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Saten Kumar, Don J. Webber and Antonio Paradiso

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Saten Kumar[†], **Don J. Webber**[‡] **and Antonio Paradiso**[§]

[†] Department of Economics, Auckland University of Technology, Auckland, New Zealand
[‡] Department of Accounting, Economics and Finance, University of the West of England, Bristol, UK
[§] Department of Economics, National Institute of Statistics, Rome, Italy

Abstract

A review of the literature reveals discrepancies between estimates of the impact of energy consumption on output and growth. This paper highlights the importance of underlying theoretical concerns, extends a neoclassical growth model to include energy consumption, applies panel data cointegration methods that deal with cross-sectional dependence and structural breaks to a sample of thirteen high energy consuming countries, and provides empirical estimates of the impact of energy consumption on output and growth. Results suggest that energy consumption has a permanent positive effect on output levels but has no statistically significant effect on growth. We suggest that rebound effects may confound the observable effects of energy on growth and that the effects on the environment of attempts to stimulate economic growth may never be forecast correctly ex ante.

Keywords: Energy consumption per capita; Level effect; Growth effect

JEL Numbers: O40; Q40

Address for correspondence: Dr Saten Kumar, Department of Economics, Auckland University of Technology, Auckland, New Zealand. Email: Saten.Kumar@aut.ac.nz

1. Introduction

A central tenet in energy economics is that energy is an essential input into production and positively enhances economic growth. Greater amounts of energy are known to have multifaceted positive effects on productivity, and these effects can be either direct, for example through the acceleration of machines, or indirect, through improving the quality of the office or learning/working environment. Energy consumption is also positively related to productivity because other factors of production often cannot operate effectively without it. The concept of countries investing in energy availability in order to raise their output, productivity and potential marginal returns and not limit future economic expansion is widely accepted in economics and is connected to the presumption that cutbacks in energy-related R&D could reduce the potential rate of innovation in the energy sector (Margolis and Kammen, 1999). Some even postulate that "Limited natural resources (such as coal, natural gas and oil supplies) imply a serious drag on *growth* that may eliminate most or all of the positive influence of technological progress on income per capita" (Arbex and Perobelli, 2010, p. 43, emphasis added).

Recent studies have attempted to highlight the importance of energy in the production process by including energy consumption per capita (or proxies thereof) in a growth model. Oh and Lee (2004), Lee and Chiang (2008), Lee *et al*. (2008), Yuan *et al*. (2008) and Wolde-Rufael (2008) all provide evidence that energy consumption contributes positively to growth. However, other studies question this relationship with, for example, Soytas and Sari (2006) and Wolde-Rufael (2009) suggesting that this relationship varies across countries. These studies fail to take comprehensive account of adjustments in consumption behaviour that occur partly because of the indirect effects of energy-saving technical change and partly because of the concomitant energy redeployments that can enhance output, growth and environmental degradation.

This paper articulates the importance of rebound effects that theoretically underpin but empirically confound the dynamic relationships between energy consumption and output. A lack of understanding of these rebound effects can result in spurious estimates of seemingly appropriate growth models. Then the paper orientates to augment the neoclassical growth model to include energy consumption and estimates this model through the application of cointegration methods that deal with cross-sectional dependence and structural breaks; application of these econometric techniques allow for any cross-sectional dependency in the errors which may be due to the presence of common shocks and/or unobserved components, such as technical improvements, which ultimately become part of the error term. It is also possible that there are shifts in time series observations due to some events, again such as technical improvements, and not controlling for structural change in time series estimations may lead to large forecasting errors and unreliable results.

The aim of this paper, therefore, is to strengthen understanding of the relationships between energy consumption and output and to assess empirically the contributory effects of energy consumption on the level and growth of national output using a sample of thirteen high energy consuming countries. Our results highlight that energy consumption enhances output, but the relationship between energy consumption and economic growth is much less clear and probably cannot be forecast accurately ex ante.

2. A review of the literature

Rebound effects

A key concern with energy consumption analyses remains the rebound effect.[1] This refers to the changes in behaviour that are due to the introduction of new technologies that increase the efficiency of resource use. Although we are unable to introduce and quantify directly the relative influence of new technologies on energy consumption and growth in our modelling approach, and in particular the decomposition of this behaviour change into income and substitution effects, it is imperative that underlying theoretical effects are explicitly considered here.

Behaviours can change due to new energy-saving technologies in three main ways:

i) New technologies improve energy efficiency and reduce energy consumption. However, they will also lower the cost of energy and therefore potentially increase energy consumption through the substitution effect, which is referred to as the *direct rebound effect*.
ii) *Indirect rebound effects* occur when energy cost savings permit greater consumption of other goods through the income effect due to lower prices and lower inflation
iii) *Economy-wide rebound effects* occur when new technologies make new goods cost effective to produce and thereby lead to supply-led growth.

For simplicity and clarity, Figure 1 illustrates the direct and indirect rebound effects of an improvement in efficiency of production. Assume an energy-saving technical change enables good *i* to be made with less energy; this is illustrated with an outward pivot of the community budget line from B_1 to B_2, and shows that more of good *i* can be produced using the same amount of energy, and therefore the energy required and the cost of producing good *i* both fall if the quantity of good *i* was held constant. The critical issue is whether a change in the price of good *i* brought about by the change in rate of energy consumption spawns an increase, decrease or no change in the consumption of goods.

{Figure 1 about here}

Assuming away corner solutions and asymptotic preferences, consider the initial equilibrium point e_1. The change in prices, keeping the level of community satisfaction constant, will result in an increase in the consumption of good *i* from i_1 to i_s, which is the direct rebound effect highlighted above, and occurs at the expense of all other goods whose consumption falls from O_1 to O_s. Therefore, as the diagram shows, it is highly unlikely that an improvement in energy efficiency in production, brought about by some technical change, will result in a directly proportional reduction in energy consumption. Figure 1 shows a direct effect that is rather small, but suggestions that this is the end of the argument would be erroneous. The indirect rebound effect of the increase in real income on the consumption of good *i* will depend on the extent to which it is considered inferior: it would be entirely possible for consumers to spend their

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[1] See Jevons (1866), Khazzoom (1980), Lovins *et al*. (1988), Brooks (1990), Grubb (1990) and Saunders (1992) for a broad discussion of rebound effect and Greening *et al*. (2000) for a useful literature review.

increase in real incomes entirely on an increase in consumption of good *i*, as illustrated at equilibrium point e_2, thereby resulting in no reduction in energy consumption and hence no reduction in the level of environmental degradation albeit with an increase in total output.

