left\{ A - \delta - \left(\frac{1-\alpha}{\alpha} \right) \hat{q} \right\}$$

As $r > 0$, λ must be approaching to zero. If we solve equation (10) via integrating factor method, we get

$$K(t) = \frac{A \cdot K_c(0)}{A - \delta - g} \cdot e^{g \cdot t} + const \cdot e^{(A-\delta) \cdot t}$$

where, *const* stands for constant term. We may easily determine the value of the constant term via the transversality condition. In particular, substituting respective values of λ and *Assets* = $p \cdot K$ in transversality condition $\lim_{t \rightarrow \infty} \{\lambda(t) \cdot \text{Assets}\} =$

⁸ Recall that growth rate of energy price is constant. Note that we may write the result also as $p(t) = p'(0) \cdot (q(t))^{-(1-\alpha)}$, $p'(0) = p(0)(q(0))^{-(1-\alpha)}$.

0 yields that *const* must be zero. In addition to this, the condition $A - \delta - g > 0$ must hold for the transversality condition converges to zero at limit.⁹ In conclusion, total capital stock path is given by,

$$K(t) = \frac{A \cdot K_c(0)}{A - \delta - g} \cdot e^{g \cdot t} \quad (12)$$

Hence, total capital stock is growing at rate g . Given that initial capital stock is defined exogenously as, $K(0) \equiv K_0 = \frac{A \cdot K_c(0)}{A - \delta - g}$, to the model, we can determine initial values of flow variables, i.e. $K_c(0)$, $K_I(0)$, $E(0)$.¹⁰

Finally, let us determine the time path of Real GDP. To this end, note that nominal GDP (NGDP) and real GDP in terms of consumption goods (Y) would be defined as:

$$NGDP = p_I \cdot Y_I + p_C \cdot Y_C \Rightarrow$$

$$Y = p \cdot Y_I + Y_C$$

One can easily show that real GDP is:

$$Y = const1 \cdot e^{[\alpha g + (1 - \alpha)g'] \cdot t} \quad (13)$$

In (13), $const1 = p(0) \cdot Y_I(0) + (K_C(0))^\alpha \cdot (E(0))^{1 - \alpha}$, a collection of initial values of the model. In conclusion, total physical capital stock, investment capital and consumption capital all grow at rate g . On the other hand, energy demand grows at rate g' and real GDP and consumption grow at rate $\alpha g + (1 - \alpha)g'$, which is the weighted growth rate of energy and physical capital. Energy price growth rate has a negative effect on all growth rates.

3. Testing the Long-run Effects of Energy Prices

In this section, we attempted to test the long-run relationship between energy prices, economic growth and energy consumption, that we have derived in theoretical part, cf., equations 11a and 11c. For empirical purposes, equations 11a and 11c can, respectively, be reformulated as:

⁹ For $\theta > 1$, $\frac{(A - \delta)\alpha(\theta - 1) + \rho}{\alpha\theta + 1 - \alpha}$ is certainly positive. If $\theta < 1$, $\rho > (A - \delta)\alpha(\theta - 1)$ must hold.

¹⁰ It is straightforward to show that $E(0) = (1 - \alpha)^{\frac{1}{\alpha}} \frac{(A - \delta - g)}{A} \cdot K_0 \cdot (q_0)^{-\frac{1}{\alpha}}$, $K_C(0) = \frac{(A - \delta - g)}{A} \cdot K_0$, $K_I(0) = \frac{\delta + g}{A} \cdot K_0$ and $p(0) = (1 - \alpha)^{\frac{1 - \alpha}{\alpha}} \cdot \frac{\alpha}{A} \cdot (q_0)^{-\frac{(1 - \alpha)}{\alpha}}$.

$$\hat{E} = \beta_{10} + \beta_1 \hat{q} \quad (11a)'$$

$$\hat{Y}_C = \beta_{20} + \beta_2 \hat{q} \quad (11c)'$$

where, $\beta_{10} = \beta_{20} = \frac{1}{\theta}(A - \delta - \rho)$, $\beta_1 = -\frac{1}{\theta} \frac{(1-\alpha+\alpha\theta)}{\alpha}$ and $\beta_2 = -\frac{1}{\theta} \frac{(1-\alpha)}{\alpha}$. The growth rates $\hat{E}$, $\hat{Y}_C$ and $\hat{q}$ can further be defined as $\frac{d}{dt}\ln(E)$, $\frac{d}{dt}\ln(Y_C)$ and $\frac{d}{dt}\ln(q)$, respectively. Therefore, integrating both sides of both (11a)' and (11c)' will lead:

$$\ln(E) = \alpha_{10} + \beta_{10}t + \beta_1 \ln(q) \quad (14a)$$

$$\ln(Y_C) = \alpha_{20} + \beta_{20}t + \beta_2 \ln(q) \quad (14b)$$

where, α_{10} and α_{20} are the constant terms emerged from integration procedure and t is the time trend component. The equations (14a) and (14b) are the long-run relationships to be tested. To this end, error-correction based panel cointegration test (Westerlund; 2007) and panel ARDL methodology (Pesaran et al., 1997 and 1999) are applied on balanced panel data, consisting of GDP per capita (Y), composite energy prices (q) and energy consumption per capita (E), covering the period between 1978 and 2011 for fifteen countries; namely Australia, Austria, Belgium, Canada, Denmark, France, Italy, Japan, Netherlands, Norway, Portugal, Spain, Sweden, United Kingdom and United States (Table 1). While, GDP per capita and energy consumption per capita have been taken from WDI, the composite energy prices for countries, defined as real index for households and industry (2005=100), have taken from International Energy Agency's (IEA) statistics database. All three variables are used in natural logarithms and indexed taking 2005 as the base year.

Table 1. Descriptive Statistics of variables (in natural logarithms) over 1978– 2011

Statistics\Variables	$\ln(Y)$	$\ln(E)$	$\ln(q)$
Mean	4.397	4.512	4.505
Std. Dev.	0.192	0.154	0.177
Minimum	3.928	3.598	3.804
Maximum	4.711	4.785	5.006
# of Countries	15	15	15
# of Observations	510	510	510

We have applied error-correction based panel data cointegration test proposed by Westerlund (2007). As correctly noted by Eggoh et al. (2011), this approach is more advantageous than other panel data cointegration tests, such as the one proposed by

Pedroni (1999), as it avoids the problem of common factor restriction. Persyn and Westerlund (2008) describe the data generating process assumed by this error-correction test as follows:

$$\Delta y_{i,t} = \delta'_i d_t + \alpha_i y_{i,t-1} + \lambda'_i x_{i,t-1} + \sum_{j=1}^{p_i} \alpha_{i,j} \Delta y_{i,t-j} + \sum_{j=-q_i}^{p_i} \gamma_{i,j} \Delta x_{i,t-j} + \varepsilon_{i,t} \quad (15)$$

where, $y_{i,t}$ is dependent variable, which in our case is either $\ln(Y)$ or $\ln(E)$ and $x_{i,t}$ is the independent variable, which is $\ln(q)$ for our case, for country i in year t . Moreover, while d_t represents the deterministic components, λ_i is defined as $-\alpha_i \beta'_i$ with α_i capturing the seed at which the system $y_{i,t-1} - \beta'_i x_{i,t-1}$ adjusts back to the equilibrium after an unexpected shock. Therefore, if $\alpha_i < 0$ model implies a cointegration between variables and thus the null hypothesis tested is $H_0: \alpha_i = 0$ for all i . Westerlund (2007) proposes four different tests; two of these, namely the group mean tests G_t and G_a , use alternative hypothesis of $H_A: \alpha_i < 0$ for at least one i . The remaining two, namely, the panel tests P_t and P_a , use the alternative hypothesis of $H_A: \alpha_i = \alpha < 0$ for all i . The optimal lag and lead lengths of the variables have been chosen via Akaike Information Criteria (AIC). Moreover, following Persyn and Westerlund (2008) the Kernel width has been set as $4(T/100)^{2/9}$, where T is the number of observations in time series dimension.

As both cointegration test and panel ARDL approach requires I(1) variables we have tested the variables for unit root using Levin-Li-Chu (LLC) and Im-Pesaran-Shin (IPS) tests proposed by Levin et al. (2002) and Im et al. (2003), respectively. Table 2 provides the results of the unit root tests. Evidently, according to these results, the first differences of all three variables are stationary, and thus they can be used in the above-mentioned methodologies.

Table 2. Panel Unit Root Test Results

Variable	LLC		IPS	
	Level	First Difference	Level	First Difference
$\ln(Y)$	0.5000	-7.9832***	2.8383	-9.2158***
$\ln(E)$	2.7042	-3.5820***	-0.1187	-12.6801***
$\ln(q)$	1.5312	-7.0430***	0.0556	-10.3811***

Notes: Tests conducted with constant and trend components. ***, **, * represent significance at 1%, 5%, 10% levels, respectively.