If good *i* is considered inferior then the energy-saving technical change could manifest itself as a movement to equilibrium point e_3, which corresponds to a reduction in the consumption of good *i* concomitant with an increase in the consumption of all other goods. It is clear that the reduction in production of good *i* is associated with a reduction in output, and potentially negative economic growth, but the same simple conclusion about the effect on energy consumption is not reachable when examining the potential impact on all other goods.[2] The reasons for this inherent uncertainty relates to a plethora of factors which includes the following:

First, equilibrium position e_3 is associated with an increase in the consumption and production of all other goods. As the energy-saving technical change is not (currently) appropriate for these other goods it is entirely possible that this change in the quantity of consumption and production of all other goods is concomitant with an increase in total energy consumption. Second, if all other goods do not use energy in their production process then the total quantity of energy consumption will fall, and the fall will also be present, albeit smaller in magnitude, if the rate of energy consumption is lower in the production of all other goods than it was in the production of good *i*. In other words, even if the change in consumption bundles do not result in an increase in output that offsets the sum of the direct and indirect effects of energy-saving technical change, the dynamic effects of energy-saving technical change on energy consumption could be positive if there is a corresponding expansion in the whole economy. It is well known that more efficient technology is equivalent to a lower price for energy resources and that changes in energy costs have a large impact on growth rates and unemployment (see, for example, Carruth *et al*., 1998). Third, it would be theoretically possible for a government to tax production in industry *i* proportional to the increase in technical efficiency (see Wackernagel and Rees, 1997); thus energy-saving technical change could result in no movement away from community indifference curve IC_1 due to a parallel shift inwards of budget constraint B_2 that is directly proportional to a tax increase, and hence there will only be substitution effects present. Fourth, increases in real incomes brought about by energy-saving technical change could be spent on imports, and will be further complicated by Rothbarth and Engel type effects as well as the country's comparative advantage in the production of luxury goods.

The magnitude and significance of these rebound effects will vary depending on scale economies and the driving forces of competition in the market. There is also evidence that the size of the rebound effect is small to moderate in developed economies and less significant than in developing economics (Greening *et al*., 2000); two prime reasons for this empirical observation is the relatively high quality of outputs across which energy consumption costs are spread in developed economies and differences in the price elasticity of demand.

Taking explicit consideration of the underlying theoretical effects of energy-saving technical progress on output and economic growth leads to the realization that energy consumption is positively related to output levels, but the dynamic relationship with between energy consumption and output growth is much less certain. It may be that these rebound effects that are at the root of the unsettled empirical debate concerning the relationship between energy

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[2] A further complication can be made when the (energy-saving) technical change makes it more favourable to produce the good overseas. A discussion of the impact of technical change on outsourcing and the coexistent rate of energy consumption brought about by the income effect is beyond the scope of this paper.

consumption and economic growth. To shine light on this issue further, below we augment a neoclassical growth model to include energy consumption and then estimate this through the application of panel cointegration methods that deal with cross-sectional dependence and structural breaks to identify whether there are level or growth effects of energy consumption on output and economic growth.

Modelling growth and energy[3]

It has been shown that energy can have an important direct effect on growth and development; for example, Venneslan (2009) claims that electricity is a fundamental input in the manufacturing production process as it enabled the achievement of scale economies which subsequently led to Norway's industrialisation. To this end, it could be argued that extant growth models are built upon a disjunction between the economy and ecology. Georgescu-Roegen (1975, 1976) was the first to point out that Marxists and neoclassical economists do not recognize non-renewable resources such as energy in the production process and argued that they treat energy as a raw material or intermediate good instead, thereby giving primary focus to labour, capital and technology. Nevertheless, the literature has since progressed along three distinct lines and can be categorised depending on their analytical framework.

A first category is made up of those contributions that consider growth models without non-renewable resources. Solow (1956, 1957) proposed the neoclassical growth model in which factor accumulation can only explain about half the variation in the growth rate. What remains, known as the Solow residual, is attributed to the growth in technical progress or total factor productivity. This model implies that the long run growth rate of an economy depends on the rate

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[3] This literature is almost exclusively based on energy demand and the causality relationships between energy consumption and income. Some conceive that energy consumption depends on real income and energy prices (for instance see, Donatos and Mergos, 1991; Al-Mutairi and Eltony, 1995; Al-faris, 1997; Chakravorty *et al*., 2000; Rafiq, 2008; Rao and Rao, 2009) that may vary with temperature, construction activity, etc (for instance see, Tserkezos, 1992; Al-Azzam and Hawdon, 1999; Hondroyiannis, 2004; De Vita *et al*., 2006) while others suggest that energy consumption is price and income inelastic (Al-faris, 1997; Rao and Rao, 2009; Chakrovorty *et al*., 2000). Cointegration relationships between energy consumption per capita and output have been identified elsewhere. For instance, Al-Azzam and Hawdon (1999) found a long run cointegrating relationship between energy consumption, real income, real energy prices and construction activity for Jordan between 1968 and 1997, De Vita *et al*. (2006) identified a cointegrating relationship between energy consumption, real GDP and air temperature for Namibia between 1980 and 2002, Lise and Montfort (2007) found that energy consumption and real income were cointegrated for Turkey between 1970 and 2003, Rafiq (2008) found a significant relationship between energy consumption, real income and energy price for six emerging economies from Asia (China, India, Indonesia, Malaysia, Philippines and Thailand) for the period 1965-2006. The evidence is mixed regarding the direction of causality between energy consumption and income. For instance, Kraft and Kraft (1978) found unidirectional causality running from income to energy consumption for USA as did Yu and Choi (1985) for Korea, Masih and Masih (1996) for Indonesia, Cheng and Lai (1997) for Taiwan, Soytas and Sari (2003) for South Korea and Al-Iriani (2006) for *GCC* countries. Stern (2000) found that a quality-weighted index of energy input Granger-causes GDP in the USA. However, some studies found unidirectional causality running from energy consumption to income, for instance see Yu and Choi (1985) for Philippines, Cheng (1997) for Brazil, Masih and Masih (1996) for Korea, Asafu-Adjaye (2000) for India, Indonesia and Turkey, Soytas and Sari (2003) for Turkey, Wolde-Rufael (2004) for Shanghai and Lee (2005) for 18 developing countries. Other studies found bi-directional causality between energy consumption and income, for instance see Hwang and Gum (1992) for Taiwan, Masih and Masih (1996) for Pakistan, Yang (2000) for Taiwan, Glasure (2002) for Korea, Hondroyiannis *et al*. (2002) for Greece, Soytas and Sari (2003) for Argentina and Oh and Lee (2004) for Korea.

of technical progress in spite of the factors that determine total factor productivity being unknown.[4] There is a consensus that a country's savings rate is important in explaining the Solow residual, with empirical evidence showing that *if the savings rate increases then it will generate a shift in the level of output with no growth effect* and, based on the rebound subsection above, an equally plausible argument is that energy consumption may also contribute to the enhancement of total factor productivity output though the effect on growth is less clear.

A second category of studies considered growth models with non-renewable resources but without technological change. The neoclassical paradigms in this strand seem to focus on the conditions that allow for sustainable growth with technical and institutional conditions determining whether sustainability – defined as non-declining consumption – is possible (see Stern and Cleveland, 2004). Solow (1974) showed that sustainability is attainable in a model with finite and non-renewable natural resources with no extraction costs and non-depreciating capital; here, sustainability is achieved through using capital and natural resources when their elasticity of substitution is unity. But this finding generated immense debate in this literature; for instance, Stiglitz (1974) and Dasgupta and Heal (1979) argued that this model highlights resource depletion and social welfare problems while both Hartwick (1977, 1995) and Dixit *et al*. (1980) showed that if sustainability is technically feasible then a constant level of consumption can be achieved by reinvesting the resource rents into other forms of capital, which subsequently permit resource substitution (Stern and Cleveland, 2004, p.11).

The third category of studies utilized endogenous growth models with non-renewable resources. Although research on this front has been shown to be somewhat limited (see Smulders and de Nooij's, 2003), Aghion and Howitt (1998) did utilize endogenous growth models to analyze both renewable and non-renewable resources and inferred that sustainable growth is feasible when using renewable resources that do not affect utility. Similarly optimistic results were obtained by Tahvonen and Salo (2001) who developed a model incorporating both renewable and non-renewable energy resources and bore results that seem to explain growth better than Solow's (1974) exogenous growth model.

Extending the neoclassical growth model to include energy

Extensions of the Solow (1956) model are not new. Prior to the early 1990s, there was the common view that the neoclassical growth model performed unsatisfactorily not least because of the prediction that capital's share of output is about 1/3rd, which is fairly inconsistent with actual data. Augmentation of the neoclassical growth model was most notably carried out by Mankiw *et*

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[4] The popular endogenous growth models started with Romer (1986) in which he explained that externalities can explain the Solow residual. This idea goes back to Arrow (1962) who argued that externalities, arising from learning by doing and knowledge spillovers, positively affect labour productivity at the aggregate level: since knowledge, by and large, is a non-rivalrous good, there are no diminishing returns and any increase in knowledge will have permanent growth effects. Elsewhere, Lucas (1988) and Barro (1991) showed that human capital creation and public infrastructure investments determine the Solow residual, respectively, while Romer (1990) and Grossman and Helpman (1991) found that expenditure on R&D (i.e. creation of knowledge capital / stock of ideas) is the most important determinant of the Solow residual. As the long run growth rates of all the factors identified by the endogenous growth models need not be zero they can be said to have permanent growth effects. To this end, implementing policies to increase these factors can increase growth rate in the short, medium and long runs. Schumpterian growth models are also a class of *EGM*; see Aghion and Howitt (1998).

al. (1992) who extended the Solow model to include human capital. Models similar to Mankiw *et al*. can be effectively applied to estimate the level and growth effects of variables of interest and hence are observationally equivalent to endogenous growth models (Rao, 2010). Brock and Taylor (2010) augmented the Solow model to incorporate technological progress in abatement and examined the relationship between growth and environmental outcomes, arguing consequently that the environmental Kuznets curve is a necessary by-product of convergence to a sustainable growth path.

An alternative approach is to employ endogenous growth models similar to Romer (1986, 1990), Lucas (1988) and Barro (1991, 1999). While these models are useful they do have a few limitations (see Parente, 2001). First, they are difficult to estimate because their structural equations are intrinsically non-linear in parameters and variables (Greiner *et al*., 2004). Second, since the dependent variable is the long run rate of growth it is necessary to proxy this rate with the average growth rate over longer time spans, which reduces the number of observations for estimation and makes it necessary to estimate endogenous growth models with a large cross-section dimension. Third, there is no theoretical endogenous growth model where more than two variables are employed. Consequently, empirical investigations based on endogenous growth models mainly use *ad hoc* specifications (Easterly *et al*., 2002).

Due to these concerns, we utilise the insights of Mankiw *et al*. (1992) and Rao (2010) to augment the Solow model with energy consumption per capita and to yield insights into whether energy consumption produces permanent effects on the level and/or growth rate of output. Accordingly, let the Cobb-Douglas production function with constant returns and Hicks-neutral technical progress be:

$$y_t = A_t k_t^{\alpha} \qquad 0 < \alpha < 1 \qquad (1)$$

where y is per worker output, A is stock of technology and k is per worker capital stock. It is well known that the steady state growth rate in the Solow model equals the rate of growth of A. It is common in the Solow model to assume that the evolution of technology is given by:

$$A_t = A_0 e^{gT} \qquad (2)$$

where A_0 is the initial stock of knowledge and the time trend is expressed as T and hence the steady state growth rate of output per worker is equal to g.

Next we introduce energy consumption (E) into the production function. To this end, the general form of the extended Solow model is given by:

$$y_t = A_0 e^{(\beta \ln E_t + g \ln E_t \times T)} k_t^{\alpha} \qquad (3)$$

Finally, the log specification of equation (3) in the panel form is:

$$\ln y_{it} = intercept + \alpha \ln k_{it} + \beta \ln E_{it} + g\,(\ln E_{it} \times T) \qquad (4)$$

where β and g capture the permanent level and growth effects of energy consumption per capita, respectively.

3. Data

Extant empirical studies of the effect of energy consumption on output have mainly employed time series and panel data estimation methods. Our sample consists of Bahrain (BRN), Canada (CAN), Finland (FIN), Iceland (ISL), Kuwait (KUW), Luxembourg (LUX), Norway (NOR), Qatar (QAT), Saudi Arabia (KSA), Sweden (SWE), Trinidad and Tobago (TRI), United Arab Emirates (UAE) and United States (USA) for which annual data on output per capita, capital per capita and total energy consumption per capita are available from 1971-2009. These countries are selected because they are the leading consumers of energy.[5]

Figure 2 illustrates the behaviour of total energy consumption per capita in these thirteen countries. Referring to 2009 per capita values, it is observed that Trinidad and Tobago and Qatar are the leading consumers of energy while countries such as Bahrain, Finland, Norway, Saudi Arabia, Sweden and Kuwait consume around 4,000 kilotonnes of oil equivalent.[6] The averages of output per worker, capital per worker and total energy consumption per capita for the panel are 13789.02 (US$), 2662.07 (US$) and 5178.58 (kilotonnes of oil equivalent), respectively.