We further proceed with the estimation of equation (15) and following the procedure described above, we have presented the results of the four-cointegration tests on Table 3. All test statistics lead us to reject the null hypothesis of no cointegration between Y and q , as well as between E and q , at either the 1% or 5% significance level.

Table 3. Panel Cointegration Test Results

Relationship Tested	G_τ	G_α	P_τ	P_α
$\ln(Y)$ vs. $\ln(q)$	-2.753**	-29.554***	-9.871**	-24.351***
$\ln(E)$ vs. $\ln(q)$	-3.488***	-26.337***	-12.562***	-22.376***

Notes: ***, **, * represent significance at 1%, 5%, 10% levels, respectively. Optimal lag and lead lengths selected via AIC are both 1 and optimal Bartlett kernel window width is set to be 3.

Having concluded that two cointegrating relationships exist, we have, subsequently, applied Pooled Mean Group (PMG hereafter) and Mean Group (MG hereafter) estimators (i.e. panel ARDL methodology) proposed by Pesaran et al. (1997, 1999). While MG estimator is based on estimating N times time-series regressions and averaging the coefficients, PMG estimator reveals pooled coefficients. Pesaran et al. (1999) suggests that PMG estimator is more efficient, yet this is only consistent when the model is homogenous, i.e. long-run elasticities are equal across countries. MG estimator is advantageous because it is consistent even when the panel data exhibits heterogeneous characteristics, which is common in cross-country studies. Following Blackburne III and Frank (2007), we have defined ARDL(1,1)¹¹ dynamic panel specification of (14) as:

$$y_{it} = \lambda_i y_{it-1} \mu_i + \delta_{10i} x_{it} + \delta_{11i} x_{it-1} + \delta_{20i} t + \varepsilon_{it} \quad (16)$$

and the error-correction parameterization as:

$$\Delta y_{it} = \phi_i (y_{it-1} - \theta_{0i} - \theta_{1i} x_{it} - \theta_{2i} t) + \delta_{11i} \Delta x_{it} + \varepsilon_{it} \quad (17)$$

where; $\phi_i = -(1 - \lambda_i)$ is the error-correction term (ECT) speed of adjustment, $\theta_{0i} = \frac{\mu_i}{1 - \lambda_i}$ is the non-zero mean of cointegration relationship, $\theta_{2i} = \frac{\delta_{20i}}{1 - \lambda_i}$ and $\theta_{1i} =$

¹¹ Lag-length of ARDL model is selected via AIC.

$\frac{\delta_{10i} + \delta_{11i}}{1 - \lambda_i}$ is the coefficient of interest, i.e. long-run estimates of elasticity β_1 and β_2 in equations (14a) and (14b), respectively. Obviously, for our case, negative and significant ϕ_i and θ_{1i} should be expected for both two relationships under consideration, i.e. $\ln(Y)$ vs. $\ln(q)$ and $\ln(E)$ vs. $\ln(q)$. The estimation results for both relationships and for both estimators (MG and PMG) have been provided on Table 4.

Table 4. Panel ARDL Long Run and ECT Estimates

	$\ln(Y)$		$\ln(E)$	
	MG	PMG	MG	PMG
Long-Run Estimates				
$\ln(q)$	-0.4488*** (0.0944)	-0.5120*** (0.1080)	-0.4779*** (0.0986)	-0.6477*** (0.0590)
t	0.0188*** (0.0031)	0.0109*** (0.0016)	0.0068*** (0.0018)	0.0026*** (0.0008)
ECT	-0.1932*** (0.0327)	-0.0750*** (0.0125)	-0.4850*** (0.0577)	-0.1640*** (0.0357)

Notes: Figures in parenthesis are standard errors. ***, **, * represent significance at 1%, 5%, 10% levels, respectively.

The results are in accordance with the expectations on the coefficients; $\beta_1 < 0$ and $\beta_2 < 0$. MG and PMG estimators estimate negative and highly significant long-run energy price elasticity of both GDP per capita and energy consumption per capita. Estimation results reveal also that elasticity of energy consumption per capita (0.48 for MG estimator and -0.65 for PMG estimator) is higher than that of GDP per capita (-0.45 for MG estimator and -0.51 for PMG estimator). These results are consistent with the theory proposed in this article, as well as with the empirical literature. For instance, Killian (2008) has estimated the price elasticity of US total energy demand as -0.45 with error bounds of -0.27 and -0.66, moreover, Cooper (2003) suggested a range between -0.03 and -0.56 for price elasticity of oil demand for different countries. Although our estimates on energy price elasticity of GDP appears to be higher than that of the literature (e.g. Brown and Yücel, 1999; Greene and Leiby, 2006), they are reasonable as the prior studies mostly concentrated only on the effects of oil prices in the short-run. Moreover, negative and significant ECT terms indicate that the deviations from the long-run path are corrected each period, thus all variables return to their long-run equilibrium.