{Figure 2 about here}

4. Results

There is some consensus in the literature that panel data models are likely to exhibit substantial cross-sectional dependence in the errors. This may be due to the presence of common shocks and/or unobserved components that ultimately become part of the error term. One reason for this result may be the increasing integration between countries, which can imply strong interdependencies between cross-sectional units. It is also possible that there were shifts in time series observations due to some events, and not controlling for structural change in time series estimations can lead to large forecasting errors and unreliable results. This paper fills a gap in the literature by utilizing panel data methods that are efficient in addressing cross-sectional dependence and structural breaks to investigate the relationship between energy consumption and output.

Panel unit root tests

The first step is to assess the degree of integration of the series. In doing so, we apply the panel unit root tests of Pesaran (2007) and Im and Lee (2001). Pesaran (2007) proposed a second generation panel unit root test which assumes a unit root as the null hypothesis. This test is a cross-sectionally augmented version of the Im, Pesaran and Shin (CIPS) test and is less

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[5] The World Resources Institute ranks countries according to their total energy consumption per capita. Netherlands Antilles is excluded due to inconsistent data availability.

[6] The data on output per worker (measured in constant 2000 US$) and capital per worker[6] (measured in constant 2000 US$) is obtained from the World Development Indicators (2011) and total energy consumption per capita (measured in kilotonne of oil equivalent) is extracted from the International Energy Agency (2011) database.

restrictive and more powerful when compared to the tests developed by Levin *et al*. (2002) and Breitung (2000) which do not allow for heterogeneity in the autoregressive coefficient. An innovative feature of the Pesaran (2007) test is that it allows for cross-sectional dependence in the errors. In contrast, the Im and Lee (2001) test based on the lagrangian multiplier (LM) principle is a first generation panel unit root test. The unit root null is rejected when the panel LM statistic is greater than the critical absolute value. The value-added of this test is that it is more powerful in the basic scenario where no level shifts are involved as well as being robust to the presence of level shifts. Further, this test does not require the simulation of new critical values that depend on the number and location of breaks.

Table 1 reports the results for both Pesaran (2007) and Im and Lee (2001) tests. For all level variables, the Pesaran test does not reject the null of a unit root at the 5% level. With regard to the first differences of the series, the test statistics are greater than the 5% critical absolute value and thus the null is undoubtedly rejected. The Im and Lee test results offer qualitatively identical conclusions, and they indicate that for the level (first difference) variables the panel LM test statistics with or without a break cannot (can) reject the unit root null at the 5% level. Thus, based on these findings we infer that y, k and E are $I(1)$ in levels and $I(0)$ in first differences.

{Table 1 about here}

Tests for cointegration

The cointegration among the variables in equation (4) is tested with the Westerlund's (2007) error correction panel method. To test if the null hypothesis of no cointegration can be rejected, Westerlund (2007) has developed two group-mean tests (G_τ and G_α) and two analogous panel tests (P_τ and P_α). These four test statistics are normally distributed. G_τ and P_τ are computed with the standard errors in a standard way while G_α and P_α are based on Newey and West's (1994) adjusted standard errors for heteroskedasticity. To overcome possible finite sample bias, bootstrap values of these four test statistics can be generated and used. In the two group-mean based tests, the alternative hypothesis is that there is cointegration at least in one cross section unit, which is the same in many traditional panel cointegration tests. Therefore, the adjustment coefficient may be heterogeneous across the cross-section units. On the other hand, in the two panel data based tests, the alternative hypothesis is that adjustment to equilibrium is homogenous across cross-section units.

Cointegration test results for equation (4) are displayed in Table 2.[7] Table 2 reports the results using a deterministic intercept and one-period lead and lag values.[8] The results indicate that all four tests reject the null of no cointegration at the 5% level, except for P_τ which rejects it at the 10% level.

{Table 2 about here}

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[7] Estimates of these four test statistics with a deterministic trend, not included here for brevity, reveal that the null hypothesis of no cointegration could be rejected at the 5% level.

[8] The length for the Bartlett kernel window was set at 3, which is closer to $T^{(1/3)}$, and the computation of bootstrap standard errors were based on 500 replications.

Further, we also tested for cross-sectional independence in the errors. The Breusch-Pagan LM test statistic was statistically significant at the 1% level which strongly indicates the presence of common factors affecting the cross-sectional units. Therefore, we bootstrapped robust critical values for the test statistics. Overall, the results imply that there exists a long run cointegrating relationship among the variables in equation (4).

Level and growth effect estimates

Having confirmed the existence of a long run relationship between the variables in equation (4), it is intuitively appealing to estimate the respective parameters to determine whether energy consumption contributes to the level of output or its rate of growth. Mark and Sul (2003) and Breitung (2005) techniques were utilized to estimate the cointegrating vector. Mark and Sul's (2003) and Breitung's (2005) methods differ in their treatment of the intercept, trend and variables that influence dynamic adjustments in the estimation of cointegrating equations.

Mark and Sul's (2003) technique, which is based on dynamic OLS estimation of a homogeneous cointegration vector for a balanced panel of N individuals observed over T time periods, allows for heterogeneity across individuals and these include individual-specific time trends, individual-specific fixed effects and time-specific effects. This estimator is entirely parametric and allows for a limited amount of cross-sectional dependence in the residuals.

The two-step technique proposed by Breitung (2005) is also parametric but it is classified as a second generation panel test and addresses the cross-sectional dependence in the errors. This technique estimates all individual-specific short run parameters in the first step and estimates the long run parameters from a pooled regression in the second step. Breitung's test procedure allows us to test a number of cointegrating relationships and to estimate a likelihood ratio statistic for testing hypotheses on the long run parameters.

Table 3 presents the Mark and Sul (2003) and Breitung (2005) estimates of equation (4). Both techniques yield consistent results. In the fixed effects model, the estimates for the level effect of energy consumption on output is around 0.08 and are statistically significant at the 1% level. The level effect estimate in the random effects model is of a similar magnitude (around 0.06) and is statistically significant at the 5% level. In all cases, the estimates of the impact of energy consumption on economic growth is positive and very small in magnitude (around 0.001 to 0.002) and are statistically insignificant at conventional levels. Furthermore, our capital share estimates are reasonable and not out of step with a priori expectations.

{Table 3 about here}

With these findings, we infer that energy consumption has a significant permanent level effect on output but there is no evidence that it contributes significantly to the rate of growth. These results are entirely within the bounds of the theoretical literature presented above, which highlights the plausibility of finding level effects but potential uncertainty of the effect of energy consumption on growth.

Robustness checks

Since the extended Solow model yields statistically significant estimates with respect to the level impact of energy consumption on output it is deemed important to test the robustness of these results. Our first robustness check tests for the presence of structural breaks using the Westerlund (2006) technique. This method tests the null hypothesis of cointegration that accommodates structural change in the deterministic component of a cointegrating panel regression. The test is based on the *LM* cointegration test of McCoskey and Kao (1998) and allows for structural breaks in both intercept and trend, which may be located at different dates for different countries. We search for break dates to construct appropriate sub-samples upon which we can assess the robustness of the results. For the purpose of developing sub-samples, we tested for two dominant breaks and our results are reported in Table 4.

{Table 4 about here}

The results reveal that there exist two breaks for USA, Qatar, United Arab Emirates, Kuwait and Luxembourg with the remaining eight countries (Bahrain, Canada, Finland, Iceland, Norway, Saudi Arabia, Sweden and Trinidad and Tobago) having only one break. Three common break dates are observed across the sample: 1984 (four countries: USA, United Arab Emirates, Saudi Arabia and Norway), 1994 (three countries: Bahrain, Canada and Luxembourg) and 1998 (four countries: Sweden, Finland, USA and Qatar). These break dates are plausible given the underlying economic changes/difficulties experienced by each country at those times, as highlighted in the footnote of Table 4. Together with other robustness scenarios, we utilize these break dates to develop sub-samples in order to investigate whether structural changes have influenced our estimates of the extended Solow model.

To assess robustness of the estimates in our extended Solow model, we estimated ten variants of the model, namely (i) sample prior to Westerlund break 1984 (i.e. 1971-1983), (ii) sample after Westerlund break 1984 (1985-2009), (iii) sample prior to Westerlund break 1994 (1971-1993), (iv) sample after Westerlund break 1994 (1995-2009), (v) sample prior to Westerlund break 1998 (1971-1997), (vi) sample after Westerlund break 1998 (1999-2009), (vii) exclude oil crisis period (1974-2009), (viii) exclude global financial crisis period (1971-2006), (ix) USA country-specific sample and (x) Trinidad and Tobago country-specific sample.[9] Equations (i) to (viii) were estimated with the Breitung's two-step estimator and, since the samples for Trinidad and Tobago and the USA are based on pure time series data, equations (ix) and (x) were estimated using the canonical cointegrating regression method of Park (1992).

Our results are displayed in Table 5. Overall, the results are found to be quite robust in the different variants considered. In particular, it is notable that the coefficients of the level (growth) effect of energy consumption are statistically significant (insignificant) at the conventional levels. However, some exceptional estimates are observed, for example in the sub-samples 1994-2009 and 1998-2009 the level effect estimates are slightly higher at around 0.3. The capital share of output varies from 0.32 to 0.45, except for Trinidad and Tobago where it is around 0.53. Further, with the exception of the 1998-2009 sub-sample, the capital share in all

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[9] We select Trinidad and Tobago and the USA samples because the former has the highest per capita energy consumption (in 2009) while the latter is the dominant country (in terms of economic activity) in our sample.

other equations is statistically significant at conventional levels. Based on these results, we infer that our original extended Solow model estimates presented in Table 3 are robust and that energy consumption has permanent level effects on output but not statistically significant effects on economic growth; both should be expected given our cited underlying theory.

{Table 5 about here}

These results imply that greater energy consumption will normally feed through into greater output, and that constraining energy consumption may constrain output levels. However, any policies that are designed to affect energy consumption will not necessarily have clear and easily identifiable impacts on growth because communities respond to such policies in different ways depending on whether such goods are considered normal or inferior. Put another way, any policies designed to reduce energy consumption will not necessarily reduce rates of economic growth, especially if they are introduced concomitantly with or preceded by other policies designed to find ways to produce output with more energy efficient production techniques.

5. Conclusions

There is an ongoing debate in the academic literature concerning the effect of energy consumption on output and growth. This paper contributes to this literature by articulating underlying consumption preferences and behaviour via rebound effects that can confound estimates and understanding of this complex relationship. The paper has presented an augmentation of the neoclassical growth model of Solow (1956) to include energy consumption per capita and has assessed the contributory effect of energy on output for a sample of thirteen high energy consuming countries over the period 1971 to 2009.

Application of the data to Pesaran (2007) and Im and Lee (2001) techniques and panel data methods that are efficient in addressing cross-sectional dependence and structural breaks revealed that the variables in the panel are $I(1)$ in levels. Application of Westerlund's (2007) panel error correction method revealed that there exists cointegration among the variables in the extended Solow model. The panel cointegrating equations were estimated using the Mark and Sul's (2003) DOLS and Breitung's (2005) two-step techniques and the results provide evidence which suggest that energy consumption has a significant permanent level effect on output, which are quite small in magnitude and may correspond only to direct rebound effects; however, application of these methods reveals no statistical evidence that energy consumption contributes or constrains the rate of economic growth. The robustness of these results was examined through application of Westerlund's (2006) structural break test and this revealed three common break dates for parts of the sample. We estimated ten variants of the extended Solow model and found evidence to suggest our earlier results are stable.

Our findings imply that the energy consumption-economic growth relationship should be interpreted cautiously. This literature is almost superfluous that energy consumption drives economic growth and hence maintains that energy conservation policies will reduce economic growth. Evidence in this paper questions the existing findings and suggests that energy consumption per capita has no significant impact on growth: energy conservation policies will reduce only the level of output. Any attempts to identify the effect on the environment of policies to stimulate economic growth may never be correctly forecasted due to uncertainties associated with behaviour responses to policy change related to rebound effects.

References

Aghion, P. and Howitt, P. (1998) *Endogenous growth theory*, Cambridge, MA: MIT Press.

Arbex, M. and Perobelli, F. S. (2010) “Solow meets Leontief: economic growth and energy consumption,” *Energy Economics* 32(1), 43-53

Arrow, K. (1962) “The economic implications of learning by doing,” *The Review of Economic Studies* 29, 155- 173

Barro, R. J. (1991) “Economic growth in a cross section of countries,” *Quarterly Journal of Economics* 106, 407-33

Barro, R. J. (1999) *Determinants of economic growth*. Cambridge, MA: The MIT Press.