4. Concluding Remarks

In this paper we have presented a two-sector endogenous growth model, following Rebelo (1991). By including energy as an input in consumption good sector, we have been able to show that the endogenous growth rate of both output and energy consumption depends negatively on the rate of growth of energy price. These findings are consistent with van Zon and Yetkiner (2003), who use the very same argument in a study of a three-sector model in which energy is identified as an input in the intermediate-good sector. By testing the theoretical relationships derived by employing error-correction based panel cointegration and panel ARDL methodologies, we found that energy prices have negative and significant impact on both real GDP per capita and energy consumption per capita in the long-run. Thus, the empirical regularity represented here supports the theoretical findings not only of this article, but also of van Zon and Yetkiner (2003).

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Appendix

Solution of the Model under Endogenous Energy Price

Suppose now that the energy is a non-renewable one. The non-arbitrage condition would then involve that the real price of energy must increase at the real interest rate:¹²

$$\hat{q} = r(t) \quad (\text{A.1})$$

Equation (A.1) is the well-known Hotelling's rule in its simplest form. Now let us use this information in the model. One may recall that we obtained $\alpha \hat{K}_C - \alpha \hat{E} = \hat{q}$ from equation (4b), $r = A - \delta + \hat{p}$ from equation (6) and $\hat{p} = (\alpha - 1)\hat{K}_C + (1 - \alpha)\hat{E}$ from equation (5). Therefore

¹² Suppose that the energy market is a perfectly competitive one and that extraction is costless. Under these assumptions, the representative firm would solve the following maximization problem (cf., Yetkiner and van Zon, 2008 and Gaitan et al., 2004):

$$\begin{aligned} \text{Max} \quad & \int_0^{\infty} q(t) \cdot E(t) \cdot e^{-\int_0^t r(\tau) d\tau} \\ \text{s. t.} \quad & \int_0^{\infty} E(t) dt \leq S_0 \\ & \lim_{t \rightarrow \infty} \left\{ q(t) \cdot E(t) \cdot e^{-\int_0^t r(\tau) d\tau} \right\} \end{aligned}$$

where S_0 is the initial stock of the nonrenewable energy. The solution of the isoperimetric calculus of variations problem leads to (12).

$$\begin{aligned}
\alpha \hat{K}_C - \alpha \hat{E} &= \hat{q} = r = A - \delta + \hat{p} \Rightarrow \\
\alpha \hat{K}_C - \alpha \hat{E} &= A - \delta + (\alpha - 1)\hat{K}_C + (1 - \alpha)\hat{E} \Rightarrow \\
\hat{K}_C &= A - \delta + \hat{E}
\end{aligned}$$

If this information is used in equation (9), we obtain

$$\begin{aligned}
\frac{\dot{C}}{C} &= \frac{1}{\theta} \{A - \delta + \hat{p} - \rho\} \Rightarrow \\
\frac{\dot{C}}{C} &= \frac{1}{\theta} \{A - \delta + (1 - \alpha)(\hat{E} - \hat{K}_C) - \rho\} \Rightarrow \\
\frac{\dot{C}}{C} &= \frac{1}{\theta} \{\alpha(A - \delta) - \rho\}
\end{aligned}$$

Hence,

$$\begin{aligned}
\hat{p} &= -(1 - \alpha)(A - \delta) \\
r = \hat{q} &= \alpha(A - \delta) \\
\hat{E} &= \frac{1}{\theta} [\alpha(A - \delta)(1 - \theta) - \rho] \equiv g' \\
\hat{K}_C &= \frac{1}{\theta} [(A - \delta)(\theta + \alpha(1 - \theta)) - \rho] \equiv g
\end{aligned}$$

Interestingly, given that $A - \delta > 0$ for a positive real interest rate and energy price growth rate, θ must be less than one. Otherwise, energy demand would be decreasing in time. As $\theta + \alpha(1 - \theta) > 0$ is always true, growth rate of physical stock employed in consumption good sector is positive as long as $(A - \delta)(\theta + \alpha(1 - \theta)) > \rho$.