Breitung, J. (2000) “The local power of some unit root tests for panel data,” in Baltagi, B. (ed.) *Advances in Econometrics: Non-stationary panels, panel cointegration, and dynamic panels*, JAI Press, Amsterdam, 161-178

Breitung, J. (2005) “A parametric approach to the estimation of cointegration vectors in panel data,” *Econometric Reviews*, 24,151-173.

Brock, W.A. and Taylor, M.S. (2010) “The green Solow model,” *Journal of Economic Growth* 15, 127-153.

Brooks, (1990) “The greenhouse effect: the fallacies in the energy efficiency solution,” *Energy Policy* 18, 199-201

Carruth, A. A., Hooker, M. A. and Oswald, A. J. (1998) “Unemployment equilibria and input prices: theory and evidence from the United States,” Review of Economics and Statistics 80(4), 621-628

Dasgupta, P. S. and G. M. Heal (1979) *Economic Theory and Exhaustible Resources*, Cambridge University Press

Dixit, A., Hammond, P. and Hoel, M. (1980) “On Hartwick's rule for regular maximin paths of capital accumulation and resource depletion,” *Review of Economic Studies* 47, 551-556

Easterly, W., Levine, R. and Roodman, D. (2002) “New data, new doubts: A comment on Burnside and Dollar’s aid, policies, and growth,” *American Economic Review* 94, 774-80

Georgescu-Roegen, N. (1976) *Energy and economic myths*: *Institutional and analytical economic essays,* Pergamon Press: New York.

Georgescu-Roegan, N. (1975) “Energy and economic myths,” *Southern Economic Journal* 41, 347-83.

Ghali, K. H. and El-Sakka, M. I. T. (2004) “Energy use and output growth in Canada: A multivariate cointegration analysis,” *Energy Economics 26*, 225-238.

Greening, L., Greene, D. L. and Difiglio, C. (2000) “Energy efficiency and consumption – the rebound effect: a survey,” Energy Policy 28, 389-401

Greiner, A., Semler, W. and Gong, G. (2004) *The forces of economic growth: A time series perspective,* Princeton University Press, Princeton, NJ.

Grossman, G. M. and Helpman, E. (1991) *Innovation and growth in the global economy*, MIT Press, Mass

Grubb, M. J. (1990) “Energy efficiency and economic fallicies,” Energy Policy 18, 783-85

Hartwick, J. M. (1977) “Intergenerational equity and the investing of rents from exhaustible resources,” *American Economic Review* 66, 972-974

Hartwick, J. M. (1995) “Constant consumption paths in open economies with exhaustible resources,” *Review of International Economics* 3, 275-283.

Im, K.S. and Lee, J. (2001) “Panel LM unit root test with level shits,” Technical Report, Department of Economics, University of Central Florida

Khazzoom, D. J. (1980) “Economic implications for mandated efficiency in standards for household appliances,” Energy Journal 1, 21-40

Knowles, S. and Owen, P. D. (1995) “Health capital and cross-country variation in income per capita in the Mankiw-Romer-Weil model,” *Economics Letters* 48(1), 99-106

Jevons, W. S. (1866) *The coal question*, MacMillan, London

Lee, C.C., Chang, C.P. and Chen, P.F. (2008) “Energy–income causality in OECD countries revisited: the key role of capital stock,” *Energy Economics* 30, 2359-2373

Lee, C. C. and Chiang, C. (2008) “Energy consumption and economic growth in Asian countries: a more comprehensive analysis using panel data,” *Resource and Energy Economics* 30, 50-65.

Levin, A., Lin, C.F. and Chu, C. (2002) “Unit root tests in panel data: asymptotic and finite sample properties,” *Journal of Econometrics* 108, 1-24

Lovins, A. B., Henly, J., Ruderman, H. and Levine, M. D. (1988) “Energy saving resulting from the aoption of more efficiency appliances: another view: a follow up,” *Energy Journal* 9, 155

Lucas, R. E. Jr. (1988) “On the mechanics of economic development,” *Journal of Monetary Economics,* 22, 3-42

Mankiw N G., Romer, D. and Weil, D. (1992) “A contribution to the empirics of economic growth,” *Quarterly Journal of Economics* 2, 407-437

Margolis, R. M. and Kammen, D. M. (1999) “Underinvestment: the energy technology and R&D policy challenge”, *Science* 285(5428), 690-692

Mark, N.C. and Sul, D. (2003) “Cointegration vector estimation by panel DOLS and long-run money demand,” *Oxford Bulletin of Economics and Statistics* 65, 655-680

McCoskey, S. and Kao, C. (1998) “A residual-based test of the null of cointegration in panel data,” *Econometric Reviews* 17, 57-84

Newey, W. K. and West, K. D. (1994) “Automatic lag selection in covariance matrix estimation,” *Review of Economic Studies* 61, 631-653

Oh, W. and Lee, K. (2004) “Causal relationship between energy consumption and GDP revisited: the case of Korea 1970–1999,” *Energy Economics* 26, 51-59

Parente, S.J. (2001) “The failure of endogenous growth,” *Knowledge, Technology and Policy* 13, 49-58

Park, J. (1992) “Canonical canonical regressions,” *Econometrica* 60, 119-143

Perlo-Freeman, S. and Webber, D. J. (2009) “Basic needs, government debt and economic growth,” *World Economy* 32(6) 965-994

Pesaran, M. H. (2007) “A simple panel unit root test in the presence of cross section dependence,” *Journal of Applied Econometrics*, 22, 265-312

Rao, B. B. (2010) “Time-series econometrics of growth-models: A guide for applied economists,” *Applied Economics* 42, 73-86

Romer, P. M. (1986) “Increasing returns and long run growth,” *Journal of Political Economy* 94, 1002-1037

Romer, P. (1990) “Endogenous technological change,” *Journal of Political Economy* 98, S71-8103

Sari, R. and Soytas, U. (2007) “The relationship between energy and production: Evidence from Turkish manufacturing industry,” *Energy Economics* 29, 1151-1165

Saunders, H. (1992) “The Khazzom-Brookes postulate and neoclassical growth,” *Energy Journal* 13, 131-148

Solow, R. M. (1956) “A contribution to the theory of economic growth,” *Quarterly Journal of Economics* 70, 65-94

Solow, R.M. (1957) “Technological change and the aggregate production function,” *Review of Economics and Statistics* 39, 312-320

Solow, R. M. (1974) “Intergenerational equity and exhaustible resources,” *Review of Economic Studies*, Symposium on the Economics of Exhaustible Resources: 29-46.

Soytas, U. and Sari, R. (2003) “Energy consumption and GDP: causality relationship in G-7 countries and emerging markets,” *Energy Economics* 25, 33-37.

Smulders, S. and de Nooij, M. (2003) “The impact of energy conservation on technology and economic growth,” *Resource and Energy Economics* 25, 59-79.

Stern, D. (2000) “A multivariate cointegration analysis of the role of energy in the US economy,” *Energy Economics 22*, 267-283

Stern, D. I. and Cleveland, C.J. (2004) “Energy and economic growth,” *Rensselaer Working Papers in Economics* No. 410

Stiglitz, J. E. (1974) “Growth with exhaustible natural resources: the competitive economy,” *Review of Economic Studies*, Symposium on the Economics of Exhaustible Resources: 139-152.

Tahvonen, O. and Salo, S. (2001) “Economic growth and transitions between renewable and non-renewable energy resources,” *European Economic Review* 45, 1379-1398

Venneslan, C. (2009) “Electrification and industrialization: An assessment of the industrial breakthrough in Norway,” *Scandinavian Economic History Review* 57(2), 124-155

Wackernagel, M. and Rees, W. (1997) “Perceptual and structural barriers to investing in natural capital: economics from an ecological footprint perspective,” *Ecological Economics* 20(3), 3-24

Westerlund, J. (2007) “Testing for error correction in panel data,” *Oxford Bulletin of Economics and Statistics*, 69, 709–748.

Westerlund, J. (2006) “Testing for panel cointegration with multiple structural breaks,” *Oxford Bulletin of Economics and Statistics* 68, 101-32

Wolde-Rufael, Y. (2008a) “The long-run relationship between petroleum imports and economic growth: the case of Cyprus,” *Resources, Energy and Developm*ent 5, 95-103

Wolde-Rufael, Y. (2008b) “Energy consumption and economic growth: The experience of African countries revisited,” *Energy Economics* 31, 217-224

Yuan, J., Kang, J., Zhao, C. and Hu, Z. (2008) “Energy consumption and economic growth revisited: evidence from China both at the aggregate and disaggregate level,” *Energy Economics* 30, 3077-3094

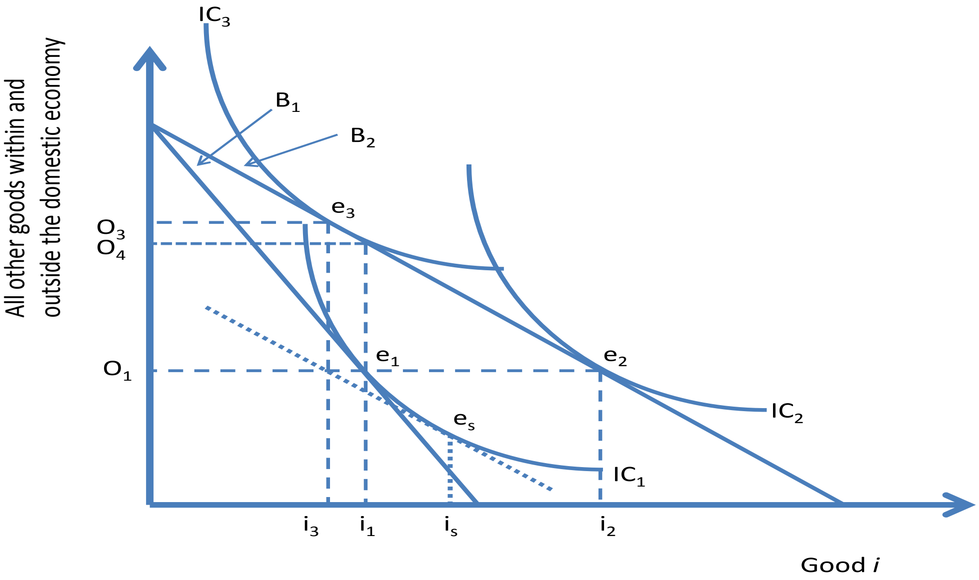

Figure 1: Hicksian decomposition into income and substitution effects

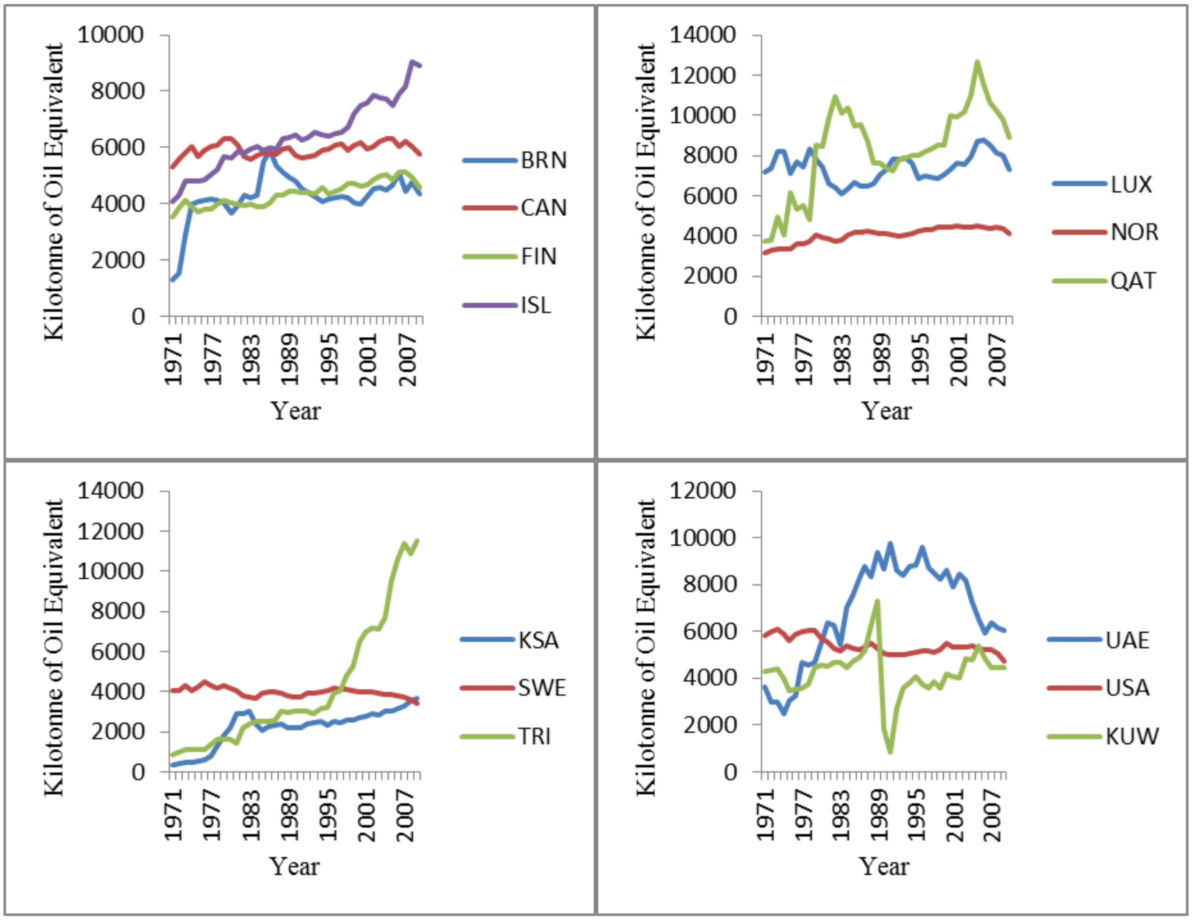

Figure 2: Plots of energy consumption per capita of selected countries

Table 1: Panel unit root tests, 1971-2009

Variables	Pesaran test	Im and Lee test	
	Test Statistic	Panel LM Statistic without a break	Panel LM Statistic with a break
$\ln y$	-1.732	-0.645	-0.994
$\Delta \ln y$	-4.350	-3.212	-1.850
$\ln k$	-2.008	-1.300	-1.047
$\Delta \ln k$	-6.735	-1.950	-3.024
$\ln E$	-0.936	-1.362	-0.265
$\Delta \ln E$	-4.371	-2.731	-2.472

Notes: In both tests, a constant and time trend is used. At the 5% level, the critical value for the Pesaran test is -2.83. The critical value for the panel LM test (with or without breaks) is -1.645.

Table 2: Westerlund cointegration tests, 1971-2009

$$\ln y_{it} = intercept + \alpha \ln k_{it} + \beta \ln E_{it} + g\,(\ln E_{it} \times T)$$

Statistics	Value	Z-value	P-value	Robust P-value
G_τ	-3.218	-1.700	0.002***	0.000***
G_α	-4.120	-0.952	0.043**	0.040**
P_τ	-2.735	-1.128	0.074*	0.061*
P_α	-6.005	-4.211	0.001***	0.000***

Breusch-Pagan LM test of independence: $\chi^2 =$ 34.116, Probability = 0.000

Notes: Statistical significance at 1%, 5% and 10% levels are denoted by ***, ** and *, respectively.

Table 3: Mark and Sul and Breitung estimates, 1971-2009

$$\ln y_{it} = intercept + \alpha \ln k_{it} + \beta \ln E_{it} + g\,(\ln E_{it} \times T)$$

	Mark and Sul's DOLS		Breitung's two-step
	Fixed Effects Model	Random Effect Model	Fixed Effects Model
Intercept	-	-	-
α	0.390 (6.72)***	0.415 (4.37)***	0.372 (7.56)***
β	0.084 (8.97)***	0.055 (2.46)**	0.076 (10.60)***
g	0.001 (1.35)	0.002 (0.98)	0.001 (1.03)

Notes: *** and ** denotes significance at 1% and 5% levels, respectively. The absolute t-statistics are reported in the parentheses.

Table 4: Westerlund tests for structural breaks, 1971-2009

Country	USA	Qatar	Bahrain	Canada	Finland	Iceland	Luxembourg	Norway	Sweden	Saudi Arabia	Trinidad-Tobago	UAE	Kuwait
Number of breaks	2	2	1	1	1	1	2	1	1	1	1	2	2
Break Dates	1984 1998	1998 2004	1994	1994	1998	1990	1994 2004	1984	1998	1984	2003	1984 2004	1982 1991

USA: 1984 = financial deregulation; 1998 = volatility in stock market
United Arab Emirates: 1984 = enforcement of UAE-Turkey Agreement on Enhancing Economic and Technical Cooperation; 2004 = free trade agreement with USA
Saudi Arabia: 1984 = OPEC oil cuts production
Norway: 1984 = increasingly dependent on oil reserves which increased consumption, costs and prices significantly; 1986 = decline in oil prices and 20% fall in exports
Bahrain: 1994 = Gulf crisis, diversification initiatives and increased government expenditure
Canada: 1994 = enforcement of North American Free Trade Agreement (NAFTA)
Luxembourg: 1994 = GDP and inflation growth; 2004 = rapid economic growth
Sweden: 1998 = fiscal consolidation programme; expansionary monetary policy (lower interest rates)
Finland: 1998 = economic reforms and impacts by joining the EU
Qatar: 1998 = rapid economic growth; 2004 = increased foreign direct investment in technology sector
Kuwait: 1982 = stock market crash; 1991 = Gulf war impacts
Iceland 1990: trading in equities commenced
Trinidad and Tobago: 2003 = rapid economic growth

Table 5: Robustness checks

$$\ln y_{it} = intercept + \alpha \ln k_{it} + \beta \ln E_{it} + g\,(\ln E_{it} \times T)$$

	Westerlund Break 1984		Westerlund Break 1994		Westerlund Break 1998		Oil Crisis	GFC	USA	Trinidad-Tobago
Sample	1971-1983	1984-2009	1971-1993	1994-2009	1971-1997	1998-2009	1974-2009	1971-2006	1971-2009	1971-2009
Intercept	-	-	-	-	-	-	-	-	-9.140 (13.27)***	-3.108 (6.50)***
α	0.395 (1.74)*	0.422 (8.61)***	0.383 (4.58)***	0.452 (1.88)*	0.395 (4.80)***	0.319 (1.20)	0.361 (9.05)***	0.403 (6.70)***	0.401 (5.73)***	0.534 (6.70)***
β	0.029 (4.70)***	0.101 (5.27)***	0.046 (1.80)*	0.315 (2.81)**	0.061 (7.95)***	0.349 (1.82)*	0.084 (5.61)***	0.045 (2.36)***	0.025 (4.04)***	0.103 (3.46)***
g	0.005 (0.43)	0.071 (1.30)	0.001 (0.71)	0.105 (1.26)	0.009 (0.84)	0.113 (1.15)	0.090 (0.82)	0.001 (0.99)	0.005 (0.80)	0.028 (1.19)

Notes: Breitung's two-step fixed effects estimates are reported. Equations for USA and Trinidad-Tobago are estimated with the time series method of Park (1992) i.e. canonical cointegration regression (CCR) method. GFC means global financial crisis. Absolute *t*-statistics are reported in the parentheses. ***, ** and * denotes statistical significance at the 1%, 5% and 10% levels, respectively.